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Bioenergy potentials from forestry in 2050

An assessment of the drivers that determine the potentials

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Abstract The purpose of this study was to evaluate the global energy production potential of woody biomass from forestry for the year 2050 using a bottom-up analysis of key factors. Woody biomass from forestry was defined as all of the aboveground woody biomass of trees, including all products made from woody biomass. This includes the harvesting, processing and use of woody biomass. The projection was performed by comparing the future demand with the future supply of wood, based on existing databases, scenarios, and outlook studies. Specific attention was paid to the impact of the underlying factors that determine this potential and to the gaps and uncertainties in our current knowledge. Key variables included the demand for industrial roundwood and woodfuel, the plantation establishment rates, and the various theoretical, technical, economical, and ecological limitations related to the supply of wood from forests. Forests, as defined in this study, exclude forest plantations. Key uncertainties were the supply of wood from trees outside forests, the future rates of deforestation, the consumption of woodfuel, and the theoretical, technical, economical, or ecological wood production potentials of the forests. Based on a medium demand and medium plantation scenario, the global *theoretical* potential of the surplus wood supply (i.e., after the demand for woodfuel and industrial roundwood is met) in 2050 was calculated to be 6.1 Gm^3 (71 EJ) and the *technical* potential to be 5.5 Gm^3 (64 EJ). In practice, *economical* considerations further reduced the surplus wood supply from forests to 1.3 Gm^3 year^{-1} (15 EJ year^{-1}). When *ecological* criteria were also included, the demand for woodfuel and industrial roundwood exceeded the supply by 0.7 Gm^3 year^{-1} (8 EJ year^{-1}). The bioenergy potential from logging and processing residues and waste was estimated to be equivalent to 2.4 Gm^3 year^{-1} (28 EJ year^{-1}) wood, based on a medium demand scenario. These results indicate that forests can, in theory, become a major source of bioenergy, and that the use of this bioenergy can, in theory, be realized without endangering the supply of industrial roundwood and woodfuel and without further deforestation. Regional shortages in the supply of industrial roundwood and woodfuel can, however, occur in some regions, e.g., South Asia and the Middle East and North Africa.

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1 Introduction

A rapid increase of the concentration of CO_2 and other greenhouse gasses in the atmosphere must be prevented to avoid an anthropogenic change in the climate system. Forests can contribute to this goal, because forests have the potential to absorb CO_2 and sequester the carbon in their biomass for long periods of time. Roughly half of the total terrestrial carbon stock is stored in forests and forest soils, equal to 1146 Gt C (Dixon et al. 1994). Carbon sequestration by forests has received widespread attention and extensive literature is available on the issue (e.g., Dixon et al. 1994; Houghton 1999; Stinson and Freedman 2001; Zhang and Xu 2003). However, discussions about the contribution of forests to greenhouse gas mitigation require a broader perspective since there are various competing ways in which forests can contribute to greenhouse gas mitigation. For example, forest biomass can also be used as a renewable and CO_2 neutral source of energy. In this study, the focus is on the potential contribution of forest biomass for energy use.

In 2001 traditional biomass usage (e.g., the use of woodfuel and manure for cooking and heating), referred to further as (traditional) woodfuel, accounted for 39 EJ year^{-1} or 9.3% of the global primary energy consumption, while modern biomass usage (e.g., the use of biomass for electricity or fuel generation), made up 6 EJ year^{-1} or 1.4% of the global primary energy consumption (Turkenburg 2000; IEA 2003). The focus of the present study was on the energy potential of woody biomass from forestry in the year 2050 (from now on also referred to as woody biomass), whereby woody biomass from forestry was defined as all of the aboveground woody biomass of trees, including all products made from woody biomass. This includes the harvesting, processing and use of woody biomass.

Various scenario studies were performed during the past decades to estimate the future demand and supply of bioenergy (Lashof and Tirpak 1990; Hall et al. 1993; WEC 1994; Fujino et al. 1999; IPCC 2000; Rogner 2000; Fischer and Schrattenholzer 2001; Hoogwijk 2004). Published estimates of the total global bioenergy production potential in 2050, for example, ranged from 0 to 1135 EJ year^{-1} (Hoogwijk et al. 2003), 0–358 EJ year^{-1} of which came from woody biomass (Sørensen 1999; Hoogwijk et al. 2003). This large range of estimates was the result of:

- *Differences in the type of biomass included*. Many studies only included logging residues, processing residues, and discarded wood-based products (WEC 1994; Yamamoto et al. 1999), while others also included surplus forest growth (Fischer and Schrattenholzer 2001; Sørensen 1999).
- *Differences in the theoretical, technical, economical, or ecological limitations related to the supply of woody biomass for energy use*. Lazarus et al. (1993), for example, only considered the decrease in (traditional) woodfuel consumption projected for the coming decades, while Fischer and Schrattenholzer (2001) focused on the potential of removals from forests accessible for industrial roundwood production (Fischer and Schrattenholzer 2001).
- *Differences in data*. Data on key parameters, such as the consumption of woodfuel, the annual growth of forests, and the efficiency of conversion, were accompanied by considerable uncertainty (Brooks et al. 1996; FAO 1998b; WRI 1999; FAO 2001).

- *Differences in scope*. Most of the existing bioenergy potential assessments focused on either the demand (e.g., WEC 1994) or the supply (e.g., Yamamoto et al. 1999) of bioenergy and consequently ignored demand–supply interactions. Moreover, most of the studies reviewed ignored existing studies on the demand and supply of wood (e.g., Lazarus et al. 1993; Sørensen 2001)[1], despite the extensive literature and data on the subject (e.g., Solberg et al. 1996a, b; FAO 1998c; Sedjo and Lyon 1998). Further, few studies assessed the maximum potential supply of wood from plantations and forests taking into account various theoretical, technical, economical and/or ecological barriers. This is relevant considering the potentially very large demand for (bio)energy.

In addition, attention was rarely paid to the uncertainties and ranges in data and to the impact of assumptions regarding the underlying factors that determine the energy potential of woody biomass from forestry.

The aim of the present study was to project the energy production potentials of woody biomass from forestry in the year 2050. Particular consideration was given to the data and projections from existing studies and the factors that determine the energy production potential of woody biomass. First, an extensive literature study of existing databases and outlook studies was carried out. Then, the most important factors that determine the bioenergy potential of woody biomass were identified. Finally, an Excel spreadsheet tool was constructed to identify and quantify the key factors that determine the energy potential of woody biomass and in which the various databases and scenarios derived from literature could be combined. Specific attention was paid to the theoretical, technical, economical, and ecological limitations of biomass production from forests. One sub-objective of the study was to identify the gaps and weak spots in the current knowledge base and their implications for the reliability of the calculated energy potential of woody biomass.

The results of this exercise are available at the national level, but in this paper results have been generated at a regional level. Eleven regions are distinguished based on the definition of regions used by the Food Agricultural Organisation (FAO 2003b)[2]: North America, Oceania, Japan, West Europe, East Europe, the C.I.S. and Baltic States, Sub-Saharan Africa, the Caribbean and Latin America, Middle East and North Africa, East Asia, and South Asia.

2 Approach

Figure 1 gives an overview of the key elements included in this study.

The demand for wood was defined as the demand for industrial roundwood plus the demand for woodfuel. The term ‘woodfuel’ refers to the use of woody biomass for cooking

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[1] For example, Lazarus et al. (1993) assumed a rapid transition from the use of traditional biomass fuels to the use of fossil and renewable fuels, while most existing studies projected a constant or increasing use of traditional biomass fuels (e.g., Solberg et al. 1996a, b; IMAGE-team 2001). Another example is the study by Sørensen (2001), who used the percentage of 30% to represent the fraction of the total annual woody biomass production in 2050 that is available for bioenergy, without specifying the future demand for industrial roundwood and traditional woodfuel.

[2] The definition of regions used in this study varies slightly from that used by the FAO, because for practical reasons small countries (mainly small island states) included in the FAO definition of regions were excluded from this study. Considering the limited size of these countries and the overall precision of the projection method, the exclusion of these countries did not have an impact on the results or conclusions of this study. Similarly, the use of data from various datasets that vary slightly with respect to the countries included, the definition of regions, and the year did not have an impact on the results of conclusions in this study.

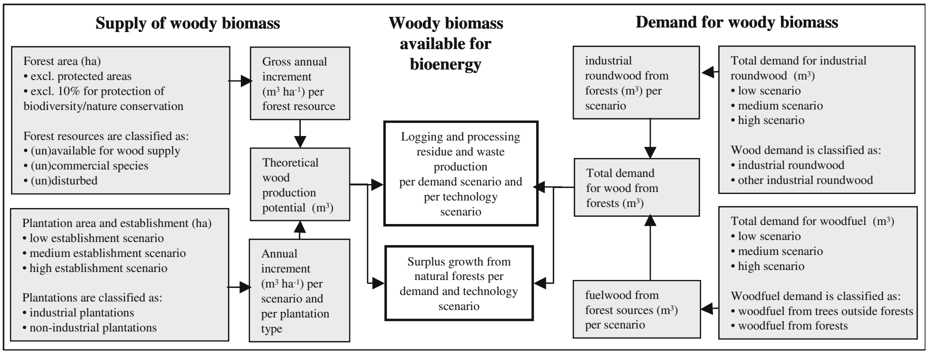

Figure 1 Overview of key parameters included in this study.

and heating, mainly in developing countries, and excludes modern biomass usage. The demand for wood is included by means of three scenarios (low, medium, and high demand) that we derived from the ranges found in the literature. Three sources of wood supply were included: plantations, trees outside forests, and natural forests. Note that natural forests as defined in this study excluded forest plantations and are referred to further as forests. Forests as defined in this study excluded plantations specifically planted for the production of modern bioenergy and are referred to further as plantations (see Section 3 for detailed definitions). Trees outside forests are defined as all trees not belonging to forests or plantations. The supply of wood from plantations was also categorized into three scenarios (low, medium, and high plantation establishment); these scenarios differed with regard to the future rate of plantation establishment and the yield level. The supply of wood from trees outside forests was estimated based on a literature review. The potential supply of wood from forests was calculated by multiplying the area of forest by the annual forest growth per hectare. Five types of potentials of the supply of biomass from forests could be distinguished; they differed with respect to the theoretical, technical, economical, and ecological limitations for forest productivity[3]. The potential supply of bioenergy from wood was calculated by comparing the demand for industrial roundwood and woodfuel with the supply of wood from plantations, trees outside forests, and forests. The potential supply of bioenergy from residues (logging residues, processing residues, and discarded forestry products) was the consumption and harvest of wood multiplied by the appropriate residue generation ratios and recoverability fractions as described below.

2.1 Surplus forest growth

In this study the bioenergy potential of forests was limited to surplus forest growth, which was defined as forest growth not needed for the production of woodfuel and industrial roundwood. Thus, the use of wood from forests as woodfuel and industrial roundwood was given priority above its use as modern bioenergy. The reason for this approach is that we

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[3] A distinction was made between five potentials for the wood supply from forests. The economical potential was estimated for both the demand and the supply of wood from sources other than natural forests, because the definition of the various potentials was only considered applicable for forest growth and/or a lack of data. For example, the theoretical demand for wood excluding the limitations of supply is obviously larger than the scenarios included in this study.

consider competition between the use of forest growth for modern bioenergy and its use for woodfuel and industrial roundwood to be unsustainable, because wood products can be a substitute for more energy-intensive products that require more fossil fuels for the production and/or can be a physical carbon pool. The global carbon stored in wood products is estimated to be 4.2 Pg (Brown et al. 1998). Competition may lead to the substitution of woodfuel and wood products for fossil fuels and this could (partially) offset the reduction of CO_2 emissions from the replacement of fossil fuels by bioenergy. Further, competition may hamper the supply of woodfuel and industrial roundwood and, consequently, economical growth. The surplus forest growth was calculated by means of a comparison of the demand and supply of woody biomass, following Equation (1) in the Appendix. On the supply side three sources of woody biomass were included:

- *Forests*. The supply of wood of forests was calculated by multiplying the forest area by the annual forest growth per hectare. Five types of potentials of wood supply from forests were included and, as a result of theoretical, technical, economical, and/or ecological barriers, differed with respect to the forest area and the forest productivity (Section 3.1).
- *Plantations*. Three scenarios were composed that represent the ranges found in the literature. They varied with respect to the rate of plantation establishment and yield level (Section 3.2).
- *Trees outside forests*. The contribution of trees outside forests to the supply of wood was estimated using values found in the literature and our own assumptions (Section 3.3).

On the demand side two categories were distinguished:

- *Industrial roundwood*. Three scenarios for the consumption of industrial roundwood in 2050 were composed based on the ranges found in the literature (Section 3.4).
- *Woodfuel*. Three scenarios for the consumption of woodfuel in 2050 were used based on the ranges of woodfuel consumption projected by other researchers (Section 3.5).

When the demand for wood is larger than the supply in one region [$F < 0$ in Equation (1) in the Appendix], the residual demand is subtracted from the supply of wood from forests in regions with a surplus ($F > 0$), or, in other words, trade is assumed to take place. In reality, demand and supply are kept in balance through price fluctuations. In this study, however, demand and supply were treated as independent variables. The three demand scenarios included in this study were based on projections that included some sort of supply-and-demand matching. Further, we acknowledge that long-distance trade of traditional woodfuel is rather unlikely between the regions used in this study. Nevertheless, the trade of woodfuel was included to avoid an overestimation of the bioenergy production potential. The allocation of a wood shortage to various regions with a surplus was based on the share that each region had in the total global surplus wood supply.

2.2 Wood logging residues

The bioenergy potential of logging residues (e.g., bark, branches, needles) was calculated by multiplying the production of woodfuel and industrial roundwood by the wood logging residue generation ratio and recoverability fraction [see further Equation (2) in the

Appendix and Section 3.6]. The logging residue generation ratio [h in Equation (2)] is the ratio between the amount of residues generated and the amount of wood harvested. The logging residue recoverability fraction (hr) is the share of the logging residues that can be realistically recovered. Data for hr were derived from the literature. Note that no clear definition of the term 'realistically' was given, although the descriptions found in the literature state that the term includes both technical and economical barriers.

2.3 Wood processing residues

The bioenergy potential of wood processing residues (e.g., woodchips, sawdust, black liquor) was calculated by multiplying the production of industrial roundwood by the wood processing residue generation ratio and the wood processing residue recoverability fraction, according to Equation (3) in the Appendix (see also Section 3.7). The wood processing residue generation ratio [p in Equation (3)] is defined as the ratio between the amount of residues generated from the processing of industrial roundwood into wood products (e.g., paper, fiberboard, plywood, sawn wood) and the total consumption of industrial roundwood. The wood processing residue recoverability fraction (pr) is the share of the processing residues that can be realistically made available for bioenergy production. The term 'realistically' is defined the same as in the definition of hr in Equation (2).

2.4 Discarded wood-based products

The bioenergy potential of wood waste (e.g., waste paper, discarded furniture, demolition wood) was estimated based on the consumption of industrial roundwood and data on the wood product generation ratio and the wood waste residue recoverability fraction, following Equation (4) in the Appendix. See Section 3.8 for results. The wood product generation ratio (wr) is the ratio of the biomass of industrial roundwood incorporated in wood products and the total biomass of industrial roundwood processed. w is equal to that part of the consumed industrial roundwood not converted into residues during the processing of industrial roundwood ($= 1 - p$). The wood waste residue recoverability fraction is the share of the waste that can be realistically recovered for bioenergy production. The term 'realistically' is defined the same as for wood logging and wood processing residues.

3 Methodology and input data for the calculations

3.1 Supply of wood from forests

The demand for wood from forests[4] was defined in this study as the demand for wood minus the supply of wood from plantations and trees outside forests. Based on data on the consumption of industrial roundwood and woodfuel and on the supply of industrial roundwood and woodfuel from plantations and trees outside forests, the supply of industrial roundwood from forests in 1998 was calculated to be 76% and the supply of woodfuel to be 34%. This corresponds with 1.2 and 0.6 Gm^3 wood, respectively (14 and 7 EJ, respectively), assuming a density of 0.58 oven dry tm^{-3} green wood (FAO 1998b) and a

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[4] Forests were defined as "land with tree crown cover (or equivalent stocking level) or more than 10% and area of more than 0.5 ha. The trees should be able to reach a minimum height of 5 m at maturity *in situ*" (FAO 1998b). In addition, plantations as defined in Section 3.2 were excluded.

higher heating value (HHV) of 20 GJ (oven dry t)$^{-1}$ (Hall 1997), both of which were used as default values in this study. According to the World Resources Institute (WRI) approximately three fourths of the industrial roundwood supply comes from forests (WRI 1999). Which portion comes from old-growth undisturbed forests and which from secondary forests (forests that have been cut down but have regrown) is not known, although estimates found in the literature indicate that roughly half the world's industrial roundwood is produced from old-growth forests (Solberg et al. 1996a, b; Sedjo and Botkin 1997).

This study used data on the Gross Annual Increment (GAI)[5] as a proxy for the wood production potential of forests. The GAI includes biological, climatological, and physiological limitations to forest growth, such as rainfall, radiation and species type, as well as theoretical, technical, economical, and ecological limitations, depending on the chosen potential. By harvesting only the annual increment, the standing stock is kept constant and thus also the carbon sequestered in forest biomass. A second reason for using the GAI as a proxy for the wood production potential is that if the standing stock is kept constant the yields can, in principle, be sustained continuously if limiting factors like nutrient depletion are disregarded. Note that the use of the GAI ignores the impact of disturbances (e.g., pests, fires, drought) that could have a large impact on wood production[6].

Data on natural forest area and GAI in 1995 from the Global Fibre Supply Model (GFSM) of the Food Agricultural Organization (FAO) of the United Nations were used (FAO 1998b). These data were available per country and aggregated regionally. Data on the GAI were available for both the total growing stock and the commercial growing stock. The commercial growing stock is "the part of the growing stock that consists of species considered as actually or potentially commercial under current (1995) market conditions (...) and includes species which are currently not exported, but potentially commercial having appropriate technological properties; species provided to the local market are include" (FAO 1998b). The difference between the (GAI of the) total growing stock and the (GAI of the) commercial growing stock was defined in this study as the noncommercial growing stock. Note that existing outlook studies on the consumption of wood generally included some form of supply-and-demand matching (e.g., Brooks et al. 1996; FAO 1998c; Sedjo and Lyon 1998). Consequently, the resulting equilibrium supply of wood from forests may differ from the wood supply from forests based on GAI.

The global average GAI of the total growing stock in 1998 was 3.4 m^3 ha^{-1} year^{-1} (39 GJ ha^{-1} year^{-1}), with a regional variation of 0.8 m^3 ha^{-1} year^{-1} (9 GJ ha^{-1} year^{-1}) in South Asia to 5.3 m^3 ha^{-1} year^{-1} (61 GJ ha^{-1} year^{-1}) in West Europe (FAO 1998b). These values are in line with other data found in the literature. Fischer and Schrattenholzer, (2001), for example, reported a global average value ranging from 30 to 38 GJ ha^{-1} year^{-1}.

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[5] The GAI is the annual above-ground forest growth per hectare measured in m^3 ha^{-1} year^{-1} for wood of a minimum diameter at breast height of 0 cm and excludes mortality. Mortality is dependent on site characteristics (climate, slope, fertility, etc.), age of the trees, management system, and the occurrence of major disturbances (fires, pests, droughts, floods, etc.). In undisturbed full-grown forests mortality offsets annual growth and the net annual increment (NAI) is zero; in undisturbed managed forests the mortality rate can be as low as a 2%–6% of the GAI (UNECE/FAO 2000).

[6] Disturbances can drastically increase mortality. For example, a mountain pine beetle epidemic in British Columbia is projected to result in a 50% mortality rate of mature pine trees in 2008, and 80% by 2013. Pine trees account for 25%–30% of the harvestable timber in British Columbia (BC 2005). Globally, some 2.6% of the worldwide area of forests is reported to be affected, but data on the total loss of biomass as a result of these disturbances are not available (FAO 2005).

Note that these global average yield levels are lower than the average yield from plantations (ca. 6 m^3 ha^{-1} $year^{-1}$ or 70 GJ ha^{-1} $year^{-1}$), but substantially higher than the present global average harvest intensity of 0.5 m^3 ha^{-1} $year^{-1}$ (5.8 GJ ha^{-1} $year^{-1}$). Depending on the scenario the current intensity was projected to increase to 0.8–0.9 m^3 ha^{-1} $year^{-1}$ (9–10 GJ ha^{-1} $year^{-1}$) in 2020 (Brooks et al. 1996). More intensive forest management schemes may result in increasing pressure on forest ecosystems, although this is not necessarily unsustainable. The large regional differences in the GAI are the result of differences in both the management scheme and the natural circumstances (e.g., climate, soil, solar radiation). Although the GAI was assumed to be constant in this study, it can change as a result of changes in forest management or climatic change.

The total global average GAI of the total growing stock is 3.4 m^3 ha^{-1} $year^{-1}$ (39 GJ ha^{-1} $year^{-1}$), of which some three fifths or 2.1 m^3 ha^{-1} $year^{-1}$ (24 GJ ha^{-1} $year^{-1}$) comes from commercial growing stock and two fifths or 1.3 m^3 ha^{-1} $year^{-1}$ (15 GJ ha^{-1} $year^{-1}$) from noncommercial growing stock. In West Europe, East Europe, and North America, the commercial growing stock made up 90% or more of the GAI of the total growing stock. In contrast, it comprised ca. 40% and 29%, respectively, of the GAI in sub-Saharan Africa and the Caribbean and Latin America The regional variation in the GAI of the commercial growing stock ranged from 0.5 m^3 ha^{-1} $year^{-1}$ (6 GJ ha^{-1} $year^{-1}$) in South Asia to 4.8 m^3 ha^{-1} $year^{-1}$ (55 GJ ha^{-1} $year^{-1}$) in West Europe. The GAI of the noncommercial growing stock varied from approximately zero in North America and the Middle East and North Africa to 2.8 m^3 ha^{-1} $year^{-1}$ (32 GJ ha^{-1} $year^{-1}$) in the Caribbean and Latin America. The ratio of the GAI of the commercial growing stock to the GAI of the noncommercial growing stock was kept constant in this study, even though it was based on the demand for species that were noncommercial under 1995 market conditions. Most of the published projections also indicated that long-term prices for wood are likely to remain stable, which supports the assumption of a constant ratio (FAO 2003b). Further, the GAI may change as a result of changes in management or climate, as explained above.

The classification of forest areas used in this study is a modified version of the GFSM classification of forest areas, as shown in Figure 2 and described below.

Inaccessible forest areas are economically inaccessible areas, which include physically inaccessible areas (e.g., due to steepness of terrain), areas far from infrastructure (e.g., industrial sites, roads, or railways), or areas unsuitable for logging due to other reasons (too low in commercial volume, degraded forest areas, or other reasons specific to each country). We adjusted the GFSM classification in two ways. First, in the original GFSM

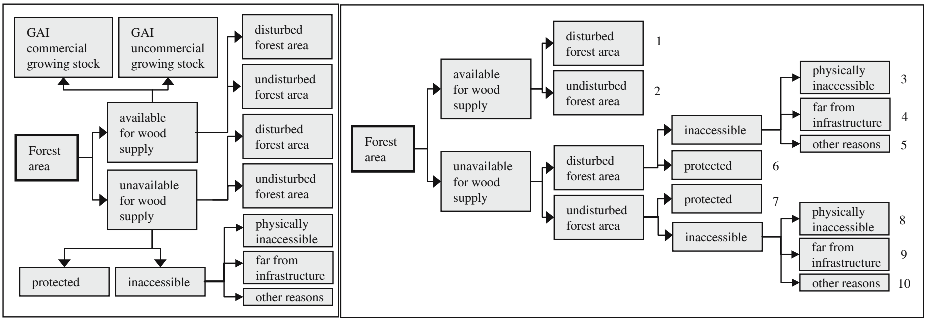

Figure 2 The classification of the natural forest area and the gross annual increment (*GAI*) used in the Global Fibre Supply Model (FAO 1998b) (*left box*) and the classification used in this study (*right box*; the GAI of the commercial and noncommercial growing stock is included for the forest areas numbered 1–5 and 8–10).

classification the unavailable forest area was divided into protected and inaccessible areas and into undisturbed and disturbed areas[7]. In this study, the unavailable forest area was divided into protected and inaccessible areas. This reclassification was done using a simple set of allocation rules: (1) the protected areas were allocated to undisturbed forests (i.e., with a minimum of 10% of the total forest area as described below) and (2) the remaining protected and inaccessible areas were allocated to disturbed areas. The rationale was that old-growth undisturbed forests are likely to be the first to qualify for protection. Second, data on the GAI were only given for forests available for wood supply. In this study the GAI of forests available for wood supply was also used for undisturbed forest areas.

Five types of forest biomass potentials were included in this study: theoretical, technical, economical, economical–ecological, and ecological. The overlap between the various potentials is depicted in Figure 3 and described below.

In all cases the protected areas were excluded as a source of biomass, with a minimum of 10% of the total forest area at a national level[8]. Ten percent is a popular goal for the protection of the most important global ecosystems and was originally proposed by the World Conservation Union (IUCN 1992). Twelve percent is also found in the literature (WCED 1987). The 10% and 12% guidelines, however, may be insufficient for the protection of biodiversity (Soulé and Sanjayan 1998). Therefore, one potential is considered in which a larger forest area was excluded from forestry operations as described below. Five types of potentials were considered in this study:

- *Theoretical potential:* The maximum wood production potential of forests. As a proxy for the theoretical potential, we used the total wood production potential of all forest areas excluding the protected areas. This corresponds to forest areas numbers 1–5 and 8–10 in Figure 2. The theoretical wood production potential in 1995 was calculated to be 9.6 Gm^3 year^{-1} (112 EJ year^{-1}) in a forest area of 2.8 Gha. The carbon sequestered in 9.6 Gm^3 roundwood is calculated to be 2.8 Gt, assuming a density of wood of 0.58 oven dry t m^{-3} green wood (FAO 1998b) and a carbon content of 50% of oven dry wood.
- *Technical potential:* The theoretical potential including limitations due to technical barriers. As a proxy for the technical potential, we used the total wood production potential of all forest areas, excluding the protected areas and the physically inaccessible areas due to factors such as steepness of terrain, because these areas cannot be harvested using conventional logging methods. This corresponds with areas 1, 2, 4, 5, 9, and 10 in Figure 2. The technical potential in 1995 was calculated to be 8.9 Gm^3 year^{-1} (104 EJ year^{-1}) in a 2.6 Gha forest. 8.7 Gm^3 roundwood represents a carbon pool of 2.6 Gt.
- *Economical potential:* The technical potential that can be produced at economically profitable levels. As a proxy we used the GAI of the commercial growing stock in 1995. The forest area included areas classified as 'available for supply', i.e., areas 1 and 2 in Figure 2. Since, in principle, all woody biomass can be used as a source of bioenergy, this potential may be an underestimation of the economical potential of bioenergy.

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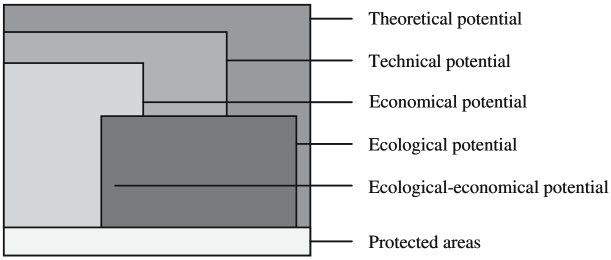
[7] Undisturbed forest was defined as "forest which shows natural forest dynamics, such as natural tree composition, occurrence of dead wood, natural age structure and natural regeneration processes, the area of which is large enough to maintain its natural characteristics and where there has been no known significant human intervention or where the last significant human intervention was long enough ago to have allowed the natural species composition and processes to have become re-established" (FAO 1998b).

[8] Worldwide, 12.4% of the world's forests is in protected areas (FAO 2001). For many countries, however, this percentage is less than 10% of the total area.

Figure 3 The overlap between the theoretical, technical, economical, and ecological potentials of forest growth, excluding protected areas (the size of the areas does not represent the true size of the forest areas).



Worldwide, the GAI of the total growing stock is 1.6 times the GAI of commercial growing stock[9]. The economical potential in 1995 was estimated to be 3.9 Gm^3 year^{-1} (45 EJ year^{-1}) in a 1.5 Gha forest. The 3.9 Gm^3 year^{-1} forest growth represents a carbon flux of 1.1 Gt.

- *Ecological–economical potential:* The economical potential taking into account an additional ecological criterion other than the 10% criterion. The 10% criterion was upheld to prevent a further decrease of biodiversity in undisturbed forests. It is more a political target supported by nature conservation organizations such as the World Wildlife Foundation than a scientifically supported threshold that ensures a sufficiently diverse biodiversity for a stable global ecosystem (Soulé and Sanjayan 1998)[10]. The ecological–economical potential is limited to the growth of the commercial stock of forests classified as 'disturbed'. The restriction to using existing disturbed forest areas avoids a further increase of the pressure on biodiversity in undisturbed old-growth forests. Consequently, the present species diversity in undisturbed forests was used as a baseline. As a result the ecological–economical wood production potential was limited to area 1 in Figure 2 and equaled 2.2 Gm^3 year^{-1} (25 EJ year^{-1}) in a 0.9 Gha forest. 2.0 Gm^3 roundwood represents a carbon pool of 0.6 Gt. Note that the inclusion of other ecological criteria, such as nutrient depletion resulting from increased biomass removals, may further limit the ecological–economical potential.

In addition to the four potentials defined above, a fifth potential was analyzed: the ecological potential. The ecological potential is the theoretical potential taking into account ecological criteria related to biodiversity as described under the ecological–economical potential and criteria related to soil erosion. This potential was based on forest growth of the commercial and noncommercial growing stocks in all already disturbed forest areas, excluding the physically inaccessible areas. In this way, forest areas in mountainous regions that are sensitive to soil erosion were excluded and a further increase in the pressure on biodiversity in undisturbed forests avoided. The ecological potential included forest areas 1, 4, and 5 in Figure 2 and was estimated to be 3.6 Gm^3 year^{-1} (42 EJ year^{-1}; 1.0 Gt C year^{-1}) in a 1.3 Gha forest.

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[9] Regional figures are 1.0 for North America, 1.2 for Oceania, 1.2 for Japan, 1.1 for West Europe, 1.1 for East Europe, 1.4 for the C.I.S. and Baltic States, 2.5 for Sub-Saharan Africa, 3.2 for the Caribbean and Latin America, 1.0 for Middle East and North Africa, 1.3 for East Asia, and 1.6 for South Asia.

[10] Protection of only 10% would make half of the earth's terrestrial species vulnerable to extinction (Soulé and Sanjayan 1998). The basis for this calculation is the species diversity–area correlation, which is $S = kA^z$ (where S is species richness, A is area, and k and z are fitted parameters, and $z < 1$); thus, the larger the area, the more diverse the species mix.

Deforestation can reduce the forest area and consequently the standing stock and the supply of woody biomass from forestry. Deforestation results of a reduction of the carbon stock in forest biomass and forest soils. The worldwide carbon stocks in forest biomass and forest soils are estimated at 359 and 787 Gt, respectively (Watson et al. 2001). The main cause of deforestation is land clearing for agricultural purposes. Two scenarios were included in this study:

- *No deforestation.* In this scenario all forest areas were kept constant at the 1995 state. Various studies projected that the global area under forest cover will decrease during the coming decades, mainly as a result of an increase in the area of agricultural land in the developing regions (FAO 2003b). More efficient food production, however, could (at least in theory) reduce the area of agricultural land without endangering the supply of food in the coming decades (Hoogwijk et al. 2003; Wolf et al. 2003; Smeets et al. 2004).
- *Deforestation.* In this scenario deforestation rates (annual forest cover change rate in % year^{-1}) were kept constant at the average rate reported for the period 1990–2000 in the Global Forest Resource Assessment 2000 (FRA 2000), (FAO 2001)[11]. This rate was applied to all forest types. When the forest area of a region increased between 1990 to 2000, the 1995 level was used for calculations. The forest area and, thereby, the wood production potential decreased as a result of deforestation: the theoretical, technical, economical, ecological–economical, and ecological potentials of the supply of wood from forests decreased to 89%, 90%, 96%, 94%, and 87%, respectively, between 1995 and 2050 compared to the potentials where deforestation was excluded. The bulk of the decrease came from the developing regions (all figures are averages of the five types of potentials): −83% for South Asia, −38% for sub-Saharan Africa, −26% for the Caribbean and Latin America, −20% for East Asia, and −17% for Middle East and North Africa[12]. The projected loss of forest area may be overestimated for two reasons. First, the assumed deforestation rates included the conversion of forests into plantations. A constant deforestation rate implies a constant plantation establishment rate. Assuming the plantation establishment rate measured in 2000 (FAO 2001), the plantation area would increase by 245 million hectares over the period from 1995 to 2050. The current plantation establishment rates, however, are likely to decrease during the coming decades (see also Section 3.2). Second, deforestation rates have decreased during the past decades (FAO 2001) and population growth,

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[11] In the FRA 2000 the definition of forests includes plantations. In this study the term forests excluded plantations. Therefore, the deforestation rates given in the FRA 2000 are increased by the annual plantation establishment rate in 2000 (given in the FRA 2000 to calculate the deforestation rate of natural forests). The present global deforestation rate of natural forests was calculated to be 0.36% vs 0.24% if plantations were included in the definition of forests.

[12] One of the few sources that provide projections of deforestation rates is the IMAGE model. The IMAGE model is a dynamic integrated assessment modelling framework to assess the impact of global change and indicate the impact of climate change mitigation policies. The IMAGE model uses various scenarios based on storylines from the Intergovernmental Panel on Climate Change (IPCC 2000), that vary with respect to the degree of globalization vs regionalization and the degree of orientation on materialistic vs social and ecological values; all IMAGE scenarios are considered equally plausible. The loss (−) or gain (+) of forest area projected by the IMAGE model between 1995 and 2050 for various regions was −7% to −53% for Saharan Africa, −23% to +10% for the Caribbean and Latin America, −90% to −40% for Middle East and North Africa, −25% to +35% for East Asia, and −88% to −24% for South Asia. Comparison between deforestation projections included in this study and the IMAGE model is, however, problematic because of differences in the definitions and because the IMAGE projections were based on scenarios.

> which is an important cause of agricultural expansion and thus deforestation, was projected to slow down in the coming decades (FAO 2001; UNPD 2003). Although these trends suggest a continuing decline in the rate of forest cover loss, the extent to which deforestation rates may decrease is difficult to quantify.

Note that the projections of the global fiber supply up to 2050, included in the GFSM, were excluded because they included various (scenario) specific assumptions that were not documented.

In theory, deforestation accounts for one fourth[13] to two fourths[14] of the global supply of industrial roundwood and woodfuel. However, deforestation as a source of woody biomass was excluded from this study for three reasons. First, we do not want to imply that wood from deforestation should be used as source of bioenergy, regardless of the cause of the deforestation. Second, data on the amount of wood from deforestation were considered not available. Finally, the contribution to the supply of woodfuel and industrial roundwood is probably limited because biomass from deforestation is often not used as a source of wood for various reasons: (1) the number of commercially tradable species may be low, particularly in unmanaged remote forest areas where deforestation is currently taking place; (2) forest areas are often burnt to clear land for agriculture; (3) the lack of infrastructure to harvest and transport wood, particularly in remote areas where deforestation is taking place today, prevents the commercial use of wood from deforestation. If deforestation as a source of wood had been included in the calculations of the global theoretical and technical wood potentials, then these potentials would have been one eighth to one fourth higher.

3.2 Supply of wood from plantations

Data regarding plantations[15] is often incomplete or unreliable (Bazett 2000; FAO 2000b, 2001). This uncertainty not only concerns the total plantation areas and establishment rates, but is also particularly relevant to data on net planted area by species, yield levels, and the purpose of plantations. This is especially true for the developing regions (Pandy and Ball 1998; Bazett 2000). Consequently, most data on plantations are derived from trend extrapolations and estimates based on available data and expert judgment (FAO 2001). Estimates of the global plantation area found in the literature ranged from 130 million hectares (Solberg et al. 1996a, b) to 204 million hectares (Siry et al. 2005) as a result of differences in definitions and base year. In this study we used data from the Global Outlook for Future Wood Supply from Plantations, which was published by FAO's Forestry Department (FAO 2000b). According to that study the plantation area in 1995 was 124 Mha. More recently, in their Forest Resource Assessment 2000 (FRA 2000), the FAO

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[13] Assuming a deforestation rate of 0.36% (FAO 2001), an average standing volume of 100 $m^3\ ha^{-1}$ (FAO 2001), a forest area of 3.2 Gha (FAO 1998b), a fraction of the total GAI that comes from commercial species of 0.6 (see Section 3.1) and a global wood consumption in 1998 of 3.4 Gm^3.

[14] Assuming an annual decrease of the carbon stock in forest biomass of 1.1 Gt (FAO 2005), a carbon content of 50% on dry weight basis, a density of 0.58 oven dry tm^{-3} green wood (FAO 1998b), a fraction of the total GAI that comes from commercial species of 0.6 (see Section 3.1), a logging residues generation ratio of 0.6 (see Section 3.6), and a global wood consumption in 1998 of 3.4 Gm^3.

[15] Plantations were defined as "forest stands established by planting and/or seeding in the process of afforestation or reforestation. They are either of introduced species (all planted stands), or intensively managed stands of indigenous species, which meet the following criteria: one or two species at plantation, even age class, regular spacing. Stands which were established as plantations, but which have been without intensive management for a significant period of time are excluded (...)" (FAO 1998b).

reported a global plantation area of 187 Mha (FAO 2001). The difference in estimates was partially caused by changes in the definitions. The data cannot, therefore, be compared directly. The FRA, 2000 data are more accurate and up-to-date than the data presented in the Global Outlook for Future Wood Supply from Plantations. Nevertheless, we used data from the latter study because, unlike the FRA 2000 study, it did include projections of the future supply of wood from plantations to the year 2050.

Two types of plantations were included in this study: industrial and non-industrial. Industrial plantations are established to produce industrial roundwood, while non-industrial plantations are established for woodfuel production or soil and water protection. The latter may also be planted for recreation or similar nonproductive purposes (FAO 2000b). The area of industrial roundwood plantations in 1995 was estimated to be 103 Mha and that of the non-industrial roundwood plantations 20 Mha (FAO 1998b). In 1995, industrial plantations supplied 24% of the total industrial roundwood production and 6% of the woodfuel production, assuming that all wood from non-industrial plantations was used as woodfuel[16].

Three scenarios (low, medium, and high) were included for the supply of wood from plantations that differ in plantation establishment rate and productivity, as projected by the FAO (1998b). The productivity of the plantations was calculated by the FAO based on an assessment of the current yield levels and age-class distribution and on the assumption that all harvested areas were replanted with the same species mix and for the same purpose after harvesting. Variations in yield levels per hectare between the base year and 2050 were the result of the age-class distribution effect, as described below (FAO 2000b). Data available at the national level were aggregated to provide regional totals.

- *The low scenario was based on a plantation area equal to the 1995 area.* Despite the constant plantation area, the wood production was projected to increase from 331 Mm^3 (3.8 EJ) industrial roundwood and 86 Mm^3 (1 EJ) woodfuel in 1995 to 612 Mm^3 (7 EJ) industrial roundwood and 175 Mm^3 (2 EJ) woodfuel in 2050. This increase was the result of the large share of young immature plantations in the present plantation age-class structure: in 1995, 54% of the industrial plantations and 80% of the non-industrial plantations were less than 15 years old (FAO 2000b). These plantations could become fully productive in the following decades, resulting in an irregular production pattern. A peak in industrial roundwood production of 670 Mm^3 (8 EJ) was projected for 2020, resulting from the medium rotation plantations (20–40 years) reaching maturity. A second peak in industrial roundwood production (710 Mm^3; 8 EJ) was projected for 2040 as a result of the coincident maturation of long rotation length plantations (40+ years) and medium rotation length plantations. A peak for woodfuel was anticipated in 2045: ca. 190 Gm^3 (2.2 EJ).
- *The medium scenario was based on a fixed 1% annual increase of the plantation area of the 1995 plantation area.* This resulted in an industrial plantation area in 2050 of 160 Mha and a non-industrial plantation area of 31 Mha[17]. The calculated wood production potentials of industrial and non-industrial plantations in 2050 were 867 and 247 Mm^3, respectively (10 and 3 EJ).

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[16] According to the FRA 2000 study these figures were 35% and 5%, respectively, for 2000 (FAO 2001).

[17] The areas refer to the *net* plantation establishment, thus excluding areas that were planted but failed to become productive plantations. In 2000, two-thirds of all newly established plantations were successful (FAO 2001).

- *The high scenario was based on the gradual reduction of the current establishment rates*[18]. Plantation establishment rates had increased during the past decades, from 0.42 Mha year^{-1} between 1946 and 1950 to 4.3 Mha year^{-1} between 1991 and 1995 (FAO 2000b). Today, Asia accounts for 63% of the plantation establishment. A decrease in the current plantation establishment rates is likely because a continuation of current trends would result in unlikely high plantation areas, particularly in Asia. In the high scenario an industrial plantation area of 234 Mha and a non-industrial plantation area of 58 Mha in 2050 would produce 1,500 and 487 Mm^3 industrial roundwood and woodfuel, respectively (17 and 6 EJ). The total global plantation area and wood production from plantations in 2050 in the high scenario were larger than in the medium scenario. In two regions, however, the plantation area and production in 2050 were smaller in the high scenario than in the medium scenario: Japan (12 Mha in the high scenario and 17 Mha in the medium scenario) and the C.I.S. and Baltic States region (28 Mha in the high scenario and 34 Mha in the medium scenario). The FAO states that the high scenario "seems to be achievable in physical terms and represents the upper boundary of new planting rates." However, it also states, "this scenario requires a significant change in current thinking about ecology and desired forest practices." Concerns have arisen in Europe and North America, in particular, the extent to which plantations are beneficial from an environmental point of view, especially with respect to possible negative impacts on water resources (FAO 2000b).

Note that due to the age class distribution effect, countries that establish plantations with medium and long rotation species, plantations established after 2025 have no or little impact on the wood production from plantations in 2050. As a result, the potential wood production from the plantation area in scenarios 2 and 3 was much larger than was realized in 2050. For example, in the high plantation establishment scenario, the area industrial plantation establishment in 2050 could, in theory, supply ca. 2.0 Gm^3 compared to the 1.5 Gm^3 production projected for 2050 (FAO 2000b). The age class distribution effect can be reduced if more short rotation plantations are established that have considerably shorter rotation cycles than the 25 years mentioned above. For example, eucalyptus plantations in Brazil have a typical rotation cycle of six to seven years (IEA 1997).

3.3 Supply of wood from trees outside forests

Trees outside forests are defined as all trees not belonging to forests or plantations. Trees outside forests are located in orchards, meadows, home gardens, and parks, alongside roads and waterways, and so on. A comprehensive global assessment of the number of trees outside forests and their products does not exist (FAO 2001); however, various regional and national assessments have provided some information. According to the Asia Pacific Forestry Sector Outlook Study, the total production of industrial roundwood and woodfuel

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[18] The description of Scenario 3 as given by (FAO 2000b) is: "annual rates of new planting in tropical and subtropical countries were taken from Pandy (1997) and current new planting rates were estimated for temperate countries. These rates of new planting were then used for the first 10 years of the scenario (i.e., 1995–2004). For the next 10 years (2005–2014), these rates were reduced by 20% (i.e., to 80% of the current rate). The same reduction (in absolute terms, i.e., the number of hectares rather than a compounded percentage) was then applied to both of the following two 10-year periods (i.e., 2015–2024 and 2025–2034) and for the final 16 years of the projection period (2035–2050). Thus, in the final 16 years of the projection period, it was assumed that the annual rate of new planting in each country will have fallen to 20% of the current new planting rate."

in the Asia–Pacific region in 2010 will be supplied for 35% by trees outside forests (FAO 1998a). Studies undertaken by FAO's Regional Wood Energy Development Programme (RWEDP) concluded that in 15 of the Asian countries covered, as much as two thirds of the woodfuel is derived from non-forest sources; national data range from 49% in India to 87% in Bangladesh (FAO 1997c). In France TOF make up 5% of the total wood production. In Morocco 20% of the land is occupied by TOF, while less than 5% of the land cover is classified as forest cover (FAO 2002).

It can be concluded that TOF (trees outside forests) contribute significantly to the supply of woodfuel in developing regions. In this study, we assumed that TOF supplied 67% of the woodfuel consumption in the developing regions in 1998 based on data reported for Asia by the RWECP. For Africa we used a figure of 50%, because woodfuel production is more commercialized in Africa than in Asia (Whiteman, personal communication). We assume that as a result in Africa a larger portion of the woodfuel supply comes from conventional/commercial forestry operations compared to Asia. For all other developing regions, we assumed that TOF accounted for 67% of the woodfuel supply in 1998. We assumed that TOF did not contribute to the supply of woodfuel in the industrialized countries and economies in transition. Note that in the industrialized and transition economies woodfuel consumption accounts for only 13% of the total wood consumption. In all regions the contribution of TOF to the supply of industrial roundwood consumption was set at 0% for two reasons. First, no detailed regional data on the contribution of TOF were available. Data were only available for France: It was suggested that 5% of the total wood supply came from TOF. Second, the introduction of assumptions regarding the contribution of TOF to the supply of industrial roundwood could lead to an overestimation of the supply of TOF and thus an underestimation of the supply of wood from forests and an overestimation of the energy potential from forest biomass.

Based on the assumptions just described, we calculated that TOF contributed one-third to the total global wood consumption and about two-thirds to the total woodfuel consumption in 1998. This is equivalent to 1.1 Gm^3 wood (13 EJ). In this study the supply of wood from TOF is assumed constant to the year 2050.

3.4 Demand for industrial roundwood

The global demand for industrial roundwood in 2002 was 1.6 Gm^3 (19 EJ) (FAO 2003a). We analyzed the various projections of the global demand for industrial roundwood in 2050 that were found in the literature. Table I shows the results of this literature scan.

As shown in Table I, the consumption of industrial roundwood in 2050 was estimated to be 0.9–6.9 Gm^3 (10–80 EJ). This large range was the result of differences in the calculation methodology applied in the various studies and the assumptions on key parameters and their correlations. Most important, however, were the objective and scope of the studies. Scenario studies are intended to describe the potential impact of assumptions and measures on future developments or to focus on the impact of assumptions about the value of a specific parameter (e.g., Brooks et al. 1996; Sohngen et al. 1997; Sedjo and Lyon 1998; IMAGE-team 2001). Most of the studies included supply-and-demand matching using demand and supply curves: The intersection of the two curves shows the equilibrium between demand and supply and the equilibrium price level. The key parameters in these studies were population growth, income growth, plantation establishment rates and costs, harvesting levels and costs, the impact of policies related to agriculture, forestry, trade, and so on. Other studies aimed at an approximation of the most likely consumption level of industrial roundwood in 2050 (e.g., Alexandratos 1994; FAO 1995, 1999; Bazett 2000).

TABLE I Selection of projections for the consumption of industrial roundwood in 2050 found in the literature (Mm^3)

Source	Mid 1990s	2000	2010	2020	2030	2040	2050	Method
Alexandratos (1994)			2,700					N/d
Apsey and Reed (1995) demand	1,660	1,790	1,940	2,250				The demand is assumed to increase at 1.5% per year; N/a
Apsey and Reed (1995) supply			1510	1680				The supply is estimated based on “judgmental extrapolation from region and country data and a network of experts”
Bazett (2000)							2,500	The average of various projections found in literature
Brooks et al. (1996) low GDP, high price		1,730	1,840	1,870	1,880	1,880	1,880	The consumption of industrial roundwood per capita is modeled as a function of income per capita and prices. Price and income elasticities are derived from historic data
Brooks et al. (1996) high GDP, high price		1,730	1,860	1,910	1,930	1,950	1,970	
Brooks et al. (1996) low GDP, medium price		1,780	1,980	2,120	2,230	2,340	2,450	
Brooks et al. (1996) high GDP, medium price		1,780	2,000	2,150	2,290	2,430	2,570	
Brooks et al. (1996) low GDP, stable price		1,810	2,080	2,290	2,490	2,710	2,930	
Brooks et al. (1996) high GDP, stable price		1,810	2,090	2,330	2,560	2,810	3,070	
Brooks et al. (1996) constant per capita consumption		1,890	2,030	2,160	2,270	2,380	2,490	
FAO (1995) in FAO (1997a)		1,900	2,280					N/a
FAO (1997b)	1,475	1,627	1,784					The Global Forests Product Model (GFPM) (Buongiorno et al. 2003) is a dynamic economical equilibrium model that predicts production, consumption, trade and prices of 14 forest products in 180 countries
FAO (1999)	1490		1870					GFPM, see (FAO 1997b)
FAO (2000a)	1491				2412			
FAO (2000b) scenario 1	1500						3100	Consumption increases at the growth rate projected by the GFPM over the period 2005–2010 (1.27% year^{-1}); see (FAO 1997b)
FAO (2000b) scenario 2	1,500						2,900	Consumption increases at the average growth rate of industrial roundwood consumption over the period 1961–1998 (1.1% year^{-1})

FAO (2000b) scenario 3	1,500						2,340	Consumption initially increases at the average growth rate of industrial roundwood consumption over the period 1961–1998 and the annual growth rate decreases by 0.03% year^{-1}
FAO (2003a)	1513	1588						Historic data
FAO (2003, unpublished data), GFPM model runs to 2030	1,621	1,689	1,887	2,155	2,470			GFPM, see (Buongiorno et al. 2003)
IIED (1996)	1,784	1,878	2,046	2,177				N/a
IMAGE-team (2001) A1 scenario	1,505	1,634	2,022	2,511	3,134	3,993	5,014	Consumption is modeled as a function of population growth, industrial value added, the availability of forests, prices and wood demand. Correlations are statistically derived from historic data
IMAGE-team (2001) A2 scenario	1,505	1,632	1,877	2,095	2,301	2,562	2,852	
IMAGE-team (2001) B1 scenario	1,505	1,633	1,778	1,896	2,023	2,191	2,341	
IMAGE-team (2001) B2 scenario	1,505	1,634	1,911	2,186	2,397	2,597	2,844	
ITTO (1999)		1,995	2,166	2,260				N/a
Nilsson (1996), demand			2,100	2,400				Methods are similar to those used by Apsey and Reed (1995)
Nilsson (1996), non-mainstream demand		1,730	1,895	2,000			2,200	Methods are similar to those used by Apsey and Reed (1995)
Poyry, 1995 in FAO (1997a)		1,500	1,700					Economical demand and supply modeling, includes population growth and economical growth; N/d
Sedjo and Lyon (1998) base case	1,700						2,300	Timber Supply Model (TSM) 1996 is a rotational expectations model. The model includes demand and supply matching. The supply is modeled as a function of e.g., forest rotation length, rate of technological change and price levels. The demand is included based on exogenous assumption on growth rates
Sedjo and Lyon (1998) decreasing demand	1,700						930	
Sedjo and Lyon (1998) high demand (FAO forecasts)	1,700						2,600	
Sedjo and Lyon (1998) very high demand	1,700						2,900	
Sedjo and Lyon (1998) low supply, low demand	1,700						1,250	
Sedjo and Lyon (1998) low supply, base case demand	1,700						1,650	
Sedjo and Lyon (1998) high demand, high plantation	1,700						6,900	
Simons (1994)				2,551				N/a

TABLE I (continued)

Source	Mid 1990s	2000	2010	2020	2030	2040	2050	Method
Sohngen et al. (1997)[a] high demand	1,500			2,150			2,500	Economical demand–supply model; includes data on e.g., plantation establishment rates, timberland management schemes and the accessibility of forests
Sohngen et al. (1997) high plantation	1,650			2,050			2,450	
Sohngen et al. (1997) high inaccessible	1,750			2,050			2,300	
	1,600							
				1,900				
Sohngen et al. (1997) baseline							2,150	
Sohngen et al. (1997) low plantation	1,600			1,850			2,000	
Sohngen et al. (1997) low demand	1,650			1,750			1,950	
Whiteman (1999)	1,493		1,881					GFPM, see (Buongiorno et al. 2003)
World Bank/WWF Alliance, unpublished in (Weiner and Victor 2000)	1,500						3,000	N/a
WRI (1998)			1,907	2,251				N/a
Constant per capita consumption		1,588	1,789	1,986	2,167	2,320	2,442	Based on population projections of the United Nations (UNPD 2003) and historic data

Source: Supplemented and modified from Weiner and Victor (2000).

N/a the publication is not available; N/d the methodology is not described.

[a] All data from Sohngen et al. (1997) are estimated from graph.

The scenario studies usually yielded a wider range in projections than studies that focused on (assumed) likely developments. Sedjo and Lyon (1998), for example, reported that the consumption of industrial roundwood ranged from 0.9 to 6.3 Gm^3 (10 and 73 EJ) in 2050, depending on various scenario variables such as the demand for wood and the plantation establishment rate. Estimates of the FAO that focused on likely developments projected a consumption of 2.4–3.1 Gm^3 in 2050 (FAO 2000b), which is in line with other baseline scenarios for 2050: e.g., 2.2 Gm^3 year^{-1} in Sohngen et al. (1997), 2.5 Gm^3 year^{-1} in Bazett (2000), and 2.3 Gm^3 year^{-1} in Sedjo and Lyon (1998). A detailed comparison or appreciation of the various studies, however, was difficult because the methodologies and assumptions were often not or insufficiently described.

Our study used three scenarios for the consumption of industrial roundwood that represent the range found in the literature:

- *The low scenario:* 1.9 Gm^3 (22 EJ) in 2050. This figure was based on the lower range of projections found in literature (Brooks et al. 1996).
- *The medium scenario:* 2.5 Gm^3 (29 EJ) in 2050. This figure was the average of the high and low scenarios.
- *The high scenario:* 3.1 Gm^3 (36 EJ). This scenario represented the higher range of estimates of industrial roundwood consumption (FAO 2000b).

The consumption of industrial roundwood in the low, medium and high scenario represents a carbon flux of 0.55, 0.73, and 0.90 Gt, respectively.

We acknowledge that the selection of these scenarios was somewhat arbitrary because, as shown in Table I, higher and lower consumption levels are possible. Nevertheless, we considered the three scenarios representative of the (assumed) likely developments found in literature. The three global scenarios were translated into regionally aggregated scenarios using data from the Global Forests Product Model (GFPM) (FAO 1998c). The GFPM is a spatial equilibrium model developed at the FAO. It is the only model that presents long-term (to 2030) projections per country and per forest product type. The consumption of woodfuel and industrial roundwood in 2050 was calculated by means of trend extrapolation based on the consumption in 2030 and the annual average increase of consumption between 2020 and 2030, as projected by the GFPM. The results were upscaled or downscaled so that the total global consumption in 2050 matched the three scenarios. For example, if in the global scenario the demand in 2050 was 20% above the projected (trend extrapolated) demand by the GFPM for 2050, we assumed as a first-order approach, due to a lack of projections, that the regional demand was 20% higher than projected by the GFPM.

3.5 Demand for woodfuel

Data on the consumption of woodfuel (including charcoal) and the sources of woodfuel are very uncertain because they are largely derived from samples and limited survey data. Sharma et al. (1992) suggested a much higher woodfuel consumption than the FAO (2.9 vs 1.7 Gm^3 in 1995) and Jones pointed out that the woodfuel consumption in India may be 10 times higher than that officially reported (Jones, 1995 in Sundquist 2003). The FAO estimated the consumption of woodfuel in 2002 to be 1.8 Gm^3 (21 EJ) (FAO 2003a)[19]. This

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[19] The 21 EJ of woodfuel consumption in 2002 mentioned here is lower than the 39 EJ of traditional biomass consumption reported in the introduction because of differences in classification: The 21 EJ includes traditional woodfuel only, while the 39 EJ also includes other bioenergy sources, such as manure and agricultural residues.

study also used the FAO data. Table II gives an overview of the various projections of woodfuel consumption found in the literature.

Projections of the use of woodfuel in 2050 that were found in the literature ranged between 0 and 3.9 Gm^3 (0 and 45 EJ). This large range was the result of differences in methodology, objectives, assumptions, or a combination of these factors. Johanssen et al. (1993b) assumed that the use of woodfuel was completely phased out between 2025 and 2050, i.e., it was replaced by other energy sources (oil, gas, coal), as a result of urbanization and increasing income. Nilsson (1996) estimated the requirements for woodfuel necessary to achieve development objectives (4.3 Gm^3 in 2010), excluding an analysis on the extent to which this demand can be met. Zuidema et al. (1994) estimated woodfuel consumption patterns including the impact of large land use and vegetation changes due to the greenhouse effect and the impact on wood supply (1.5 Gm^3 in 2010). These three studies resulted in unlikely high or low levels of consumption because supply and demand interactions were excluded or the impact of a certain parameter was exaggerated, at least compared with other studies, namely Alexandratos (1994), Apsey and Reed (1995), Brooks et al. (1996), and IMAGE-team (2001), and various FAO projections. All of these studies included some sort of supply-and-demand matching or aimed at an estimation of a (assumed) most likely scenario. We composed three scenarios for the consumption of woodfuel in 2050 based on the ranges reported in these studies.

- *The low scenario:* Set at 1.7 Gm^3 (20 EJ) in 2050. This scenario represented the lowest projection found in the literature: the IMAGE B1 scenario (IMAGE-team 2001). We disregarded the 0 Gm^3 assumed by Johanssen et al. (1993b).
- *The medium scenario:* 2.2 Gm^3 (25 EJ) in 2050, which was the average of the low and high scenarios.
- *The high scenario:* 2.6 Gm^3 (30 EJ) in 2050. This scenario was based on a constant woodfuel consumption per capita and an increase in global population to 2050 following the medium population growth scenario projected by the United Nations Population Division (UNPD 2003). We included the scenario because some of the projections to 2010 and 2020 that exclude projections for 2050 were based on higher consumption growth rates than the projections to 2050 [compare, e.g., the various IMAGE projections (2001) with the projections in Alexandratos (1994)].

The low, medium and high scenario represent a carbon flux of 0.49, 0.62, and 0.75 Gt, respectively.

Regionally aggregated data on woodfuel consumption in 2050 were estimated based on trend extrapolations of the projections for 2030 by the GFPM (FAO 1998c). The same methodology was applied here as for industrial roundwood.

3.6 Wood logging residues

Logging residues are also called primary residues and include e.g., twigs, branches, and stumps. The bioenergy potential of logging residues is dependent on a large number of variables, e.g., the tree species, the harvesting system, the amount of residues that can be recovered, the alternative use of residues as animal bedding, protection against soil depletion or soil erosion, and the loss of biodiversity.

Considering the large number of factors involved and the lack of detailed data on most of them, no detailed assessment of the availability of residues for bioenergy was carried out. Instead, we used formula 2 in the Appendix, which includes data on:

- *The harvest of roundwood from forests and plantations.* Logging residues from trees outside forests were excluded because trees outside forests are scattered over the land area and thus limit the amount of residues that can be recovered realistically. Moreover, we did not want to overestimate the bioenergy potential of logging residues.
- *The logging residue generation ratio (h).* This is the ratio between the amount of residues generated and the amount of wood harvested. The residue generation ratio for industrial roundwood was set at 0.6 (FAO 1990; Hall et al. 1993). Other researchers reported comparable figures, ranging from 0.65 to 0.82 (Kauppi et al. 1992). The same residue generation ratio was assumed for woodfuel. For woodfuel, however, we acknowledge that the whole tree is suitable for energy use and thus the whole tree may be harvested. Harvesting and processing entire trees may, however, be impractical, particularly in the case of commercial woodfuel production in Africa and specifically in charcoal production. Consequently, *h* varies per region and the energy potential from logging residues may, therefore, be overestimated, but this is uncertain because no region specific data are available.
- *The logging residue recoverability fraction (hr).* This is the fraction of generated residues that can be realistically harvested. Values found in the literature for industrial roundwood logging range from 25% (Hall et al. 1993) to 50% (Johanssen et al. 1993b). The recoverability fraction was set at 25% in this study to avoid an overestimation of the bioenergy production potential. The same value was used for woodfuel logging residues.

3.7 Wood processing residues

Processing residues are also called secondary residues and include e.g., sawdust, woodchips, and black liquor. The energy potential of secondary residues is dependent on a variety of factors like the efficiency of the process, the amount of residues that can be realistically gathered, and the alternative use of residues as pulpwood, animal bedding, or woodfuel. It goes beyond the scope of this study to analyze in detail the potential of wood processing residues. As a result, we used formula 3 in the Appendix to calculate the potential. It includes data on:

- *The consumption of industrial roundwood and woodfuel.*
- *The wood processing residue generation fraction (p).* This is the fraction of consumed wood that is converted into residues during the processing of wood. Hall et al. (1993) reported a wood processing residue generation fraction of 0.5. Other studies mentioned comparable figures: 0.42 and 0.60 were reported by Heath et al. (1996) and Plantinga and Birdsey (1993), 0.45 to 0.55 for sawmills and plywood plants by the FAO (1990), and 0.50 for sawn wood and 0.58 for pulpwood by Plantinga and Birdsey (1993) in Sohngen and Sedjo (2000). The World Resources Institute reported a figure of 0.30 for the best sawmills in Europe and the USA and 0.7 for many developing countries (GFTN/WWF 2000). This study used 0.5 as the wood processing residue generation fraction, due to a lack of region specific data.

TABLE II Selection of projections for the consumption of woodfuel in 2050 found in the literature (Mm^3)

Source	Mid 1990s	2000	2010	2020	2030	2040	2050	Method
Alexandratos (1994)			2,400					N/d
Apsey and Reed (1995)[a]			2,325	2,607				N/a
FAO (1995)	1,940	2,090	2,380					N/d
Brooks et al. (1996) lower GDP growth		1,900	1,980	2,030	2,030	2,060	2,100	Economical supply demand matching: demand is projected based on GDP projections; supply is projected based on assumptions on price levels
Brooks et al. (1996) higher GDP growth		1,900	1,940	1,930	1,880	1,850	1,860	
Brooks et al. (1996) constant per capita consumption		2,120	2,440	2,730	3,020	3,350	3,710	
FAO (1997b)	1,736	1,885	2,052					The Global Forests Product Model (GFPM) (Buongiorno et al. 2003) is a dynamic economical equilibrium model that is used to predict production, consumption, trade and prices of 14 forest products in 180 countries
FAO (2003a)	1,735	1,761						Historic data
FAO (2003, unpublished data), GFPM model runs to 2030	1,778	1,828	2,020	2,273	2,585			GFPM, see (Buongiorno et al. 2003)
FAO (2000a)			2,200					Based on an annual 1.4% increase in consumption as projected by Alexandratos (1994)
IMAGE-team (2001)[b] A1 scenario	1,789	1,874	1,997	2,053	2,065	2,028	1,954	Based on a fixed fraction of the demand for traditional biofuels, calculated by the TIMER (Targets Image Energy Regional) model. TIMER is an economical energy supply demand model
IMAGE-team (2001) A2 scenario	1,789	1,887	2,121	2,306	2,416	2,474	2,480	
IMAGE-team (2001) B1 scenario	1,789	1,876	1,987	1,937	1,937	1,840	1,734	
IMAGE-team (2001) B2 scenario	1,789	1,858	1,933	1,961	1,941	1,868	1,768	

Johanssen et al. (1993b)					0	Based on the assumption that woodfuel is phased between 2025 and 2050
Nilsson (1996)		3,800	4,250			Based on the per capita demand for woodfuel necessary to achieve development objectives (taken from FAO, 1981 in Nilsson (1996) multiplied by the population projections of the United Nations Populations Division
Sharma et al. (1992) in (Brooks et al. 1996)	2,800	3,050	3,400	3,900		N/a
Solomon in (Nilsson 1996)			2,520	2,920		N/a
Whiteman et al. (1999)	1,802		2,210			GFPM, see (Buongiorno et al. 2003)
Zuidema et al. (1994)			1,500			N/a; projections include the impact of large land use and vegetation changes due to the greenhouse effect and the impact on wood supply
Constant per capita consumption		1,761			2,621	Based on population projections of the United Nations (UNPD 2003) and historic data

Source: Supplemented and modified from Weiner and Victor (2000).

N/a the publication is not available; N/d the methodology is not described.

[a] Projections given by Apsey and Reed (1995) are based on a higher estimate on the present woodfuel consumption and consequently project a higher woodfuel consumption for 2010.

[b] The relatively low level of woodfuel consumption projected by the IMAGE-team compared to other projections can be explained by the relatively strong increase in income in particularly the developing countries. Income projections from the World Bank, on which FAO projections are based, indicate a slower increase in income.

- *The wood processing residue recoverability fraction (pr).* This is the fraction of processing residues that can be realistically collected. Data on the recoverability fraction found in the literature vary considerably: roughly from 0.33 (Hall et al. 1993) to 0.75 (Johanssen et al. 1993b; Williams 1995). Yamamoto and co-workers (1999) reported a recoverability fraction of 0.42 for sawmill residues in developing countries and 0.75 in developed countries. This study used a recoverability fraction of wood processing residues of 0.75.

3.8 Wood waste

In the end all forest products become available as waste, also referred to as tertiary residues (e.g., discarded furniture, demolition wood, and waste paper). An assessment of the bioenergy potential of tertiary residues requires a detailed assessment of the amount of wood products produced, their life span, the energy content, the recoverability fraction, the recycling of, e.g., waste paper. Such an assessment goes beyond the scope of this paper. In order to obtain a "first order of magnitude" estimate, therefore, we used formula 4 in the Appendix. It includes:

- *The consumption of industrial roundwood.*
- *The wood product generation ratio (w).* This is the fraction of the processed industrial roundwood that is incorporated into final wood products. w is equal to the share of the consumed industrial roundwood not included in residues, or $1 - p$ (see Section 3.7). Nearly all wood products become available as waste after a time delay. This delay can vary from several weeks as in the case of paper to hundreds of years as in the case of construction wood.
- *The wood waste residue recoverability fraction (wr).* This is the fraction of waste that can be realistically harvested. No data are available for the recoverability fraction. This study set the recoverability fraction at 0.75, which is the same as the recoverability fraction of wood processing residues and municipal solid waste (e.g., Fujino et al. 1999).

3.9 Technological change

Despite the importance of changes in wood processing and recycling technologies, technological change is usually not specifically included in outlook studies on wood consumption. The conversion efficiency of roundwood to wood products has increased considerably during the last decades: The use of roundwood has decreased from 3.1 m^3 per ton product in 1945 to 2.4 m^3 per ton product in 1990 (Solberg et al. 1996a,b). The Global Fibre Supply Model (GFSM) of the FAO included data on the efficiency of wood conversion for various products; however, these values were fixed in time (FAO 1998b). Table III shows data derived from the GFSM for the conversion efficiency of roundwood to various wood products in different regions of the world in 1998. The data are regional averages based on national data and are weighed on the basis of the production volume. The bottom row shows the conversion efficiency based on the best available technology, which was the value obtained in countr(y)(ies) with the highest efficiency. Table III also shows the potential reduction of roundwood input if the currently installed technologies are replaced by the best available technologies.

TABLE III Average conversion efficiency of roundwood to wood products in 2000 for different regions and for the best available technology (input per unit of output; dimensionless)

Roundwood to dimension	Sawn wood	Reduction (%)	Pulp wood	Reduction (%)	Particle board	Reduction (%)	Fibre board	Reduction (%)	Mechanical pulp	Reduction (%)	Chemical pulp	Reduction (%)
North America	1.51	2	1.80	0	1.50	20	1.60	25	2.50	20	3.50	13
Oceania	1.51	2	1.89	5	1.36	12	1.24	3	2.19	9	3.25	6
Japan	1.50	2	1.80	0	1.20	0	1.20	0	2.00	0	2.90	0
West Europe	1.62	9	1.86	3	1.33	10	1.44	16	2.34	14	3.48	11
East Europe	2.10	30	2.34	23	1.73	31	1.81	34	2.93	32	4.14	30
C.I.S. & Baltic States	1.87	22	2.15	16	1.68	29	1.79	33	2.68	25	3.94	25
Sub-Saharan Africa	2.52	42	3.69	51	1.84	35	2.14	44	3.77	47	4.80	44
Caribbean & Latin America	2.08	29	2.28	21	1.66	28	1.78	33	3.08	35	4.13	29
Middle East & North Africa	1.70	13	2.20	18	1.50	20	1.62	26	3.00	33	4.21	22
East Asia	1.84	20	1.93	7	1.46	18	1.55	22	2.89	31	3.73	20
South Asia	1.76	17	1.96	8	1.47	18	1.55	23	2.90	31	3.86	19
World	1.70	13	1.88	4	1.45	17	1.56	23	2.50	20	3.54	16
Best available technology	1.47		1.80		1.20		1.20		2.00		2.00	

Input reductions are indicated if the best available technology is used (in %). All product specific conversion factors are the weighed average conversion factors based on national data on the roundwood conversion efficiency and production of the product on volume basis. The average reduction of the required roundwood is the unweighed average of the reduction of all five wood conversion processes. Source: FAO (2003, unpublished data).

Finally, Table III presents the potential to increase the efficiency of wood processing and its potential impact on the demand for wood. The data show that even without further technological developments, i.e., other than the implementation of the best available technologies that exist today, there is a considerable potential to reduce the demand for industrial roundwood. Globally, the demand for wood could decrease by 16% if the best available technology were applied. The calculated decrease of 16% was the average unweighed decrease in wood demand for the six production processes included in Table III. Regional figures ranged from 0% in Japan to 44% for Sub-Saharan Africa.

The growth in the demand for wood may be reduced further by various other technologies and technology-driven developments. These include:

- *Increasing the utilization of recycled wood fibers.* The recycling of wood fibers was rarely explicitly included in the projections found in the literature. According to the FAO, however, 41%−77% of the 390 million tons of paper consumption projected for 2010 could be recycled, compared to 44% of the 120 million tons consumed in 1995 (Mabee 1998). Feber and Gielen (2000) estimated that, in theory, maximum application of wood cascading and recycling could reduce the demand for wood by 45% in 2030.
- *Increasing the utilization of new fiber products, such as medium density fiberboard, oriented strand board, and laminated boards.* These products maximize the utilization of low grade small size fiber and have a considerable potential to temper the increase in wood demand (Solberg et al. 1996a,b; Whiteman 1999; GFTN/WWF 2000). Quantitative projections are not, however, available.
- *New processes that expand the range of types and qualities of wood and non-wood fibers that can be processed into useful products, such as rubberwood fibers, oil palm fibers, straws, and bagasse* (Pande 1998; Whiteman 1999). The potential impact on wood consumption or on the bioenergy production potential is, however, difficult to estimate.

4 Results

Figure 4 shows the demand for industrial roundwood and woodfuel in 1998 and the assumed demand in 2050. Figures for the supply of wood from trees outside forests, plantations, and forests are also presented.

The global consumption of wood (industrial roundwood and woodfuel) increased from 2.3 Gm^3 (27 EJ) in 1961 to 3.3 Gm^3 (38 EJ) in 2002 and was projected to increase to 3.6–5.7 Gm^3 (42–66 EJ) in 2050. Slightly more than half of this consumption comprised industrial roundwood, the remaining was woodfuel. The global supply of woodfuel from trees outside forests was assumed to remain stable, namely the equivalent of 1.1 Gm^3 year^{-1} (13 EJ year^{-1}) roundwood. Consequently, the supply of roundwood from plantations and forest growth had to increase from 2.2 Gm^3 (26 EJ) in 1995 to 2.5–4.6 Gm^3 (29–53 EJ) in 2050 in order to meet the projected demand. The supply of wood from plantations was projected to increase considerably, from 0.5 Gm^3 (6 EJ) in 1995 to 0.8–2.0 Gm^3 (9–23 EJ) in 2050. The remaining demand for wood from forests was estimated to range from 0.5 to 3.8 Gm^3 year^{-1} (6 to 44 EJ year^{-1}), whereby these values represent two extreme scenarios: a low demand/high plantation establishment scenario and a high demand/low plantation establishment scenario. In the case of a medium demand/medium plantation scenario, the demand was calculated to be 2.5 Gm^3 year^{-1} (28 EJ year^{-1}).

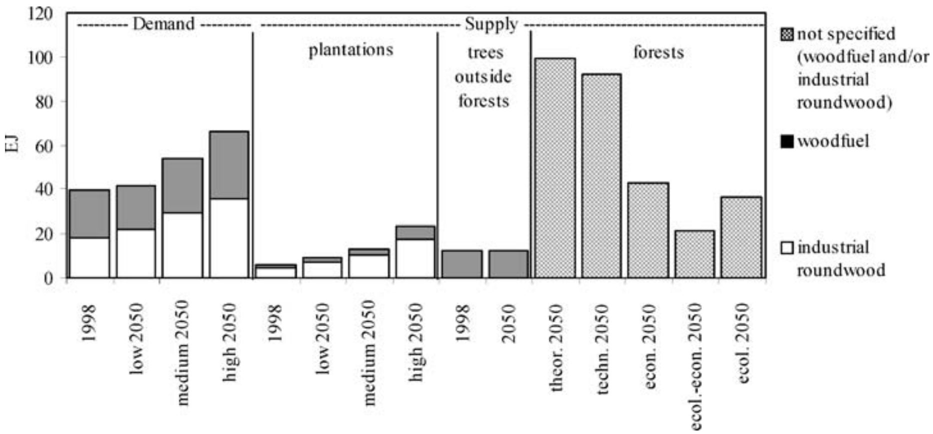
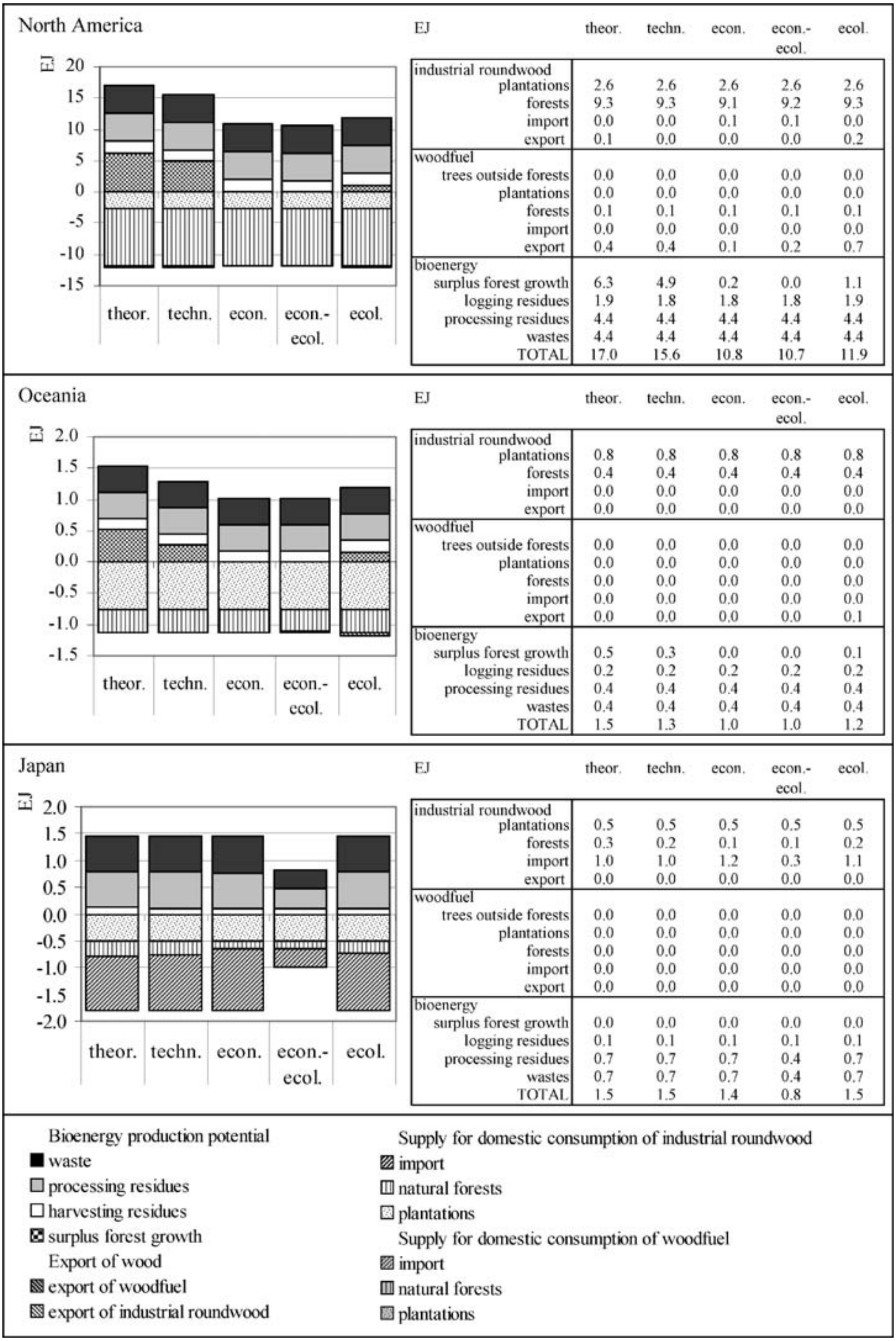


Figure 4 Demand for industrial roundwood and woodfuel in 1998 and 2050, the supply of wood from plantations and trees outside forests in 1998 and 2050, and the potential supply of wood from forests in 2050 based on the theoretical, technical, economical, economical–ecological, and ecological supply potentials of wood from forests (including deforestation; in EJ).

The theoretical potential of the 2050 wood supply from forests, excluding protected areas, was calculated to be 8.5 Gm^3 year^{-1} (99 EJ year^{-1}) including deforestation and 9.6 Gm^3 year^{-1} (112 EJ year^{-1}) excluding deforestation. When protected areas were included, the potential rose 15% and 13%, respectively. These figures excluded the growth of leaves, twigs, needles, etc. When this type of biomass was also included, then the total gross annual increment of woody biomass increased 67%, which is equivalent to 14 Gm^3 year^{-1} (165 EJ year^{-1}) including deforestation and 16 Gm^3 year^{-1} (186 EJ year^{-1}) excluding deforestation. The carbon content of these quantities is 4.1 and 4.6 Gt, respectively. Spurr (1979, in Sundquist 2003) reported that the net primary productivity of forests equals 13 Gt. For comparison: the total worldwide net primary productivity is estimated at 60 Gt C year^{-1} and the total net ecosystem productivity (net primary productivity minus losses from the decomposition of organic material) was estimated at 10 Gt C year^{-1} (Watson et al. 2001). The technical potential of the 2050 wood supply was estimated to be 8.0 Gm^3 (92 EJ) including deforestation and 8.9 Gm^3 (103 EJ) excluding deforestation. The economical potential in 2050 was lower: 3.7 Gm^3 (43 EJ) including deforestation and 3.9 Gm^3 (45 EJ) excluding deforestation, which is in line with the results of other authors. Hagler (1995) and Sundquist (2003), for example, estimated that forests can support a sustainable long-term harvest of 3.7 Gm^3 (43 EJ) and 4.3 Gm^3 year^{-1} (50 EJ year^{-1}), respectively. Their data did, however, exclude the production of leaves, needles, and twigs. When this production and the logging residue generation ratio and the logging residue recoverability fraction as defined in Section 3.6 were included, then the economical potential increased by 17%. When the ecological criteria were also included, then the potential supply from forests in 2050 was limited to 1.8 Gm^3 (21 EJ) including deforestation and 2.0 Gm^3 (23 EJ) excluding deforestation. When the supply of wood from forests was restricted by ecological criteria only, then the supply of wood was 3.1 Gm^3 year^{-1} (36 EJ year^{-1}) including deforestation and 3.6 Gm^3 year^{-1} (42 EJ year^{-1}) excluding deforestation.

The data in Figure 4 show that the theoretical, technological, economical, and ecological potential supplies of wood from forests in 2050 (including deforestation) are, in general, large enough to fulfill the projected demand for wood from forests. The surplus forest growth available for bioenergy production was calculated by subtracting the demand for



North America

EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	2.6	2.6	2.6	2.6	2.6
forests	9.3	9.3	9.1	9.2	9.3
import	0.0	0.0	0.1	0.1	0.0
export	0.1	0.0	0.0	0.0	0.2
woodfuel					
trees outside forests	0.0	0.0	0.0	0.0	0.0
plantations	0.0	0.0	0.0	0.0	0.0
forests	0.1	0.1	0.1	0.1	0.1
import	0.0	0.0	0.0	0.0	0.0
export	0.4	0.4	0.1	0.2	0.7
bioenergy					
surplus forest growth	6.3	4.9	0.2	0.0	1.1
logging residues	1.9	1.8	1.8	1.8	1.9
processing residues	4.4	4.4	4.4	4.4	4.4
wastes	4.4	4.4	4.4	4.4	4.4
TOTAL	17.0	15.6	10.8	10.7	11.9

Oceania

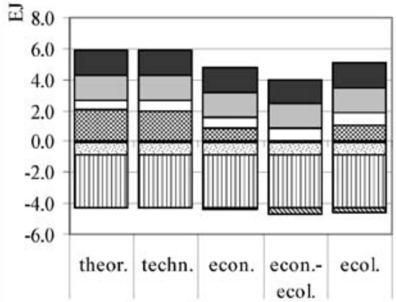
EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.8	0.8	0.8	0.8	0.8
forests	0.4	0.4	0.4	0.4	0.4
import	0.0	0.0	0.0	0.0	0.0
export	0.0	0.0	0.0	0.0	0.0
woodfuel					
trees outside forests	0.0	0.0	0.0	0.0	0.0
plantations	0.0	0.0	0.0	0.0	0.0
forests	0.0	0.0	0.0	0.0	0.0
import	0.0	0.0	0.0	0.0	0.0
export	0.0	0.0	0.0	0.0	0.1
bioenergy					
surplus forest growth	0.5	0.3	0.0	0.0	0.1
logging residues	0.2	0.2	0.2	0.2	0.2
processing residues	0.4	0.4	0.4	0.4	0.4
wastes	0.4	0.4	0.4	0.4	0.4
TOTAL	1.5	1.3	1.0	1.0	1.2

Japan

EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.5	0.5	0.5	0.5	0.5
forests	0.3	0.2	0.1	0.1	0.2
import	1.0	1.0	1.2	0.3	1.1
export	0.0	0.0	0.0	0.0	0.0
woodfuel					
trees outside forests	0.0	0.0	0.0	0.0	0.0
plantations	0.0	0.0	0.0	0.0	0.0
forests	0.0	0.0	0.0	0.0	0.0
import	0.0	0.0	0.0	0.0	0.0
export	0.0	0.0	0.0	0.0	0.0
bioenergy					
surplus forest growth	0.0	0.0	0.0	0.0	0.0
logging residues	0.1	0.1	0.1	0.1	0.1
processing residues	0.7	0.7	0.7	0.4	0.7
wastes	0.7	0.7	0.7	0.4	0.7
TOTAL	1.5	1.5	1.4	0.8	1.5

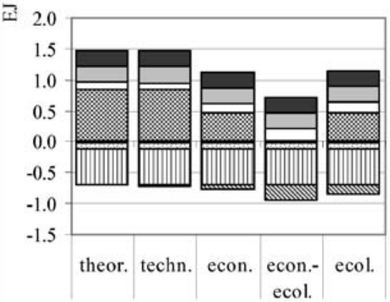
Figure 5 Regional demand and supply of industrial roundwood and woodfuel in 2050 and the potential for bioenergy production from surplus forest growth and residues and waste (based on a medium demand/ medium plantation establishment scenario; EJ). *Positive values* indicate the bioenergy production potential from surplus forest growth and residues, *negative values* indicate the sources of the domestic supply of wood.

West Europe



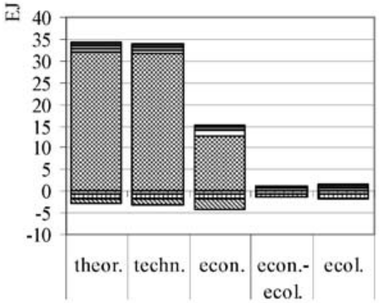
EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.9	0.9	0.9	0.9	0.9
forests	3.4	3.4	3.4	3.4	3.4
import	0.0	0.0	0.0	0.0	0.0
export	0.0	0.0	0.1	0.5	0.4
woodfuel					
trees outside forests	0.0	0.0	0.0	0.0	0.0
plantations	0.0	0.0	0.0	0.0	0.0
forests	0.0	0.0	0.0	0.0	0.0
import	0.0	0.0	0.0	0.0	0.0
export	0.1	0.1	0.4	0.9	0.7
bioenergy					
surplus forest growth	2.0	2.0	0.9	0.0	1.1
logging residues	0.7	0.7	0.7	0.8	0.8
processing residues	1.6	1.6	1.6	1.6	1.6
wastes	1.6	1.6	1.6	1.6	1.6
TOTAL	5.9	5.8	4.8	4.0	5.1

East Europe



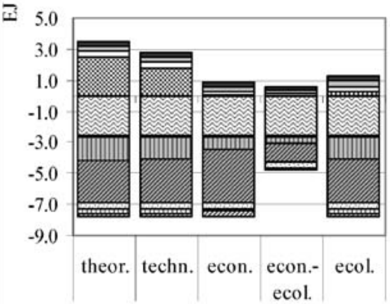
EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.1	0.1	0.1	0.1	0.1
forests	0.6	0.6	0.6	0.6	0.6
import	0.0	0.0	0.0	0.0	0.0
export	0.0	0.0	0.1	0.3	0.2
woodfuel					
trees outside forests	0.0	0.0	0.0	0.0	0.0
plantations	0.0	0.0	0.0	0.0	0.0
forests	0.0	0.0	0.0	0.0	0.0
import	0.0	0.0	0.0	0.0	0.0
export	0.1	0.1	0.2	0.5	0.3
bioenergy					
surplus forest growth	0.8	0.8	0.5	0.0	0.5
logging residues	0.1	0.1	0.1	0.2	0.2
processing residues	0.3	0.3	0.3	0.3	0.3
wastes	0.3	0.3	0.3	0.3	0.3
TOTAL	1.5	1.5	1.1	0.7	1.1

C.I.S. and Baltic States



EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.5	0.5	0.5	0.5	0.5
forests	1.2	1.2	1.2	0.7	1.0
import	0.0	0.0	0.0	0.1	0.2
export	1.1	1.2	2.6	0.0	0.0
woodfuel					
trees outside forests	0.0	0.0	0.0	0.0	0.0
plantations	0.0	0.0	0.0	0.0	0.0
forests	0.1	0.1	0.1	0.0	0.1
import	0.0	0.0	0.0	0.0	0.0
export	2.1	2.4	5.1	0.0	0.0
bioenergy					
surplus forest growth	32.1	31.7	12.6	0.0	0.0
logging residues	0.7	0.8	1.4	0.2	0.2
processing residues	0.6	0.6	0.6	0.5	0.6
wastes	0.6	0.6	0.6	0.5	0.6
TOTAL	34.1	33.8	15.3	1.3	1.5

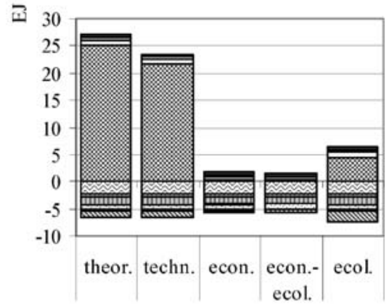
sub-Saharan Africa



EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.4	0.4	0.4	0.4	0.4
forests	0.3	0.2	0.1	0.1	0.3
import	0.2	0.2	0.4	0.1	0.2
export	0.0	0.0	0.0	0.0	0.0
woodfuel					
trees outside forests	2.5	2.5	2.5	2.5	2.5
plantations	0.2	0.2	0.2	0.2	0.2
forests	1.4	1.4	0.7	0.4	1.3
import	2.8	2.9	3.5	1.2	2.9
export	0.0	0.0	0.0	0.0	0.0
bioenergy					
surplus forest growth	2.5	1.8	0.0	0.0	0.3
logging residues	0.3	0.3	0.2	0.2	0.3
processing residues	0.3	0.3	0.3	0.2	0.3
wastes	0.3	0.3	0.3	0.2	0.3
TOTAL	3.5	2.8	0.9	0.6	1.3

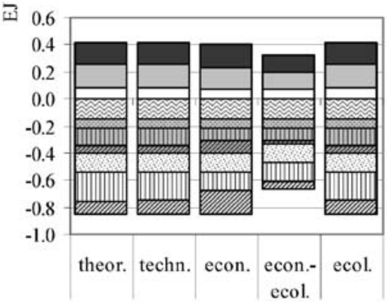
Figure 5 (continued)

Carribean & Latin America



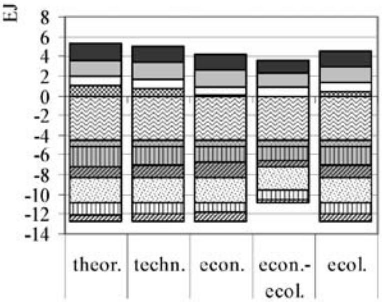
EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	1.1	1.1	1.1	1.1	1.1
forests	0.2	0.2	0.2	0.2	0.2
import	0.0	0.0	0.0	0.0	0.0
export	1.1	1.1	0.3	0.3	1.8
woodfuel					
trees outside forests	2.4	2.4	2.4	2.4	2.4
plantations	0.5	0.5	0.5	0.5	0.5
forests	1.3	1.3	1.2	1.1	1.3
import	0.0	0.0	0.1	0.0	0.0
export	1.6	1.6	0.0	0.1	2.9
bioenergy					
surplus forest growth	25.2	21.7	0.4	0.0	4.3
logging residues	0.9	0.9	0.5	0.5	1.2
processing residues	0.5	0.5	0.5	0.5	0.5
wastes	0.5	0.5	0.5	0.5	0.5
TOTAL	27.0	23.5	1.8	1.4	6.4

Middle East & North Africa



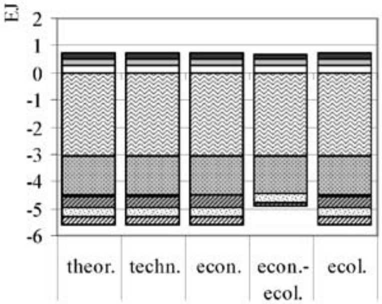
EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.1	0.1	0.1	0.1	0.1
forests	0.2	0.2	0.1	0.1	0.2
import	0.1	0.1	0.2	0.1	0.1
export	0.0	0.0	0.0	0.0	0.0
woodfuel					
trees outside forests	0.1	0.1	0.1	0.1	0.1
plantations	0.1	0.1	0.1	0.1	0.1
forests	0.1	0.1	0.1	0.1	0.1
import	0.1	0.1	0.1	0.0	0.1
export	0.0	0.0	0.0	0.0	0.0
bioenergy					
surplus forest growth	0.0	0.0	0.0	0.0	0.0
logging residues	0.1	0.1	0.1	0.1	0.1
processing residues	0.2	0.2	0.2	0.1	0.2
wastes	0.2	0.2	0.2	0.1	0.2
TOTAL	0.4	0.4	0.4	0.3	0.4

East Asia



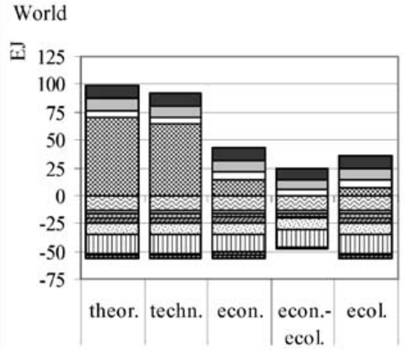
EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	2.5	2.5	2.5	2.5	2.5
forests	1.2	1.2	1.0	0.9	1.1
import	0.6	0.7	0.9	0.3	0.8
export	0.0	0.0	0.0	0.0	0.0
woodfuel					
trees outside forests	4.4	4.4	4.4	4.4	4.4
plantations	0.7	0.7	0.7	0.7	0.7
forests	2.1	2.0	1.6	1.5	1.9
import	1.1	1.2	1.6	0.5	1.3
export	0.0	0.0	0.0	0.0	0.0
bioenergy					
surplus forest growth	1.0	0.8	0.1	0.0	0.4
logging residues	1.0	0.9	0.9	0.8	0.9
processing residues	1.6	1.6	1.6	1.4	1.6
wastes	1.6	1.6	1.6	1.4	1.6
TOTAL	5.2	5.0	4.2	3.6	4.6

South Asia



EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	0.3	0.3	0.3	0.3	0.3
forests	0.0	0.0	0.0	0.0	0.0
import	0.3	0.3	0.3	0.1	0.3
export	0.0	0.0	0.0	0.0	0.0
woodfuel					
trees outside forests	3.1	3.1	3.1	3.1	3.1
plantations	1.4	1.4	1.4	1.4	1.4
forests	0.1	0.0	0.0	0.0	0.0
import	0.4	0.4	0.4	0.0	0.4
export	0.0	0.0	0.0	0.1	0.0
bioenergy					
surplus forest growth	0.0	0.0	0.0	0.0	0.0
logging residues	0.3	0.3	0.3	0.3	0.3
processing residues	0.2	0.2	0.2	0.2	0.2
wastes	0.2	0.2	0.2	0.2	0.2
TOTAL	0.8	0.8	0.8	0.7	0.8

Figure 5 (continued)



EJ	theor.	techn.	econ.	econ.-ecol.	ecol.
industrial roundwood					
plantations	9.8	9.8	9.8	9.8	9.8
forests	16.9	16.8	16.1	15.6	16.5
import	2.0	2.4	3.0	1.0	2.6
export	2.0	2.4	3.0	1.0	2.6
woodfuel					
trees outside forests	12.5	12.5	12.5	12.5	12.5
plantations	2.9	2.9	2.9	2.8	2.9
forests	5.2	5.0	3.8	3.2	4.8
import	4.4	4.6	5.7	1.7	4.7
export	4.4	4.6	5.7	1.7	4.7
bioenergy					
surplus forest growth	70.5	63.9	14.6	0.0	7.7
logging residues	6.2	6.2	6.2	5.1	6.2
processing residues	10.9	10.9	10.9	9.4	10.9
wastes	10.9	10.9	10.9	9.4	10.9
TOTAL	98.4	91.9	42.5	24.0	35.6

Figure 5 (continued)

wood from forests from the total forest growth. The surplus theoretical forest growth available for bioenergy production was then estimated to range from 4.7 Gm^3 (54 EJ) to 8.0 Gm^3 (93 EJ), depending on the combination of the demand (low, medium, high) and the plantation establishment (low, medium, high) scenarios. Based on a medium demand/medium plantation scenario, the theoretical surplus forest growth was estimated to be 6.1 Gm^3 year^{-1} (70 EJ year^{-1}). The surplus forest growth based on the technical potential ranged from 4.1 to 7.4 Gm^3 year^{-1} (48 and 86 EJ year^{-1}). Assuming a medium demand/medium plantation scenario, the technical potential was valued at 5.5 Gm^3 year^{-1} (64 EJ year^{-1}). When twigs and leaves were included and the wood processing residue recoverability fraction excluded, the surplus theoretical and technical forest growth increased 67%. The surplus forest growth (including deforestation) based on the 2050 economical, ecological, and economical–ecological potentials ranged from 0 to 3.2 Gm^3 (37 EJ), 0 to 2.6 Gm^3 (30 EJ), and 0 to 1.3 Gm^3 (15 EJ), respectively. Wood supply shortages may arise, depending on the plantation establishment scenario, the demand scenario, and the potential of the biomass from forests: up to 2% of the total demand for wood may not be met if the economical potential is considered, up to 13% in the case of the ecological potential, and up to 35% in the case of the economical–ecological potential (including deforestation). When the medium demand/medium plantation establishment scenario was applied, the surplus forest growth based on the economical and ecological potentials of forest growth in 2050 were calculated to be 1.3 Gm^3 (15 EJ) and 0.7 Gm^3 (8 EJ), respectively. When the economical–ecological potential was considered, a shortage of 13% of the global demand for wood was calculated, i.e., 0.6 Gm^3 (7 EJ).

The total potential of residues available for bioenergy in 2050 was calculated to be 1.8–3.0 Gm^3 (21–35 EJ), depending on the demand and the supply of wood. Based on a medium demand/medium plantation establishment scenario, the potential of residues was 2.4 Gm^3 year^{-1} (28 EJ year^{-1}). Of this potential, 39% consisted of processing residues, 39% waste, and 22% logging residues.

Figure 5 gives an overview of the projected regional demand and supply of wood and the potential for bioenergy from residues and surplus forest growth in 2050. The results were based on the medium demand/medium plantation establishment scenario and included deforestation. Like above, the surplus forest growth available for bioenergy production was calculated by subtracting the demand for wood from forests from the total forest growth. The demand for wood from forests was calculated as the domestic demand for wood minus the domestic supply of wood from plantations, minus the domestic supply of trees outside forests, plus exports to compensate for wood shortages in forest scarce regions. Figure 5 presents the demand for wood in negative values and the bioenergy production potentials in positive values.

Figure 5 also shows that the bulk of the technical and theoretical bioenergy potentials of surplus forest growth came from the C.I.S and Baltic States, the Caribbean and Latin America, and, to a lesser extent, North America and West Europe. The economical potential of surplus forest growth came mainly from the C.I.S and Baltic States, while the ecological–economical potential came mainly from West Europe, Eastern Europe, and the Caribbean and Latin America. The annual theoretical, technical, economical, ecological–economical, and ecological surplus forest growth in the C.I.S and Baltic States were estimated to be 2.8 Gm^3 year^{-1} (32 EJ year^{-1}), 2.7 Gm^3 year^{-1} (32 EJ year^{-1}), 1.1 Gm^3 year^{-1} (13 EJ year^{-1}), 0 Gm^3 year^{-1} (0 EJ year^{-1}), and 0 Gm^3 year^{-1} (0 EJ year^{-1}), respectively. The data show that although the C.I.S. and Baltic States region had large surplus supplies of forest growth available at present economical market prices for timber, the realization of this potential required the logging of previously undisturbed forests. Only ca. 3% of the forest area, however, was disturbed in the C.I.S and Baltic States. The region with the second lowest share of disturbed forest area was the Caribbean and Latin America (42%). The Caribbean and Latin America region was projected to have theoretical, technical, ecological potentials of surplus forest growth of 2.0 Gm^3 (23 EJ), 1.9 Gm^3 (22 EJ), and 0.4 Gm^3 (4 EJ), respectively, in 2050. The economical potential of surplus forest growth was 32 Mm^3 year^{-1} (0.4 EJ year^{-1}). The regions with the highest ecological–economical potential supply of wood were North America and West Europe, but the supply in these regions was needed for domestic consumption.

It was projected that the other regions had a very limited potential of surplus forest growth. For example, the 2050 theoretical and technical surpluses in sub-Saharan Africa were calculated to be only 218 Mm^3 (2.5 EJ) and 156 Mm^3 (1.8 EJ), respectively, and there was virtually no surplus with regard to the other types of potentials. This was due to the combination of high woodfuel consumption and low annual forest growth per hectare (less than half of that of South America). The domestic supply of wood in Japan, South Asia, and the Middle East and North Africa was projected as probably being insufficient to meet the projected demand. If this were true, then these regions would have to depend on imports to meet their demand in 2050. East Asia had no 2050 potentials of surplus forest growth because of a lack of forest resources in combination with an increasing demand for woodfuel and industrial roundwood. When deforestation was excluded, the amount of forest growth available for bioenergy increased. This was particularly true for Sub-Saharan Africa and the Caribbean and Latin America. The theoretical and technical potentials of surplus forest growth in these regions increased by half. The surplus forest growth in the industrialized countries also increased as a result of reduced exports to forest-scarce regions. The global picture remained roughly the same, however: the theoretical and technical potential supplies of wood from forests were large enough to meet the demand for wood from forests in 2050. Yet, economical and ecological criteria could reduce the amount of wood harvested from forests and thus result in wood shortages in 2050.

The supply of wood processing residues originated particularly from regions with high levels of industrial roundwood consumption, i.e., mainly North America, West Europe, East Asia, and the C.I.S. and Baltic States. The same was true for the potential supply of bioenergy from waste, such as discarded forest production, and demolition wood. The supply of logging residues was concentrated in those regions with a large demand for woodfuel and industrial roundwood in combination with a supply large enough to meet the demand (e.g., in North America and West Europe) or in regions with a large supply that is used for the production and export of wood to forest-scarce regions (e.g., the C.I.S. and Baltic States and the Caribbean and Latin America).

5 Discussion and conclusions

In this study a bottom-up analysis was used to determine the energy production potential of woody biomass from forestry to 2050. First, an extensive literature review was carried out to identify the key drivers that determine these potentials. Second, the key drivers are included in a spreadsheet to calculate the energy, using existing databases and scenarios derived from the literature. The results show that, in theory, the demand for woodfuel and industrial roundwood in 2050 can be met, both with and without further deforestation, although regional shortages may occur. Further, the results indicate that woody biomass from forests, plantations, trees outside forests, and wood logging and processing residues can, in theory, be a large source of bioenergy in 2050, up to 8.5 Gm^3 (98 EJ) including deforestation and 9.6 Gm^3 (111 EJ) excluding deforestation. These amounts represent a carbon content of 2.5 and 2.8 Gt, respectively. Economical and ecological criteria may, however, limit the supply of wood from forests. As a result, the economical–ecological potential of the wood supply from natural forests will be insufficient to meet the projected demand for 2050. Based on a medium demand/medium plantation establishment scenario, the total global bioenergy production potentials including deforestation of forests in 2050 were estimated to be 6.1 Gm^3 year^{-1} (71 EJ year^{-1}), 5.2 Gm^3 year^{-1} (64 EJ year^{-1}), 1.3 Gm^3 year^{-1} (15 EJ year^{-1}), 0 Gm^3 year^{-1} (0 EJ year^{-1}), and 0.7 Gm^3 year^{-1} (8 EJ year^{-1}), based on the theoretical, technical, economical, ecological–economical, and ecological potentials, respectively, of wood supplies from forests. The most promising woody biomass suppliers were the Caribbean and Latin America (biomass from already disturbed forest areas), the C.I.S. and Baltic States (biomass from economically attractive forest areas), and, in part, North America. Other regions with some potential included West Europe (mainly residues), East Asia (mainly residues), and Sub-Saharan Africa (based on the theoretical and technical wood supplies). Japan, South Asia, and the Middle East and North Africa were projected to have wood shortages in 2050. These data correspond with those found in the literature. Fischer and Schrattenholzer (2001), for example, reported 2050 values of 91–114 EJ for the potential supply of wood from accessible forest areas and 322–407 EJ for the total potential supply of wood from forests, both depending on the harvest intensity. Sørensen (1999) estimated the total wood resource in 2050 to be 358 EJ, 107 EJ of which was considered available for bioenergy.

Our results also showed that residues and waste may add an amount equivalent to 3.0 Gm^3 year^{-1} (35 EJ) roundwood, which stems mainly from the industrialized regions with high levels of wood consumption. These results are in line with data found in the literature. The potential supply of bioenergy from wood logging residues and wood processing residues in this study was estimated to be 13–22 EJ in 2050. Other researchers reported values of 10–13 EJ in the year 2025 (Hall et al. 1993; Johanssen et al. 1993a; Williams 1995) and 11 EJ in 2050 (Johanssen et al. 1993a; Williams 1995).

The key factors included in this study to determine the energy production potential of woody biomass from forestry were the future demand for woodfuel and industrial roundwood, plantation establishment rates, and, in particular, the supply of wood from forests. The supply of wood from forests depends on the size of the forest area available for wood harvesting and the yield level. For most of these factors, scenarios were used that capture (at least some of) the uncertainty related to the poor quality of the data and the uncertainty related to future developments. Data and projections on average annual long-term harvest intensity are especially uncertain for various reasons. For example, data on this issue are scarce and largely dependent on the estimates of varying degrees of reliability, and economical and ecological considerations determine the actual logging intensity. The implementation of sustainable forest management (SFM) principles in particular may put a limit on the future harvest intensity[20].

We acknowledge that the methodology used in this study was based on a static approach to the demand and supply of forest growth, forest areas, wood demand, etc. In reality, complex iterative processes and feedback mechanisms related to supply-and-demand matching and the socio-economical system in general determine the penetration of bioenergy from woody biomass into the future energy mix. This applies to all markets, but particularly to a very dynamic market like the demand and supply of wood and is visible in the large range in projections of demand and supply found in the literature. In addition, technological change in the wood processing and plantation industries may increase the global bioenergy potential. No attempt was made in the present study to include these dynamics because the complexity of the correlations included in the socio-economical system makes it very difficult to calculate the implementation potential of bioenergy. The results presented here, therefore, provide a rough estimate of the energy potential of woody biomass in 2050. Our approach did, however, have the advantage of being transparent: it clearly showed the key variables for the supply of energy from woody biomass. These variables are potential targets for policymakers: e.g., the plantation establishment rates, the forest areas available for wood harvesting, and the productivity (management) of these areas. The key uncertainties in this study and thus targets for further research include the supply of wood from trees outside forests, woodfuel consumption, and the impact of various theoretical, technical, economical, or ecological limitations on forest productivity and, in particular, the impact of SFM on these limitations.

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[20] There are various definitions for SFM. We used the following definition: "The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems." (MCPFE 1993).

Appendix

Equation (1). Bioenergy potential of (surplus) forest growth

$$F = FG + PLA + TOF - IRW - WF \left[Gm^3\ year^{-1}\right] \text{ or } \left[EJ\ year^{-1}\right] \tag{1}$$

where

F	bioenergy potential of (surplus) forest growth
FG	forest growth (Section 3.1)
PLA	production of wood from plantations (Section 3.2)
TOF	production of wood from trees outside forests (Section 3.3)
IRW	consumption of industrial roundwood (Section 3.4)
WF	consumption of (traditional) woodfuel (Section 3.5)

Equation (2). Bioenergy potential of wood logging residues

$$HR = (IRWP + WFP) \times h \times hr \left[Gm^3\ year^{-1}\right] \text{ or } \left[EJ\ year^{-1}\right] \tag{2}$$

where

HR	bioenergy potential of logging residues (Section 3.6)
$IRWP$	production of industrial roundwood from forests and plantations
WFP	production of (traditional) woodfuel from forests and plantations
h	logging residue generation ratio
hr	logging residue recoverability fraction

Equation (3). Bioenergy potential of wood processing residues

$$PR = IRW \times p \times pr \left[Gm^3\ year^{-1}\right] \text{ or } \left[EJ\ year^{-1}\right] \tag{3}$$

where

PR	bioenergy potential of processing residues (Section 3.7)
IRW	consumption of industrial roundwood
p	wood processing residue generation ratio
pr	wood processing residue recoverability fraction

Equation (4). Bioenergy potential of discarded wood-based products

$$WA = IRW \times w \times wr \left[Gm^3\ year^{-1}\right] \text{ or } \left[EJ\ year^{-1}\right] \tag{4}$$

where

WA	bioenergy potential of wood waste (Section 3.8)
IRW	consumption of industrial roundwood
w	wood product generation ratio
wr	wood waste residue recoverability fraction

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