Ecological Economics 119 (2015) 326–337

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Global patterns and trends of wood harvest and use between 1990 and 2010

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 10 September 2015
Accepted 20 September 2015
Available online xxxx

Keywords:
Wood carbon flows
Wood biomass
Woodfuels
Harvested wood products
Cascade use

ABSTRACT

Wood biomass forms the basis for a variety of products and it represents an important source of technical energy. Woodfuels and forests play an important role for climate change mitigation, by their ability to replace fossil fuel and sequester atmospheric carbon. At the same time, wood extraction is an important driver for deforestation. However, large uncertainties relate to the amount and spatio-temporal pattern of wood use. We here present a comprehensive assessment of wood biomass flows in 11 world regions from 1990 to 2010. We found that global total biomass appropriation (TBA) amounts to 1.81 GtC/year in 1990 and 1.94 GtC/year in 2010 (+7%). In 2010, TBA represents 4% of the global forest net primary production. Only 54% of TBA enters socioeconomic systems while 46% remain in forests or represent waste flows. About 56% of economically used wood biomass enters the energy sector. There are considerable regional variations in wood biomass flows among world regions, owing to differences in population, affluence, and area. Global demand for wood is expected to increase in the near future, putting additional pressure to forest ecosystems. We discuss the potential of cascading use of wood as a means to reduce impacts related to resource use.

1. Introduction

Wood biomass is among the most important natural resources for society. Already in the early civilizations, biomass, mainly in the form of traditional fuel such as firewood and charcoal, was the single most important source of energy for cooking, heating, and other domestic use (Tillman, 1978), and was one of the most important resources for construction materials. During the industrial revolution, wood has been largely replaced by fossil fuels (e.g. oil, coal and natural gas) for transportation, industries, and heating in most industrialized regions while it remained an important source of energy in many developing countries, especially in rural areas (FAO, 2008). The significant growth of fossil fuel used in the past led to increased atmospheric CO_2 concentration contributing about 78% of the total GHG emission increase from 1970 to 2010 (IPCC, 2014). We are now facing the situation of increasing human-induced climate change, mainly caused by the combustion of fossil fuels. Due to this concern, in recent years wood energy has regained importance. Wood biomass is increasingly promoted by industrialized countries as a carbon-neutral source of energy, based on the idea that for biomass, only the amount of carbon previously absorbed in the course of plant growth will be released to the atmosphere. While this assertion may only be correct under rare circumstances (Haberl et al., 2013; Schulze et al., 2012; Searchinger et al., 2009), the promotion of woodfuels as a climate change mitigation option is continued, adding another driver to the global consumption of wood biomass.

In consequence, the modern use of wood biomass for energy provision gained a significant share in the global energy market during the last years, especially in developed regions such as the European Union and North America (Roos and Brackley, 2012; Cocchi et al., 2011; Heinimö and Junginger, 2009). For example, the production of global wood pellets grew by 12% in 2013, reaching 22 million metric tons (FAO, 2014b). At the same time, traditional biomass remains the dominant source of energy for heating and cooking in the rural areas of most developing countries. However, wood extraction for fuel has been identified as one of the principal drivers of forest degradation and depletion of forest carbon storage, trends initiatives like the 'Reducing Emissions from Deforestation and Degradation of forests (REDD) programmes' aim to halt or at least slow down (Schure et al., 2014; Rudel, 2013). This shows that there is a potential trade-off between the sustainability goals of poverty reduction, climate change mitigation and energy security and the preservation of ecosystem services provided by forests.

An accurate assessment of these trade-offs requires an improved understanding of global patterns and trends of wood harvest and use. An enhanced knowledge of how biomass is flowing through different socioeconomic compartments represents the prerequisite to assess issues of carbon neutrality or trade-offs of wood biomass use. However, the current understanding is limited due to the lack of a consistent and robust account on global wood biomass flows. This is mainly due to the large uncertainties that prevail on existing widely used databases. For instance, woodfuel removals are known to be under-reported in FAO

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http://dx.doi.org/10.1016/j.ecolecon.2015.09.011
0921-8009/

statistics and illegal logging or unrecorded industrial wood removals are not captured in the national statistics provided to FAO (Nellemann, 2012; Meyfroidt and Lambin, 2009). To our knowledge, only Sims et al. (2006, 2007) have so far quantified global wood flows, but only focusing on energy use and disregarding other uses of wood. Other wood flow studies focused on Europe at regional (Mantau, 2012) and national levels (Kalt, 2015; Jungmeier and Subotić, 2011; METLA, 2011).

This study aims at assessing flows of wood biomass in a comprehensive manner, following its pathway from primary production in forest ecosystems, along the different stages of economic processing to final consumption, in order to draw a comprehensive picture of global wood C flows. It explicitly includes direct (i.e. primary wood removals) and indirect wood flows (i.e. logging residues and belowground biomass losses, appropriated but not subject to further socio-economic use). By combining data from different sources and following a sound accounting framework, it detects discrepancies in official statistical data regarding industrial wood removals and provides alternative estimates (minimum and maximum) on woodfuel removals. It covers all wood biomass uses such as paper and paperboards, semi-finished wood products (e.g. sawnwood, veneer and wood panels), other wood products (e.g. poles, piles, etc.), energy use, wood wastes and losses. It allows to estimate the apparent consumption of traditional (e.g. fuelwood and wood charcoal) and modern (e.g. wood pellets and wood for heat and power) woodfuels and their respective consumers (e.g. residential, wood industries and other industries). Wood biomass flows were calculated for the years 1990, 2000, and 2010 on the country level and aggregated to 11 world regions. This database allows to analyse and discuss trends and patterns of wood biomass flows, its share in the total primary energy consumption, and its relation to population, forest area and forest productivity. In the last section we discuss factors influencing regional patterns of wood biomass use and strategies to meet the future demand for wood resources.

Table 1
The definition of the indicators referred to in text and in Fig. 1.

Used extraction (UE)	The amount of extracted wood biomass entering the socioeconomic system for further processing or consumption (Fischer-Kowalski et al., 2011), including woodfuels and industrial roundwood. It is equivalent to "wood removals" and to indicator "domestic extraction (DE)" as it is used in Material Flow Accounts (Haberl, 2001).
Unused extraction (UnE)	The amount of wood biomass that are killed through harvest but not economically used thereafter, includes logging residues and below ground biomass losses.
Total biomass appropriation (TBA)	The sum of used extraction (UE) and unused extraction (UnE). It is equivalent to Human Appropriated Net Primary Production ($HANPP_{harv}$), the amount of carbon in wood biomass harvested or killed during harvest within a year (Krausmann et al., 2013; Erb et al., 2009).
Net trade (imports−exports)	Imports minus exports of all roundwood and wood biomass products.
Apparent consumption	Used extraction plus net trade, equivalent to "domestic biomass consumption (DBC)" in MFA.
Waste flows	These flows include unutilized industrial residues and wood losses produced in wood processing industry which were commonly disposed of in landfills and incinerators. Post-consumer wastes are not included in this study.
Recycling flows	These flows include recovered paper that have been collected and re-used for the manufacture of paper and paperboard.
Wood biomass supply	The sum total of all types of used extraction plus net imports.
Wood biomass use	The sum total of all types of wood biomass use plus net exports.
Forest harvest intensity	Used extraction per unit area of forest (tC/ha/year) or per unit of actual NPP (%).

2. Data and Methods

In order to ensure consistency, we applied the standard of material- and energy flow accounting (MEFA; Fischer-Kowalski et al., 2011; EUROSTAT, 2001) throughout this study. Fig. 1 shows the schematic representation of global wood biomass flows based on MEFA and Table 1 provides an overview on the used terminology. We accounted wood biomass from ecosystems, along the different stages of economic processing to final consumption. We compiled and calculated data on wood flows for 188 countries in a decadal time series from 1990 to 2010. In 1990, only 166 countries were included, as the 15 countries forming the USSR (Union of Soviet Socialist Republics) then represented a single statistical entity and due to some data gaps related to a few other countries (see Table S1). Only countries with complete availability of international statistics on forestry production (FAO, 2014a) were included in the assessment. We aggregated countries into 11 world regions, with macro-geographical (continental) regions and geographical sub-regions according to UNSD (2006; Table S1). Wood flows are consistently accounted in ton Carbon (tC). As all primary data from FAO were given in solid cubic metre (m^3), all data were converted into tons of dry matter (0% water content) by applying region-specific wood density coefficients (Table S2) for coniferous (C) and non-

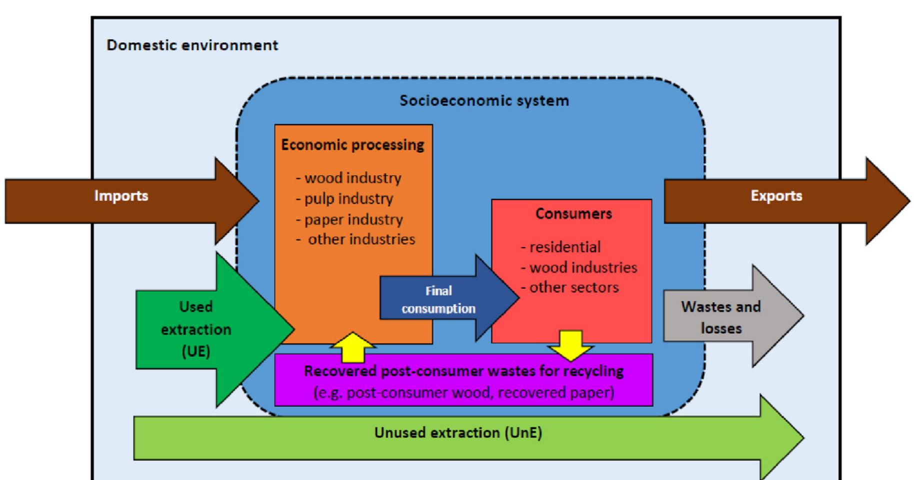

Fig. 1. A schematic representation of wood biomass flows in and between countries.

coniferous (NC) wood and a dry matter carbon content of 50% (IPCC, 2006).

2.1. Net Primary Production and Total Biomass Appropriation

Net primary production (NPP) is defined as the net amount of biomass or carbon produced annually by green plants through photosynthesis, calculated as gross production minus the energy required for the plant metabolism (i.e. plant respiration; Krausmann et al., 2008; Haberl et al., 2007). The NPP of the actual forest vegetation (NPP_{act}) was taken from Haberl et al., 2007. This dataset has been derived from the Lund-Potsdam-Jena (LPJ) Dynamic Global Vegetation Model, a process-based ecosystem model (Sitch et al., 2003), that modelled NPP prevailing in the period between 1990 and 2010 in the absence of land use, termed potential NPP (NPP_{pot}). Following Haberl et al. (2007) and Erb et al. (2009) and in the absence of robust information, we assumed NPP_{pot} to equal actual NPP (NPP_{act}) in forests. The spatially explicit NPP information (resolution 5 arc min) was aggregated to the national level using Geographic Information System software (Krausmann et al., 2013).

Total biomass appropriation (TBA; Table 1) is the sum of used extraction (UE) and unused extraction (UnE) of wood biomass. UE is corresponding to "wood removals" and denotes fellings actually removed from the forest (UN, 2000). UE includes industrial roundwood and woodfuels, including bark (Fig. S1). As FAO data on UE are reported in volume underbark (i.e. excluding bark), we additionally estimated bark removals by using average factors for the ratio between wood harvest underbark and overbark (between 85% and 90% according to Arets et al., 2011; UNECE/FAO, 2010; FAO, 2001). Industrial roundwood was divided into sawlogs/veneer logs, pulpwood and other industrial roundwood. UnE includes logging residues and below ground biomass losses (i.e. root biomass killed through wood harvest). Logging residues and belowground biomass losses were calculated by applying region-specific recovery rates and shoot–root ratios (Table 2). In order to reflect higher collection rates in woodfuel gathering, we increased recovery rates for woodfuel harvest in tropical countries by 50%, derived from previous work of Krausmann et al. (2008).

2.2. Socioeconomic Uses and Consumers of Wood Biomass

The socioeconomic uses of wood biomass (Fig. S1) for each country include: (a) paper and paperboards; (b) semi-finished wood products (e.g. sawnwood, veneer, plywood and wood panels); (c) other industrial wood for the production of poles, posts, fencing, tanning, etc.; (d) traditional woodfuels (e.g. firewood and wood charcoal); and (e) modern woodfuels (e.g. wood pellets, wood chips and industrial residues for heat and power production). Other wood biomass uses include losses, wood wastes, and net trade.

Table 2
The roundwood recovery rates and root-shoot ratios by world regions.

World regions	Sawtimber	Woodfuels	Root-shoot ratio[a]
North Africa and Western Asia	0.54	0.81	0.28
Sub-Saharan Africa	0.54	0.81	0.25
Central Asia and Russian Federation	0.80	0.80	0.28
Eastern Asia	0.46	0.69	0.31
Southern Asia	0.46	0.69	0.30
South-Eastern Asia	0.46	0.69	0.30
Northern America	0.80	0.80	0.22
Latin America and the Caribbean	0.56	0.84	0.22
Western Europe	0.80	0.80	0.26
Eastern and South-Eastern Europe	0.80	0.80	0.26
Oceania and Australia	0.46	0.69	0.33

Source. Dykstra, 1992; Pulkki, 1997.
[a] FAO, 2011.

ForesSTAT dataset (FAO, 2014a) is the primary data source for quantifying pulp, paper- and wood-product production flows. Based on the FAO forest product classification, we assumed that sawlogs/veneer logs were used for the production of sawnwood, veneer, and plywood production. Pulpwood logs and industrial residues were used for the production of wood pulp and wood panels (i.e. particleboard and fibreboard) (Fig. S1). Other industrial roundwood was set aside for the production of poles, piling, posts, fencing, pit props, tanning, etc. Wood pulp and recovered fibre pulp from recovered paper (3.40 m^3/t conversion factor; Mantau, 2012) were assumed to be utilized for paper and paperboard product production. The quantity of recovered post-consumer wood that could be used as raw material for the production of pulp, wood panels, and energy is beyond the scope of this study.

The energy use of wood biomass included in this study was divided into two categories, traditional and modern woodfuels. Traditional woodfuels included in this study consist of wood charcoal and firewood. Data on wood charcoal is available in ForesSTAT datasets (FAO, 2014a) which is reported in metric tons. A multiplication factor of 6 (UNECE/FAO, 2010) is commonly used to estimate the primary raw materials required (in rwe) for wood charcoal production. Firewood (or fuelwood) is a traditional wood biomass that is not highly processed, mainly in the form of log or branch, compared to other forms of woodfuels like pellets or chips. The quantity of firewood was calculated as total volume of woodfuels minus volume of wood for the production of charcoal, heat, and power. The volume of woodfuels used for the production of heat and power were taken from UN statistics (UN, 2014). Modern woodfuels include wood pellets and heat and power produced from wood. Black liquor and industrial residues were assumed to be used for the production of heat and power. We assumed that recovered bark was only utilized by wood industries for their own use in industrialized regions. Data on wood pellets was taken from various reports (Audigane et al., 2012; Roos and Brackley, 2012; Cocchi et al., 2011; Pellet Atlas, 2009a, 2009b). It is reported in tons per year, a factor of 1.87 m^3/t (Mantau, 2012) has been used to estimate the volume of raw materials required per tons of wood pellets produced. It was assumed that wood pellets were made from industrial residues.

Industrial residues (e.g. planer shavings, trimmings, sawdusts, etc.) were calculated as the difference between the total volume of estimated primary raw materials required for the production of harvested wood products (HWP; e.g. pulp, paper, paper- and wood- products and others like poles, piling, etc.; Penman et al., 2003) and total volume of HWP. The volume of primary raw material required for HWP production was estimated by converting the volume of HWP to roundwood equivalent by applying region-specific conversion factors (Table S3). Wood losses (e.g. shrinkages losses, unrecoverable sawdusts and sander dusts) in wood industries were assumed to range from 5 to 8% of the volume of primary raw materials, depending on the type of wood products (UNECE/FAO, 2010; Koopmans and Koppejan, 1997). Wood wastes (i.e. unutilized industrial residues) were commonly disposed of in landfills and incinerated (Ogunbode et al., 2013; Steffen, 1995). Wood wastes were calculated as the total volume of industrial residues recovered minus the volume of industrial residues used for the production of wood pulp, panels, wood pellets, heat, and power. Net trade is the aggregate net trade of roundwood, HWP, wood pellets, charcoal, wood residues and woodchips and particles.

In this study, wood-based energy use is segmented into 3 consumers: 1) residential and other industries; 2) wood industries own use; and 3) transformation to other forms of energy (e.g. wood pellets, heat and power) for commercial purposes. It was assumed that traditional woodfuels were fully consumed by the first consumer. Industrial residues like bark and black liquor were assumed to be used by wood industries (2nd consumer) to satisfy the electricity and heat needs for their processes. Woodchips made directly (i.e. from forest) from roundwood were assumed to be processed into heat and power and other industrial residues into wood pellets. These modern woodfuels were assumed to be commercialized and consumed by residential, public and industrial sectors.

2.3. Uncertainties of Data on Wood Biomass Used Extraction

In order to meet concerns about the accuracy of FAO data on woodfuel removals (or used extraction of woodfuels; Whiteman et al., 2002), we calculated minimum and maximum estimates, based on an extensive literature survey (UN, 2014; FAO, 1999a, 1999b, 2011; EPE, 2010; IBGE, 2010; RWEDP/FAO, 1997,1996). To estimate the uncertainties in industrial wood removals (or used extraction of industrial wood), the volume of HWP taken from FAO statistics were converted to roundwood equivalent (rwe) volume using conversion factors (Table S3). These conversion factors were assumed to be constant throughout the years (1990–2010), because gains in processing efficiency were compensated by the decrease in the diameter of logs due to increased dependence on wood from plantation forests (Meyfroidt and Lambin, 2009). This allows for the estimation of the primary raw materials required for HWP production. The discrepancies between data on volumes of industrial roundwood removals from FAO statistics and calculated raw materials required (in rwe) for HWP production allowed us to estimate the "unrecorded" industrial wood removals.

3. Results

3.1. Global Wood Biomass Carbon Flows

Fig. 2 (upper) shows the global flows of wood C (carbon) from net primary production in forests, along the different stages of economic processing to socioeconomic uses in the year 2010. The estimated NPP_{act} from forest ecosystems is 49 GtC/year. The total biomass appropriation is 4% (1.94 GtC/year) of the global forest productivity (i.e. NPP_{act}). About 46% (886 MtC/year) of TBA is unused extraction left in the forest floor or stand, of which 54% and 46% are aboveground (i.e. logging residues) and belowground biomass losses (i.e. root biomass killed through wood harvest), respectively. These large flows do not enter the socioeconomic system and represent on-site backflows of harvested wood biomass to natural biogeochemical cycles, which provides important ecosystem services such as soil organic carbon (SOC) and nutrient cycling. About 54% (1050 MtC/year) of the TBA enter the socioeconomic systems (i.e. used extraction). Only 28% (297 MtC/year) of used extraction was utilized for HWP production, 56% (591 MtC/year) for energy use and 15% (162 MtC/year) was lost during the processing and disposed of by either open dumping, open burning, landfill and/or incineration (Ogunbode et al., 2013; Steffen, 1995). Approximately 36% (169 MtC/year) of HWP were produced from post-consumer recycled materials (i.e. recovered paper and paperboard).

A detailed flow chart of wood biomass C flows in 2010 is shown in Fig. 2 (below; see Figs. S2 and S3 for 1990 and 2000). TBA amounted to 1.81 GtC/year in 1990 and 1.94 GtC/year in 2010, an increase by 7%. Both used extraction of industrial roundwood and woodfuels increased by 4% between 1990 and 2010. In 2010, approximately 62% of industrial roundwood were utilized in the wood processing industry for the production of semi-finished wood products, 30% in the pulp industry and 8% in other industries for the production of poles, piling, post, and so on. An estimated 211 MtC/year of industrial residues have been recovered, of which 24% (50 MtC/year) were consumed in the wood processing industry, 9% (19 MtC/year) in the pulp industry, 35% (75 MtC/year) for energy use (54% black liquor, 37% bark, 9% for wood pellets) and 32% (67 MtC/year) were disposed of in landfills and incinerators. From 1990 to 2010, the utilization of industrial residues in pulp and wood industries increased by 32% (Figs. 2 and S2). Sixty two percent of papers and paperboards produced in 2010 were made from recovered fibre pulp from recovered paper and paperboard (excluding non-wood plant fibre). About 16% (92 MtC/year) of woodfuels (roundwood) were used for the production of wood charcoal, 75% (69 MtC/year) of this total amount were lost during the production process, while only 25% (23 MtC/year) were actually converted into charcoal. Two percent (12 MtC/year) of woodfuels were transformed into heat and power and 82% (481 MtC/year) were directly consumed for cooking and heating without any further transformation. The share of total wood energy consumed by residential sectors amounts to 85% (504 MtC/year), while wood industries consumed 12% (68 MtC/year) of the total wood energy for their own operations. The rest of woodfuels (3%) were transformed into other forms of energy (e.g. wood pellets and woodchips for heat and power).

3.2. Relations Between Socioeconomic Wood Biomass Flows and Population, Forest Area and Productivity

TBA amounts to 344 kgC/cap/year in 1990 and 280 kgC/cap/year in 2010, a decrease by 18%, while UE amounts 191 kgC/cap/year in 1990 and 152 kgC/cap/year in 2010, a decrease by 20% (Tables 3 and S2). UE and TBA vary by a factor of 10 and 15 among the 11 world regions, respectively (Table 3). TBA in sparsely populated Oceania amounts to 1325 kgC/cap/year, of which 490 kgC/cap/year (37%) is UE, whereas Northern African/Western Asian countries appropriated only 91 kgC/cap/year and used about 50 kgC/cap/year. At the national level, used extraction per capita is highest in countries with a high share of forest cover and a low population density, such as Canada, Sweden, Finland and New Zealand, while it is lowest in sparsely forested Western Asian countries such as Kazakhstan, Iran, and Saudi Arabia (Fig. 3a).

The global apparent consumption of wood biomass is 192 kgC/cap/year in 1990 and 151 kgC/cap/year in 2010, a decrease of 27% (Tables 3 and S2). Among world regions, apparent consumption is highest in Northern America (305 kgC/cap/year) and lowest in Northern Africa/West Asia (70 kgC/cap/year; Table 3). The apparent consumption in Northern Africa/Western Asia and Eastern Asia is mainly being met by net imports to those regions. At the national level, apparent consumption is highest in Finland, Sweden, Austria, and Bhutan (>1 tC/cap/year) and lowest in Iraq, Yemen, and Turkmenistan (<0.01 tC/cap/year.; Fig. 3b).

Forest harvest intensity at the national level is shown in Fig. 3c and d. Countries with high forest harvest intensity measured as UE per forest area (>5 tC/ha/year) are mostly located in regions of Southern Asia (i.e. Pakistan, Bangladesh), Northern Africa/Western Asia (i.e. Egypt, Oman) and Sub-Saharan Africa (i.e. Ethiopia, Kenya, Niger, Nigeria, Ghana, Mauritania; Fig. 3c). Usually, those regions with the largest forested areas have the lowest forest harvest intensity (e.g. Latin America and Russian Federation). Countries with high forest harvest intensity measured as UE per current NPP (>30%) include Niger, Bangladesh, and Pakistan (Fig. 3d). Accordingly, these countries have been shown to face immense problems in terms of deforestation and forest degradation in recent years (Behnassi et al., 2014; Kibria et al., 2011). It is lowest in the Russian Federation, Australia, African countries such as Sudan, Congo, and Angola, and Latin American countries such as Venezuela, Columbia, Peru, and Bolivia. Moreover, there are very few cases, such as Egypt and the United Emirates, in which TBA is larger than forest NPP. This questionable numbers might be explained by uncertainties either relating to woodfuel removal data or NPP data. Globally, UE and TBA are approximately 2% and 4% of the current NPP of forest ecosystems, respectively. UE per current NPP varies by a factor of 21 among 11 world regions.

3.3. Trends of Wood Energy use and its Share in Total Primary Energy Consumption

Traditional woodfuels are highly relevant in global wood biomass flows. The consumption of traditional woodfuels is almost 48% of the global apparent consumption in 2010 (Table 3). In the regions of Sub-Saharan Africa and Southern Asia, this share even reaches >70%, while the lowest value is found in Northern America, where only 11% of

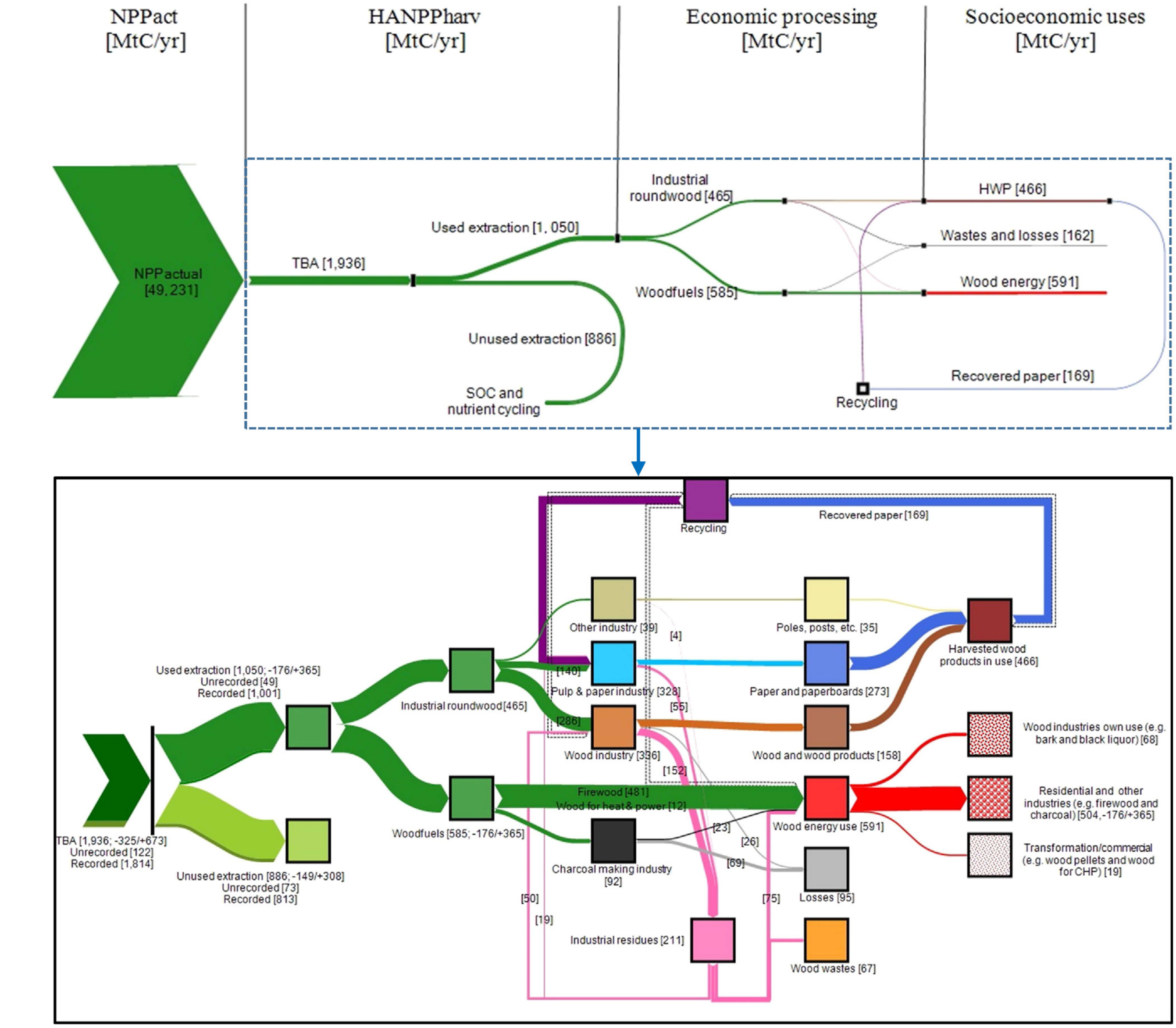

Fig. 2. Global wood carbon flows from forest NPP, along the different stages of economic processing to socioeconomic uses and final consumption in 2010 (the width of the line is proportional to the flow). Dotted lines indicate unquantified flows of wood biomass (i.e. post-consumer wood) and [−/+] values indicate global average woodfuels minimum (−) and maximum (+) estimates. Unrecorded used extraction (UE) means unrecorded industrial wood removals and recorded UE means recorded wood removals (i.e. both industrial wood and woodfuels) from FAO data.

apparent consumption are traditional woodfuels (Table 3). Traditional woodfuels remain the most important wood biomass use in least developed countries, with a share of more than 90% in socioeconomic uses of wood biomass (Fig. 4). However, consumption of traditional woodfuels in least developed countries decreased by 23% from 1990 to 2010. On the other hand, modern woodfuels become increasingly important in industrialized countries, as shown by the increase of consumption by 82% from 1990 to 2010.

As shown in Fig. 5a, the share of wood energy (in traditional form) in total primary energy consumption (IEA, 2014) in Sub-Saharan Africa is considerably higher than in all other world regions during all considered years, with 85% in 1990 and 71% in 2010. The lowest share of traditional wood energy can be found in Northern America, where only 0.44% of the total primary energy consumption is covered by traditional woodfuel in 2010. In contrast to this trend for traditional woodfuels, the share of modern woodfuels in total primary energy consumption increased considerably in European regions from 1990 to 2010, reaching 1.48% in Western Europe and 1.85% in East and South-eastern Europe in 2010 (Fig. 5b). The lowest shares of modern wood energy in primary energy consumption can be found in Northern Africa/Western Asia, with about 0.02% in 2010.

3.4. Uncertainties

In the global total, the estimated unrecorded industrial wood removals is 49 MtC/year or 5% of used extraction (Fig. 3) and estimated minimum and maximum woodfuel removals is 409 MtC/year (585 MtC/year minus 176 MtC/year) and 950 MtC/year (585 MtC/year plus 365 MtC/year), respectively (see Table S7 for country level data). There is significant variation on TBA uncertainties between world regions (Fig. S4). Estimated uncertainties (both industrial wood and woodfuels) range from 3 to 142 MtC/year (maximum estimates) and from 0 to 42 MtC/year (minimum estimates). Uncertainties are highest for Southeast Asia and lowest for Northern

Table 3
Net primary production (NPP), total biomass appropriation (TBA), used extraction (UE), apparent consumption and net trade in 11 world regions in 2010 (kgC/cap/year).

	N. Africa/W. Asia	Sub-Saharan Africa	C. Asia/Russian Fed.	Eastern Asia	Southern Asia	S-E. Asia	Northern America	Latin America	Western Europe	E. & S.E. Europe	Oceania & Australia	World
Population (1000 capita)	391,114	866,908	205,311	1,593,572	1,681,407	597,096	346,379	591,764	411,649	184,780	36,280	6,906,260
Land area (1000 km^2)	10,537	23,643	20,304	11,560	6400	4341	18,241	20,115	3631	2124	8484	129,381
Population density (cap/km^2)	37	37	10	138	263	138	19	29	113	87	4	53
GDP per capita (US$/cap)	7753	1496	8499	7861	1483	3114	47,845	8823	37,720	8430	35,853	9141
Net Primary Production (forest)	533.90	11,323.68	33,077.52	1595.79	625.86	6608.79	16,359.23	26,269.02	2804.94	3,546.08	50,689.75	7,126.65
Total biomass appropriated	90.91	396.96	320.21	186.26	156.42	365.29	530.50	465.45	324.95	388.97	1,324.85	280.36
Used extraction	49.82	244.24	200.13	77.11	79.86	159.47	347.87	264.10	206.31	246.97	489.66	152.01
Industrial roundwood + bark	15.41	25.98	160.63	41.91	6.32	68.83	311.61	112.76	155.77	167.59	395.34	67.22
Woodfuel + bark	34.41	218.26	39.50	35.12	73.53	90.65	36.26	151.34	50.55	79.38	94.32	84.78
Apparent consumption	69.57	239.99	143.53	102.40	82.12	142.47	304.91	237.00	249.26	193.58	278.14	151.37
Harvested wood products												
Semi-finished wood products	21.55	2.89	25.26	27.85	2.95	12.08	90.75	24.91	64.95	46.23	66.25	22.67
Wood pulp	3.80	1.11	14.91	16.15	1.88	8.87	71.96	6.23	70.85	15.55	39.27	14.74
Poles, piles, etc.	0.63	9.25	23.16	6.03	0.47	6.84	1.75	5.68	2.37	11.53	7.36	5.04
Wood energy use												
Firewood/fuelwood	22.03	160.03	33.74	32.36	69.57	80.64	31.36	118.96	39.30	51.07	75.92	69.59
Wood charcoal	3.43	14.14	0.17	0.69	0.99	1.86	1.38	7.22	0.91	0.61	0.51	3.30
Industrial residues (i.e. bark)	0.04	0.44	18.51	0.44	0.00	0.00	30.14	0.00	20.31	17.84	31.47	4.07
Black liquor	0.25	0.79	6.99	2.63	0.40	4.20	45.42	11.09	16.54	3.96	12.69	5.78
Wood pellets	0.00	0.00	0.50	0.29	0.00	0.00	2.17	0.04	11.23	1.39	0.32	0.90
Wood for heat & power	0.07	0.01	4.94	0.74	0.02	1.13	0.00	1.98	9.45	18.71	16.33	1.74
Losses and wastes												
Losses	10.26	46.94	5.66	4.58	3.32	11.60	14.96	28.77	7.56	14.59	19.47	13.67
Unutilized industrial residues	7.56	4.39	9.86	10.64	2.52	15.25	15.04	32.12	5.79	12.09	8.55	9.87
Net trade (total)	19.75	−4.25	−56.60	25.29	2.26	−17.00	−42.96	−27.10	42.95	−53.39	−211.52	−0.64
Roundwood	1.43	−1.45	−26.05	7.87	1.04	−2.79	−7.15	−0.55	15.78	−28.06	−111.24	0.15
Wood pulp	3.19	−0.93	−7.53	9.18	0.65	−0.94	−28.37	−19.94	11.70	3.95	−10.97	−0.35
Wood products	13.40	−0.54	−17.20	3.51	0.56	−6.78	−2.15	−1.35	−0.59	−15.75	−11.57	−0.20
Wood pellets	0.00	−0.01	−1.51	0.10	0.00	0.00	−1.90	−0.01	3.96	−4.04	−1.04	0.00
Wood charcoal	0.18	−0.19	0.00	0.12	0.01	−0.31	0.11	−0.26	0.79	−0.29	0.05	0.01
Wood residues	0.00	−0.01	−1.34	0.02	0.00	−0.01	−1.16	0.09	5.44	−5.34	−0.37	0.09
Wood chips and particles	1.55	−1.12	−2.96	4.50	0.00	−6.17	−2.34	−5.09	5.86	−3.85	−76.39	−0.35

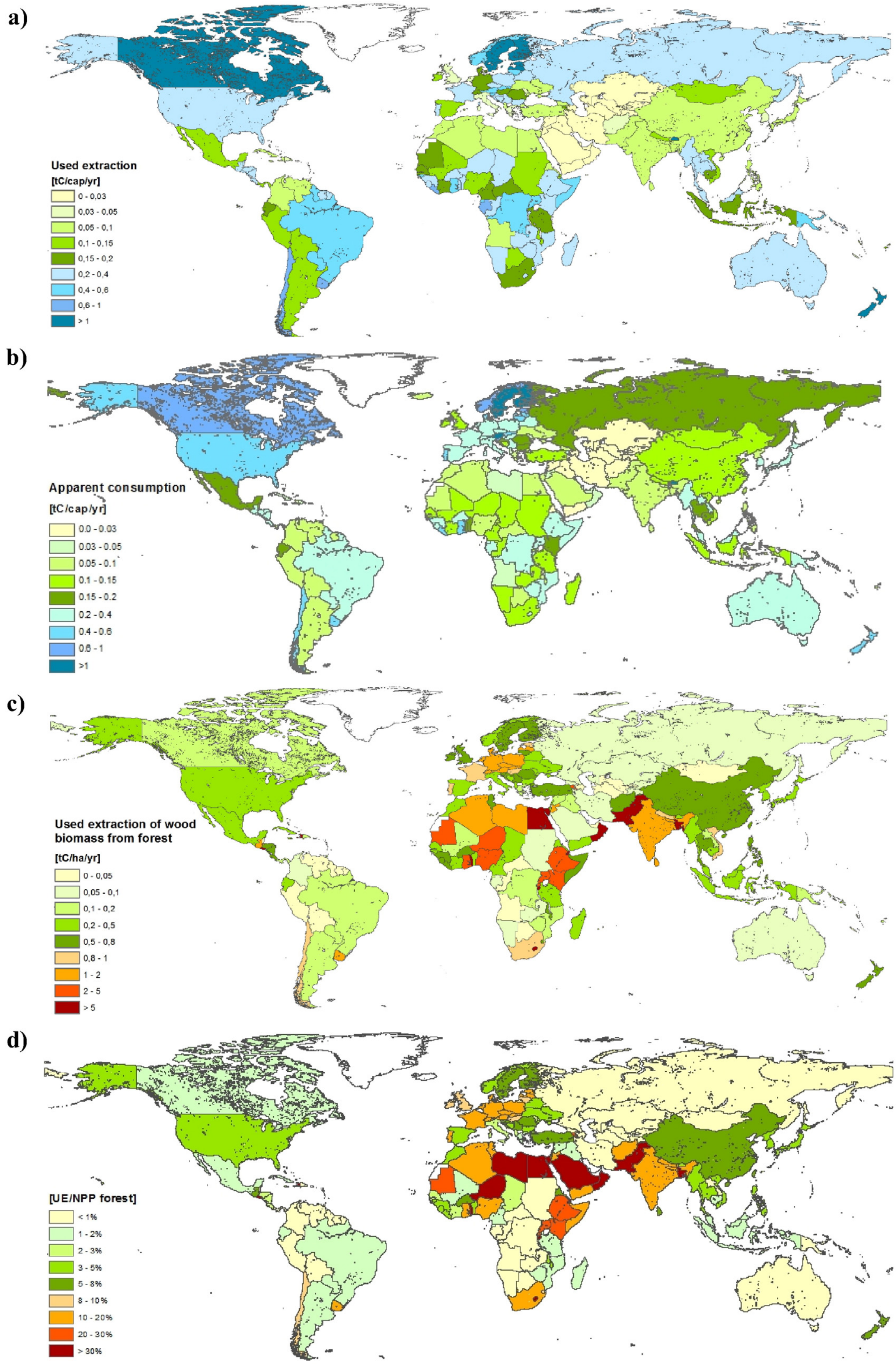

Fig. 3. Wood harvest, harvest intensity, and consumption. a) used extraction per capita, b) apparent consumption per capita, c) forest harvest intensity measured as UE per forest area, d) forest harvest intensity measured as UE per current NPP. All values refer to the year 2010. Antarctica and Greenland are not included in the assessment.

America. If the high estimate for global wood biomass flows is applied (Fig. 2), TBA and UE increase from 1936 MtC/year to 2609 MtC/year and from 1050 MtC/year to 1414 MtC/year, respectively. This would result in a 1% increase of forest harvest intensity measured as used extraction per current forest NPP (Fig. S5). Among world regions, this increase is more evident in Southern Asia, with

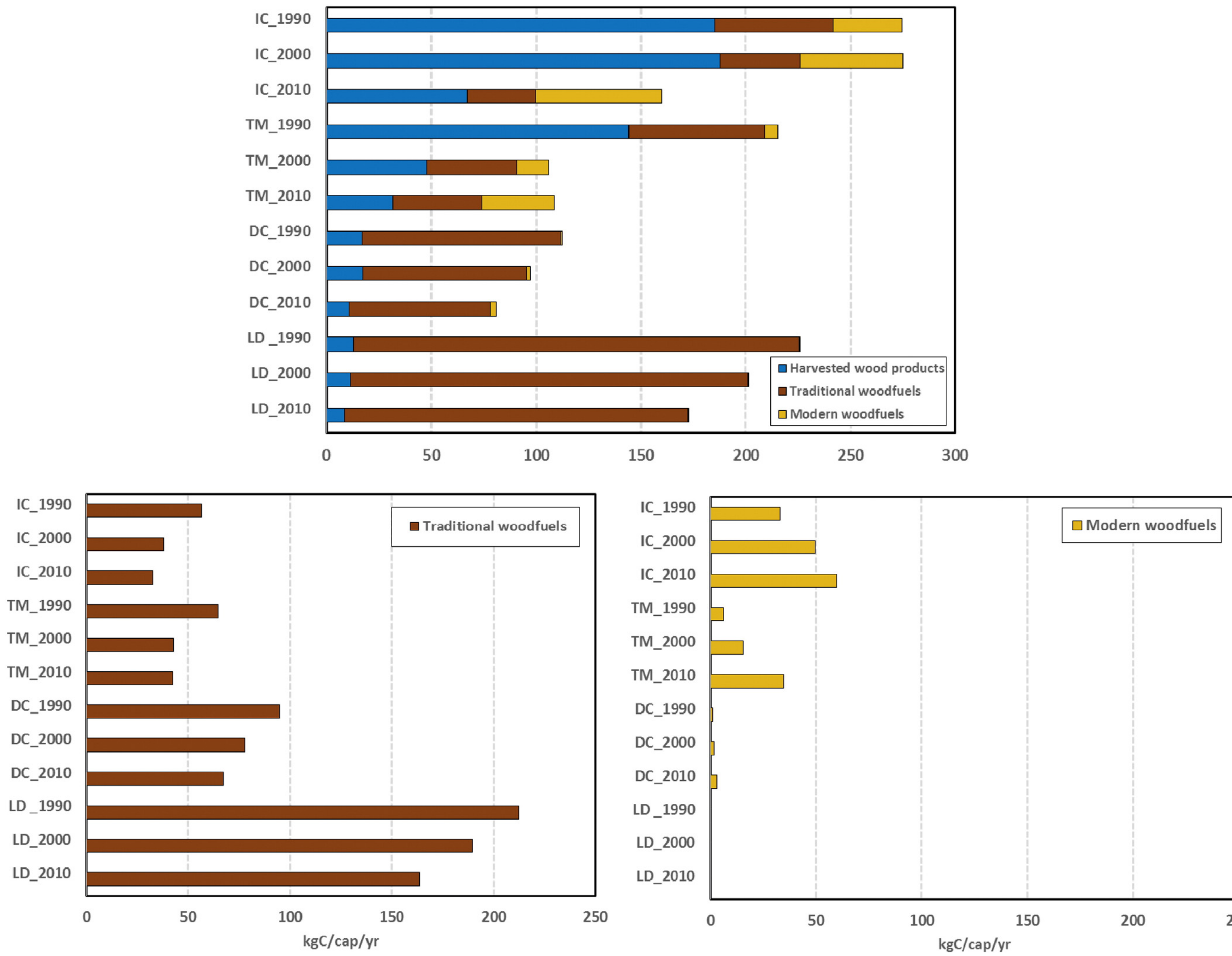

Fig. 4. Trends of per capita wood domestic use: industrial roundwood, traditional woodfuels, and modern woodfuels in 4 country groups: 1) Industrialized countries (IC); 2) Transition markets (TM); 3) Developing countries (DC) and; 4) Least developed countries (LD) from 1990 to 2010 (see Table S6). (Note the different scales in the upper graph and lower graphs).

an increase from 13% to 18% by using the higher estimate for wood biomass flows (Fig. S5).

4. Discussion

4.1. Comparison to Other Wood Flow Estimates

We established a consistent and comprehensive estimate on global wood flows from primary production down to the socio-economic uses and final consumption for the years 1990, 2000, and 2010 at national levels. Uncertainties in industrial wood removals and woodfuel removals (i.e. minimum and maximum estimates) were estimated and taken into account.

So far, only Sims et al. (2006, 2007) provide datasets that potentially could be compared with our results. Sims et al., however, put the focus of their analysis on woodfuels, present their results in energy units (Exajoules, EJ/year) and for the reference year 2004, which hampers comparability. To still allow for such a comparison, we converted our estimate to EJ and took the average value of 2000 and 2010 (see Table S8 in the supplementary material) as basis for comparison.

The comparison between our study and those of Sims et al. (2006, 2007) show a relatively high consistency with our results for some parameters, while others differ considerably. With regard to global woodfuel supply, the estimate of Sims et al. (2007) is only 2% lower and the estimate by Sims et al. (2006) is 5% lower than our own estimate. For traditional woodfuel supply (i.e. fuelwood and wood charcoal), Sims et al. (2006) is 5% lower than our estimate. In terms of modern woodfuel supply, numbers given by Sims et al. (2006) are 11% lower than our average estimate. The quantity of fuelwood from both forests and non-forests is 4% lower than our average maximum estimate. However, the discrepancy between the primary source (i.e. forests) and the flow of fuelwood in the Sims et al. (2006) energy flow chart is not reflected in our data.

These differences can mostly be explained by the adoption of global factors for all regions in the study by Sims et al. (2006). Additionally, we did not restrict modern woodfuel production to black liquor as Sims et al. (2006), but quantified the contribution of all raw materials utilized, including black liquor as well as bark for energetic use in wood industry, other industrial residues for wood pellet production, and wood chips (directly from the forests) for combined heat and power production.

4.2. Socioeconomic Wood Biomass Flows, Trends and Drivers

On the global total, about 4% of the current NPP of forest ecosystems are harvested, with high variation at the national level, ranging from 0.04% to >70% among countries. It is important to note that not all of the annual NPP of a forest accumulates in carbon stocks and is thus accessible for harvest. Much of the NPP is consumed by herbivores or added to the litter pool and further decomposed in the detritus food chain in the very same year of production (Schulze et al., 2012). Thus,

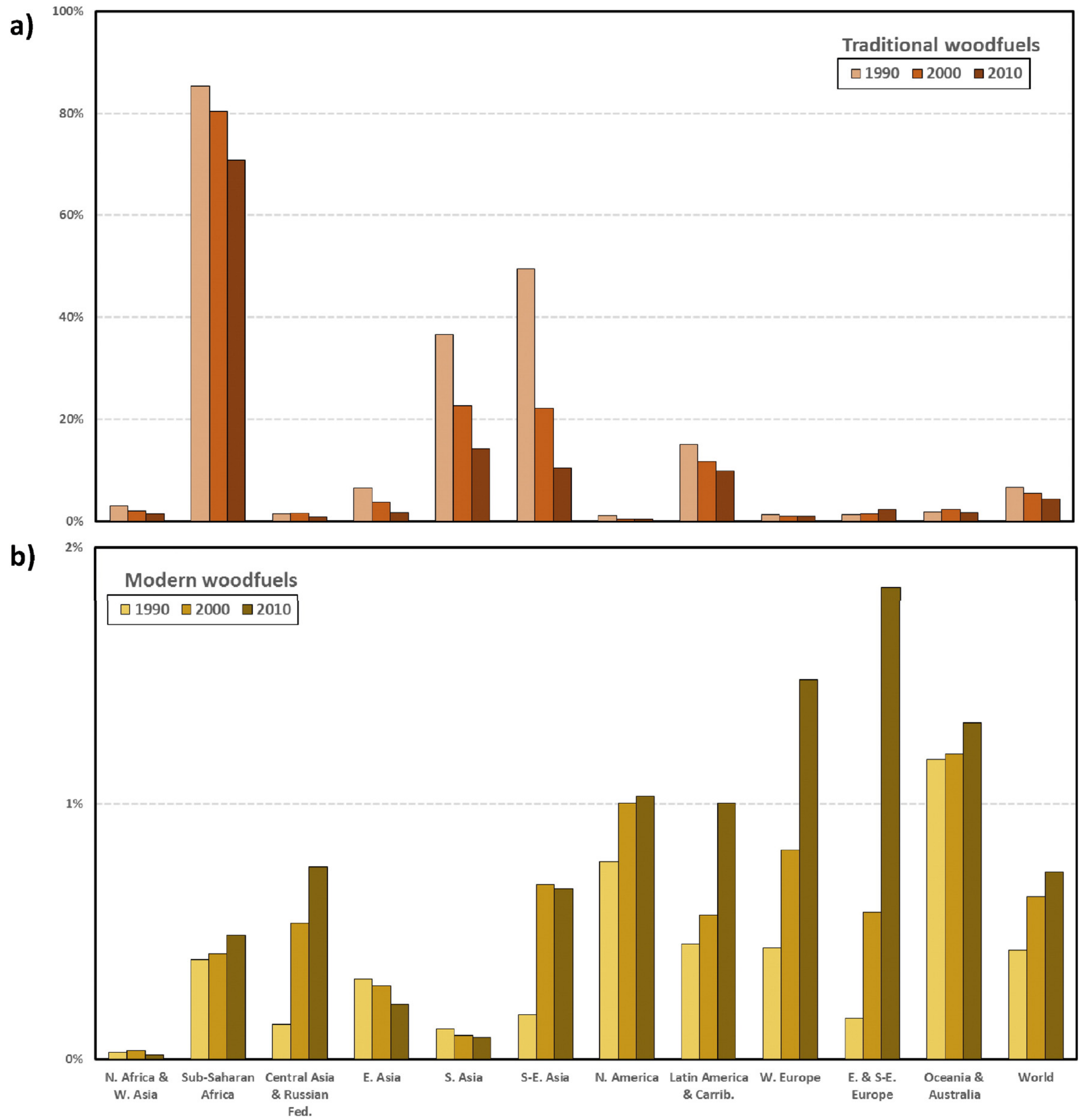

Fig. 5. Share of per capita (a) traditional and (b) modern woodfuels in total primary energy consumption (IEA, 2014) for 11 world regions, for the years 1990, 2000 and 2010.

the maximum fraction of human appropriated NPP that can be harvested from forests is significantly below 100%. For instance, according to Schulze et al. (2012), a continued appropriation levels of about 60–70% (stemwood harvest to increment) will result in the degradation of biomass pools and depletion of soil fertility. On the global level, the harvest intensity of forests, measured as harvest to increment is around 13% and thus far below this threshold. However, in Southern Asian and Sub-Saharan countries, a harvest intensity at or above 60% is prevailing. The global figure appears even less severe if harvest intensity is measured in the unit harvest per NPP. Only 4% of the actual NPP of forests is currently appropriated in the form of biomass products. However, in terms of NPP the threshold might be significantly lower than the 60% related to stemwood, because a large fraction of NPP is herbaceous (e.g. leaves) and thus does not contribute to stemwood increment. Assuming that half of NPP consists of herbaceous tissue, and does thus not accumulate within forests biomass, the threshold would be reduced to 30%. This is still large in comparison to the current global harvest intensity. However, in 8% of the countries (contribution 0.16% (6.5 Mha) of the global forest area), harvest intensity is above 30% of actual NPP. (Fig. 3d).

The availability of forest resources, e.g. the extent of forestland and its current forest productivity, has a significant influence on used extraction of domestic wood in a region, as it is the most important factor for the option space of wood extraction. In the last 20 years, global forest productivity increased with an annual growth rate of 7%, while global used extraction remained relatively stable, with an annual growth rate of 0.2%. Among world regions, Sub-Saharan Africa and Latin America, the two world regions with the largest forest area and highest forest productivity (i.e. NPP per unit area) also show a high domestic wood used extraction. In contrast, the region of Northern Africa/Western Asia, characterized by the lowest forest area and productivity, also the lowest domestic level of wood used extraction prevails (Fig. 3, Table 3). However, this pattern is not transferable to all world regions in a straightforward way. For instance, while the Russian Federation has a high forest area and forest NPP_{act}, it is among those regions with the lowest rate for used extraction of wood. Large parts of Russia's vast forest areas are difficult to exploit because of poor infrastructure development (e.g. undeveloped transportation), altitude limits, and relatively restricted by protected areas (FAO, 2001). Still, in general a high availability and productivity of forest and wooded lands in most cases is related to a high level of domestic used extraction of wood per capita. This result supports findings by Krausmann et al. (2008) and Weisz et al. (2006). Forest productivity and domestic used extraction of wood are highly correlated with a country level regression (we find a Pearson's correlation coefficient (r) of 0.65; Fig. S9).

Economic development or affluence, as measured by per capita GDP, is considered as an important factor for the explanation of regional variations of the socioeconomic metabolism (Schandl and Eisenmenger, 2006; Weisz et al., 2006). The data assembled in Fig. 4 suggests that the patterns of per capita apparent consumption of wood is strongly influenced by economic performance. This holds true in particular for the consumption of harvested wood products (HWP). Per capita consumption of HWP is higher in industrialized countries and lower in least developed nations in all reference years. GDP and HWP consumption are highly correlated, with a country-level regression Pearson's correlation coefficient (r) of 0.85 (Fig. S9). Traditional woodfuels play a prominent role in low income regions such as Sub-Saharan Africa, South Asia and Southeast Asia (Table 3 and Fig. 5). The incidence of poverty is the most significant parameter for the traditional use of woodfuels (Zaku et al., 2013). The global trends of traditional woodfuel consumption are decreasing with an annual growth rate of −0.1%. The dependency on traditional wood energy tends to decrease with increasing level of economic development. On the other hand, industrialized or high income regions (e.g. Europe) increased their consumption of modern woodfuels during the last decades (Figs. 4 and 5). The global annual growth of modern woodfuels lies at 6%. The primary driver of increasing wood energy consumption in modern form in industrialized countries (e.g. the European Union) is policy intervention (i.e. subsidies and emission reduction target) favouring the use of renewable materials like wood which has been seen as carbon neutral (Junginger et al., 2008). It is to expect that technology development will also contribute to a major shift in the importance of wood energy (FAO, 2008, 2010). Moreover, climate change and natural disturbances such as storms, fires and pest attacks also influence the trends of wood extraction as well as patterns of wood use (Kleine et al., 2010).

4.3. Future Trends of Global Wood Biomass Flows

The use of wood biomass is expected to increase considerably over the next decades due to the projected growth in population and the increased use of bioenergy as promoted by governments in response to climate change and the scarcity of fossil fuels. Population is expected to exceed 9 billion in 2050 (UN, 2013), with a more pronounced increase in less developed countries that are highly dependent on traditional woodfuels. An example for the promotion of wood based bioenergy (i.e. wood pellets) is provided by the ambitious and strict 20% renewable energy target by 2020 in the European Union (EU), where wood-based energy plays a significant role in its strategies to expand the use of bioenergy (European Commission, 2009; ITTO, 2008). Recently, the EU set a target of at least 27% share of renewable energy consumption by 2030. In the last 20 years, forest areas in Europe increased with an annual growth rate of 2%, while the use of modern woodfuels increased considerably faster (annual growth rate 12%; Fig. 5). Given these past trends, in terms of availability of forest resources and policy interventions driven by climate change and the scarcity of fossil fuels, many expect that the demand for modern woodfuels continues to increase during the next decades. For example, the European Commission (2013) expects that wood removals increase by 30% from 2010 to 2020. According to Mantau et al. (2010), biomass demand from power plants in the EU-27 could reach 242.3 million m^3 by 2020 and 377.1 million m^3 by 2030. Residential wood energy demand is projected to reach 232 million m^3 in 2020 and afterwards to stay constant through 2030. Wood pellet consumption in the EU-27 residential sector is expected to increase from 23 million m^3 in 2010 to 69 million m^3 in 2020 and to reach 82 million m^3 in 2030 (Mantau et al., 2010). The share of per capita wood energy in total primary energy is expected to increase further, especially in the regions of Western Europe and East and South-eastern Europe (Fig. 5; Junginger et al., 2008).

Consumption of traditional woodfuels is expected to decrease in Asia (except in rural areas), due to a shift to fossil fuels, driven by their fast growing economies (Fig. 5a and b). However, the overall wood consumption might continue to increase due to shifts towards the industrial use of wood (FAO, 2010). In less developed countries, consumption of wood energy for traditional use (in absolute numbers) is expected to increase, mainly due to high population growth rates (Global Environment Fund, 2013), while consumption might decrease on a per capita basis, largely following historical trends (Fig. 4). Many regions in Sub-Saharan Africa, with high population growth rates and low economic development are already confronted with fuelwood shortages (Jepma, 1995).

This increase in the consumption of modern fuelwood, in line with the growing interest in the so-called bioeconomy, in which fossil fuels and other conventional materials are increasingly replaced by biomass, might lead to an increased pressure on wood biomass resources and forest ecosystem. Maximizing the efficiency of wood biomass conversions along the life cycle of wood products by the cascading use of biomass (i.e. the prioritization of wood biomass for higher-added value products, and as material input over energy use; Ciccarese et al., 2014; Keegan and Kretschmer, 2013; Haberl and Geissler, 2000) can contribute to alleviate this increased pressure. Cascading use of wood biomass maximizes the amount of carbon sequestered in biomaterials and it delays carbon emissions. According to Keegan and Kretschmer (2013), this principle can also be applied in the bioenergy sector by restructuring their bioenergy generation towards increased use of waste wood, industrial residues and/or recycled products and advanced conversion technologies. Our data indicate that large amounts of biomass are lost during wood processing and wood charcoal conversion due to poor production efficiencies (Fig. 2 and Table 3). Improved kilns could contribute significantly to production efficiency, for instances, brick or metal kiln and industrial retort achieve considerably higher conversion efficiencies (>20%) than traditional earth kiln (10% conversion efficiency; NL Agency, 2013). However, adoption of improved kiln efficiencies is not successful in Sub-Saharan Africa due to the high initial cost involved. According to Chidumayo and Gumbo (2010), the conversion efficiency of traditional earth kiln can be improved by 50% at low cost simply through improved kiln operation. Increasing the efficiency of wood charcoal conversion from a factor of 8 to 6 (in Africa and Latin America) and from 6 to 5 (in developed countries), reducing wood processing losses by 50% and replacing virgin wood resources by industrial residues for paper, panels and energy production would reduce global used extraction of wood by 10% (106 MtC/year) in 2010. Another effective measure could be the use of more efficient cooking stoves in low-income regions, which has been shown to reduce fuelwood consumption and carbon emissions (Bailis et al., 2015). The increased use of post-consumer wood waste (i.e. lumber from construction scraps or demolition projects) is another potential to reduce virgin resources in the production of wood products (e.g. particleboard and paper) and energy use (Mantau, 2012). According to Mantau (2012), the recovery rate of post-consumer wood based on the total market volume of wood products in EU 27 is 22.3%.

5. Conclusions

Our analysis suggests that still considerable uncertainties on global used extraction of wood, especially of woodfuels, prevail. We find massive regional variations in the patterns of wood flows among 11 world regions, also owing to their differences in population, affluence and area, diverging by a factor of 14 between the lowest (Northern Africa/ Western Asia) and highest (Oceania/Australia) consumers. The patterns of wood biomass use are mainly influenced by forest area and productivity, affluence, and policy intervention. In the last 20 years, the trends of global forest productivity is increasing with an annual growth rate of 7%, while global wood used extraction remains stable, with annual growth rate of 0.2%. However, global demand for the services of wood is expected to increase considerably in the near future (up to 2030) due to high population growth in developing countries, strict renewable energy mandates and the adoption of bioeconomy strategies in industrialized nations. A substantial rise in wood removals for meeting future demands for wood-based products and energy might put additional pressure to forest ecosystems. For this reason, it is essential to reduce uncertainty levels in the estimates of global wood flows, as they represent an important pillar for informed decision making. Furthermore, increase the efficiency of wood biomass utilization, can be a vital and promising mean to reduce the environmental impacts related to resource use. Our analysis of global wood biomass flows and the associated uncertainties suggest that fostering research efforts to further analyse the impacts of cascade use of wood biomass are required, in order to develop strategies of sustainable wood biomass use.

Acknowledgments

The authors would like to thank Tamara Fetzel for her help with mapping the data and the anonymous reviewers for their valuable comments and suggestions. The research leading to these results has been supported by the EU through the Marie Curie Initial Training Networks (ITN) action CASTLE, grant agreement no. 316020. The authors are grateful for funding from the European Research Council ERC-2010-Stg-623522 LUISE. The contents of this publication reflect only the author's/authors' views and the European Union is not liable for any use that may be made of the information contained therein. This article contributes to the Global Land Project (www.globallandproject.org).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2015.09.011.

References

Arets, E.J.M.M., van de Meer, P.J., Verwer, C.C., Hengeveld, G.M., Tolkamp, G.W., Nabuurs, G.J., van Oorschot, M., 2011. Global wood production: assessment of industrial roundwood supply from forest management systems in different global regions. Alterra Report 1808. Alterra Wageningen UR, The Netherlands.

Audigane, N., Bentele, M., Ferreira, J.M.F., Gyurik, A., Jossart, J.-M., Mangel, A.-C., Martin, M., Masdemont, P.R., Mörner, H., Paniz, A., Pieret, N., Rechberger, P., Rakos, C., Schlagiweit, C., Sievers, A.K., Tuohiniitty, H., 2012. European pellet report. PellCert project, 2012 April. http://www.enplus-pellets.eu/wp-content/uploads/2012/04/Europe_pellet_report_April2012.pdf.

Bailis, R., Drigo, R., Ghilardi, A., Masera, O., 2015. The carbon footprint of traditional woodfuels. Nat. Clim. Chang. 5, 266–272. http://dx.doi.org/10.1038/NCLIMATE2491.

Chidumayo, E.N., Gumbo, D.J., 2010. The Dry Forests and Woodlands of Africa: Managing for Products and Services. Earthscan, pp. 164–165.

Ciccarese, L., Pellegrino, P., Pettenella, D., 2014. A new principle of the European Union forest policy: the cascading use of wood products. Ital. J. For. Mt. Environ. 69 (5), 285–290. http://dx.doi.org/10.4129/ifm.2014.5.01.

Cocchi, M., Nikolaisen, L., Junginger, M., Goh, C.S., Heinimö, J., Bradley, D., Hess, R., Jacobson, J., Ovard, L., Thrän, D., Hennig, C., Deutmeyer, M., Schouwenberg, P.P., Marchal, D., 2011. global wood pellet industry market and trade study. Task 40: Sustainable International Bioenergy Trade, IEA Bioenergy (http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final_R.pdf).

Dykstra, D.P., 1992. Wood residues from timber harvesting and primary processing: a global assessment for tropical forests. Food and Agriculture Organization of the United Nations, unpublished mimeograph. 93 pp.

Behnassi, M., Shahid, S.A., Mintz-Habib, N., 2014. Science, Policy and Politics of Modern Agricultural System: Global Context to Local Dynamics of Sustainable Agriculture. Springer Dordrecht, p. 148.

EPE, 2010. Empresa de Pesquisa Energetica. Relatório Final do Balanço Energético Nacional. Final Report of the National Energy balance (https://ben.epe.gov.br/BENSeriesCompletas.aspx).

Erb, K.-H., Krausmann, F., Gaube, V., Gingrich, S., Bondeau, A., Fischer-Kowalski, M., Haberl, H., 2009. Analyzing the global human appropriation of net primary production — processes, trajectories, implications. An introduction. Ecol. Econ. 69, 250–259. http://dx.doi.org/10.1016/j.ecolecon.2009.07.001.

European Commission, 2013. A new EU Forest Strategy: for Forests and the Forest-Based Sector. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission, COM, Bruxxelles (659 def. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0659:FIN:en:PDF).

European Commission, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union L 140, 16–47 (5 June http://faolex.fao.org/docs/pdf/eur88009.pdf).

EUROSTAT, 2001. Economy-wide material flow accounts and derived indicators. A Methodological Guide, Eurostat, European Commission. Office for Official Publications of the European Communities, Luxembourg.

FAO, 2014a. FAOSTAT: ForesSTAT. FAO Forest Statistical Database. FAO, Rome (Accessed on May 2014. http://faostat.fao.org/site/626/default.aspx#ancor).

FAO, 2014b. Forest products statistics: global forest products facts and figures. Yearbook of Forest Products 2013. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2011. Global Forest Resources Assessment 2010. Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2010. Asia-Pacific forests and forestry to 2020. A report of the second Asia-Pacific Forestry Sector Outlook Study. Asia-Pacific Forestry Commission RAP Publication 2010/6. FAO, Bangkok.

FAO, 2008. Forests and energy: key issues. FAO Forestry Paper 154. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2001. Global forest resources assessment 2000. Main Report. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 1999a. The role of wood energy in Africa. Wood Energy Today for Tomorrow (WETT). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 1999b. The role of wood energy in the near east. Wood Energy Today for Tomorrow (WETT). Food and Agriculture Organization of the United Nations, Rome, Italy.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting. J. Ind. Ecol. 15, 855–876. http://dx.doi.org/10.1111/j.1530-9290.2011.00366.x.

RWEDP/FAO, 1997. Regional study on wood energy today and tomorrow in Asia. Working Paper No: APFSOS/WP/34. Regional Wood Energy Development Program in Asia. FAO of the United Nations, Bangkok. November.

RWEDP/FAO, 1996. Wood energy data. Wood Energy News, Volume 11 No. 2. Regional Wood Energy Development Program in Asia (GCP/RAS/154/NET) (June 1996).

Global Environment Fund, 2013. Africa will import — not export — wood (Maryland, United States).

Haberl, H., Schulze, E.-D., Körner, C., Law, B.E., Holtsmark, B., Luyssaert, S., 2013. Response: complexities of sustainable forest use. GCB Bioenergy 5, 1–2. http://dx.doi.org/10.1111/gcbb.12004.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc. Natl. Acad. Sci. 104, 12942–12947. http://dx.doi.org/10.1073/pnas.0704243104.

Haberl, H., 2001. The energetic metabolism of societies, part I: accounting concepts. J. Ind. Ecol. 5, 11–33.

Haberl, H., Geissler, S., 2000. Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecological engineering 16 (Supplement 1), 111–121. http://dx.doi.org/10.1016/S0925-8574(00)00059-8.

Heinimö, J., Junginger, M., 2009. Production and trading of biomass for energy — an overview of the global status. Biomass Bioenergy 33, 1310–1320. http://dx.doi.org/10.1016/j.biombioe.2009.05.017.

IBGE, 2010. Instituto Brasileiro de Geografia e Estatistica. Sinopse preliminar do censo demografico vol. 7 (ISSN 0104-057X. Rio de Janeiro, Brazil p. 1–1–5–5, 2000 http://www.ibge.gov.br/home/presidencia/noticias/imprensa/ppts/0000000237.pdf).

IEA, 2014. International Energy Statistics. IEA Independent Statistics and Analysis, U.S. Energy Information Administration Accessed on May 2014. (http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=44&aid=2&cid=all,&syid=1990&eyid=2010&unit=QBTU).

IPCC, 2014. Summary for Policymakers. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2006. IPCC guidelines for National Greenhouse Gas Inventories. IGES, Japan.

ITTO, 2008. Energy Grows on Trees. A Report of the International Conference of Wood-Based Bioenergy. ITTO Technical series 31 (Hanover, Germany).

Jepma, C.J., 1995. Tropical Deforestation: A Socio-Economic Approach. Earthscan LtD., London, UK.

Junginger, M., Bolkesjøb, T., Bradley, D., Dolzand, P., Faaij, A., Heinimö, J., Hektor, B., Leistad, Ø., Ling, E., Perry, M., Piacente, E., Rosillo-Calle, F., Ryckmans, Y., Schouwenbergk, P.-P., Solberg, B., Trømborg, E., da Silva Walter, A., de Wit, M., 2008. Developments in international bioenergy trade. Biomass Bioenergy 32, 717–729. http://dx.doi.org/10.1016/j.biombioe.2008.01.019.

Jungmeier, G., Subotić, V., 2011. Country report Austria. IEA Bioenergy Task 42. Joanneum Research, Graz, Austria (28 pp.).

Kalt, G., 2015. Biomass streams in Austria: drawing a complete picture of biogenic material flows within the national economy. Resour. Conserv. Recycl. 95, 100–111. http://dx.doi.org/10.1016/j.resconrec.2014.12.006.

Keegan, D., Kretschmer, B., 2013. Cascading use: a systematic approach to biomass beyond the energy sector. Biofuels Bioprod. Biorefin. 7, 193–206. http://dx.doi.org/10.1002/bbb.1351.

Kibria, M.G., Rahman, S.A., Imtiaj, A., Sunderland, T., 2011. Extent and consequences of tropical forest degradation: Successive policy options for Bangladesh. J. Agric. Sci. Technol. 29–37 (ISSN: 1939-1250).

Kleine, M., Buck, A., Eastaugh, C., 2010. Making African Forests Fit for Climate Change: a Regional View of Climate-Change Impacts on Forests and People, and Options for Adaptation. International Union of Forest Research Organizations.
Koopmans, A., Koppejan, J., 1997. Agricultural and forest residues — generation, utilization and availability. Paper Presented at the Regional Consultation on Modern Applications of Biomass Energy, 6–10 January 1997, Kuala Lumpur, Malaysia.
Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. http://dx.doi.org/10.1073/pnas.1211349110.
Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. Ecol. Econ. 65 (3), 471–487. http://dx.doi.org/10.1016/j.ecolecon.2007.07.012.
Mantau, U., Saal, U., Prins, K., Steierer, F., Lindner, M., Verkerk, H., Eggers, J., Oldenburger, J., Asikainen, A., Anttila, P., 2010. EUwood — real potential for changes in growth and use of EU forests. Final Report. Hamburg, Germany, June 2010 (160 pp.).
Mantau, U., 2012. Wood flows in Europe (EU 27). Project Report, Commissioned by CEPI (Confederation of European Paper Industries) and CEI-Bois (European Confederation of Woodworking Industries) 24 Celle, Germany.
METLA, 2011. Wood flows in Finland 2010. Finnish statistical yearbook of forestry 2011. http://www.metla.fi/metinfo/tilasto/julkaisut/vsk/2011/vsk11_wood_flows_in_Finland_2010.pdf.
Meyfroidt, P., Lambin, E.F., 2009. Forest transition in Vietnam and displacement of deforestation abroad. PNAS 106 (38), 16139–16144. http://dx.doi.org/10.1073/pnas.0904942106.
Nellemann, C., 2012. In: INTERPORl Environmental Crime Programme (Ed.), Green carbon, black trade: illegal logging, tax fraud and laundering in the worlds tropical forests. A rapid response assessment. United Nations Environment Programme, Norway.
NL Agency, 2013. Charcoal Production From Alternative Feedstocks. Ministry of Economic Affairs, The Netherlands (http://English.rvo.nl/sites/default/files/2013/12/Charcoal%20production%20from%20alternative%20feedstocks%20-%20June%202013.pdf).
Ogunbode, E.B., Fabunmi, F.O., Ibrahim, S.M., Jimoh, I.O., Idowu, O.O., 2013. Management of sawmill wastes in Nigeria: case study of Minna, Niger State. Greener J. Sci. Eng. Technol. Res. 3 (2), 034–041.
Pellet Atlas, 2009a. Pellet market country report in Europe. Development and Promotion of a Transparent European Market Creation of a European Real-Time Pellets Atlas.
Atlas, P., 2009b. Wood pellets production and trade in Russia, Belarus and Ukraine. Market Research Report. WP 6.1 Assessment of International Pellet Trade Developments in Non-EU Countries.
Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. IGES-IPCC, Hayama, Kanagawa, Japan.
Pulkki, R.E., 1997. Literature synthesis on logging impacts in moist tropical forests. Global Fibre Supply Study Working Paper GFSS/WP/06. Rome, FAO.
Roos, J.A., Brackley, A.M., 2012. The Asian Wood Pellet Markets. Gen Tech Rep. PNW GTR-861. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR (25 pp.).
Rudel, T.K., 2013. The national determinants of deforestation in sub-Saharan Africa. Philos. Trans. R. Soc. B 368, 20120405.
Schandl, H., Eisenmenger, N., 2006. Regional patterns in global resource extraction. J. Ind. Ecol. 10, 133–147. http://dx.doi.org/10.1016/j.gloenvcha.2014.03.013.
Schulze, E.-D., Körner, C., Law, B.E., Haberl, H., Luyssaert, S., 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. Glob. Chang. Biol. Bioenergy 4, 611–616. http://dx.doi.org/10.1111/j.1757-1707.2012.01169.x.
Schure, J., Dkamela, G.P., van der Goes, A., McNally, R., 2014. An Approach to Promote REDD+ Compatible Wood-Fuel Value Chains. REDD+ Energy and Agriculture Programme (REAP), SNV Netherlands Development Organization (SNV), The Netherlands.
Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Robertson, G.P., Schlesinger, W.H., Tilman, G.D., 2009. Fixing a critical climate accounting error. Science 326, 527–528.
Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., Torres-Martínez, J., Turner, C., Uchiyama, Y., Vuori, S.J.V., Wamukonya, N., Zhang, X., 2007. Energy supply. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Sims, R.H., Hastings, A., Schlamadinger, B., Taylors, G., Smith, P., 2006. Energy crops: current status and future prospects. Glob. Chang. Biol. 12, 2054–2076. http://dx.doi.org/10.1111/j.1365-2486.2006.01163.x.
Steffen, A., 1995. Better utilization of tropical timber resources in order to improve sustainability and reduce negative ecological impacts. Volume 1, Part 3: Final Report of the Mill Studies. ITTO-Project PD 74/90 (F,I). International Tropical Timber Organization (ITTO), Hamburg.
Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Chang. Biol. 9 (2), 161–185. http://dx.doi.org/10.1046/j.1365-2486.2003.00569.x.
Tillman, D.A., 1978. Wood as an Energy Resource. Academic Press, Inc., New York, USA.
UN, 2013. World Population Prospects: the 2012 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, New York.
UN, 2000. Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand (industrialized temperate/boreal countries). UN-ECE/FAO Contribution to the Global Forest Resources Assessment 2000. Main Report ECE/TIM/SP/17. United Nations Publications, New York, Geneva.
UN, 2014. UNdata, Fuelwood Statistics. United Nations Statistics Division (Accessed on November 2014 at http://data.un.org/Data.aspx?q=fuelwood&d=EDATA&f=cmID%3aFW).
UNECE/FAO, 2010. Forest Products Conversion Factors for the UNECE Region, Geneva Timber and Forest Discussion Paper 49. United Nations, Geneva.
UNSD, 2006. Composition of macro geographical (continental) regions, geographical subregions, and selected economic and other groupings (http://unstats.un.org/unsd/methods/m49/m49regin.htm) United Nations Statistical Division.
Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.-H., Hubacek, K., Fischer-Kowalski, M., 2006. The physical economy of the European Union: cross-country comparison and determinants of material consumption. Ecol. Econ. 58, 676–678. http://dx.doi.org/10.1016/j.ecolecon.2005.08.016.
Whiteman, et al., 2002. The Revision of Woodfuel Estimates in FAOSTAT. FAO, Rome.
Zaku, S.G., Kabir, A., Tukur, A.A., Jimento, I.G., 2013. Woodfuel consumption in Nigeria and the energy ladder: a review of fuel wood use in Kaduna state. J. Pet. Technol. Altern. Fuels 4 (5), 85–89. http://dx.doi.org/10.5897/JPTAF 12.023.