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Residential Heating Using Woody Biomass in Germany—Supply, Demand, and Spatial Implications

Ralf-Uwe Syrbe [1,*], Tran Thuc Han [2], Karsten Grunewald [1], Suili Xiao [1] and Wolfgang Wende [1]

1 Leibniz Institute of Ecological Urban and Regional Development (IOER), Weberplatz 1, 01217 Dresden, Germany
2 Landschaftsforschungszentrum Dresden e.V., Am Ende 14, 01277 Dresden, Germany
* Correspondence: r.syrbe@ioer.de; Tel.: +49-351-4679219

Abstract: Low-carbon energy requires more land than the non-renewable resources. This paper balances holistic assessments of the land demands for biomass heating and their ecosystem services. It is predicted that biomass will continue to play an important role in the heating sector in Germany by 2050, as it is one way to increase the use of renewable energy and reduce CO_2 emissions. To balance this out, it is important to ensure that the substitution of fossil fuels with fuelwood does not result in losses in biodiversity, natural forest, and agricultural land. Based on the observed types of fuel demand, the need for space in terms of the growing area is characterized as the corresponding land under the consideration of a given land-use type. Formulas have been applied at the federal level in Germany. The area required to supply an average German household is 0.64 ha if all the wood harvested is used for energy purposes, but this is in competition with all other types of timber use. Fuelwood from thinning alone cannot meet the domestic demand. However, a sustainable supply of woody biomass is possible if residues mainly from forestry and the wood processing industry are used, causing a land demand of 2.69 ha per house, possibly in combination with smaller shares of the above-mentioned types of use. Thus, the shares of pellets and wood chips for heating purposes should be expanded, which would also bring ecological advantages. The qualitative consideration of forest ecosystem services shows that changing the forest composition or management may increase the fuelwood supply but does not necessarily decrease forest ecological services.

Keywords: renewable energy; land demand; fuelwood; carbon sequestration; ecosystem services

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1. Introduction

With regard to research on the spatial aspect of the energy transition, "energy sprawl" has been seen as the largest driver of land use change and land conflict [1–4]. There is growing evidence showing that low-carbon or zero-carbon materials and energy, such as wood, require much more land than non-renewable resources, and the resulting emissions are rather significant [5–8]. However, recent research has found that, in some cases, fuelwood substitution can be even worse than burning fossil fuels due to hidden emissions [9,10]. Furthermore, there is not enough land to offset emissions through planting forests or the substitution of our current energy consumption methods with bioenergy [11,12].

Given the limits on the land and planetary capacity, it is important to ensure that the substitution of fossil fuels with woody fuels does not result in a loss of biodiversity, near-natural forest, or agricultural land. Therefore, further research and better assessments are needed in this area to obtain holistic solutions regarding how to best use the woody biomass on available land for heating while reducing emissions. Using the case study of Germany, this paper demonstrates a holistic assessment of the land demands for biomass heating and its ecosystem services. Ecosystem services (ES) are the contributions of ecosystems to the welfare of people [13]. They include supply and demand aspects that were mapped by [14,15] using indicators. These indicators make it possible to monitor land use assessment values [16], identifying whether the potential of nature is being used sustainably and providing valuable suggestions for planning and management [17]. Comparing the supply and demand reveals mismatches between the potential of ecosystems to sustainably provide goods and services and the socially triggered demands, indicating possibly irresponsible use [18]. The consequences of increased fuelwood use on landscape functionality have not yet been rendered completely measurable. This can be accomplished using an area-based balance of forest ES and other wood-producing areas. Similar to the production of energy from agricultural by-products [19], wooden fuels from silvicultural or industrial by-products can also be used to save areas that need to be reserved for timber production and address issues of biodiversity. Such a balance should provide information on whether the desirable increase in the use of wood for heating purposes can be satisfied sustainably and whether there are trade-offs to the detriment of the timber supply or different forest ES in Germany.

To address this knowledge gap, the research questions are: To what extent does the fuelwood demand compete with the timber demand instead of the desired cascade use? What are the footprint and ecosystem implications of the trade-off between fuelwood consumption and carbon sequestration in natural forests in the context of biodiversity conservation? Can alternative biomasses fill potential gaps in the biofuel supply, e.g., short-rotation coppices on cropland, in horticulture, and in urban green or landscape management?

Traditionally, biomass combustion has been one of the main energy sources for residential heating, but there is a debate about its future in Germany. However, the provision of energy is by no means the primary function of forests, as society requires timber and many other services referred to as forest ES. The forest area in Germany covers 11.3 million ha, which corresponds to 31% of the national territory. Between 2002 and 2012, a wood stock of 3.7 billion m^3 was developed in this area, with an average annual increment of 121.6 million m^3. This provision of the ES timber and wood generation required an annual logging rate of about 76 million m^3 of raw wood and timber [14], with a gross utilization potential of EUR 7.1 billion per year [15]. The optimization of one ES can alter the generation of other ES, such as the ES climate protection sum of EUR 2.1 billion or the ES recreation sum of EUR 2.0–2.4 billion per year [15]. Logging has increased during hot and dry periods in recent years, rising to a new record high since the German reunification of 80.4 million m^3 in 2020. However, there is a need for a change in the tree species composition of the forests in Germany due to the challenge of climate change and the need to strengthen the forests by enhancing their biodiversity [20].

A holistic assessment of the land demands for biomass heating and other ES is necessary to avoid damaging essential ES when Germany shifts its energy base from fossil fuels to renewables, as it is politically targeted. Recently, it has been debated whether biomass will continue to play an important role in the heating sector in Germany by 2050, as it represents an opportunity to increase the use of renewable energy and reduce emissions, but it is also considered a critical source of fine dust pollution that is harmful to health [21]. Additionally, materials and energy that are considered greenhouse-gas-neutral, such as wood, require more land than other resources [22]. The ongoing forest conversion (from coniferous to deciduous tree species and methods aiming to adapt forests to climate change) and the different forms of ownership of German forests have to be taken into account, as they affect the areal shares and, thus, the ES provided. For example, Elsasser et al. [15] predict that a 10% increase in the proportion of beach trees will result in annual gains of EUR 150 million in nature conservation but losses in raw wood production (EUR −300 million) and climate protection (EUR −21 million).

There is a need for a cascade use of forest products, meaning that the harvested wood is first used as a material and only the residues produced at each stage of processing should be used for energy, including the final energy use of waste wood after the lifetime of the material. Similarly, the use of wooden materials for the construction and manufacturing of furniture should be enhanced, as these products can store carbon over a long period. For example, in the construction of wooden houses, each processing step (from harvesting timber in the forest to the sawmill and the final processing of the wood products) generates residual material that can be used for heating. However, a higher bioenergy demand (from 2014 to 2018, +2% wood logs and +26% pellets) can become too large and rule out the possibility of timber use [23], as the same report notes that almost half of the fuelwood used in Germany in 2018 was industrially usable heartwood without bark. However, the forest area is limited, and its management should be adjusted to provide all the demanded ES in the given area. Thus, an area-based balance of the supply and demand is crucial for the potential of the further energy transition.

It is important to ensure that the substitution of fossil fuels with woody fuels does not result in a loss of biodiversity, natural forest, or agricultural land. Therefore, further research and better assessments are needed in this area to identify holistic solutions regarding how to best use the woody biomass on available land for heating while reducing emissions. The most important wood-based fuel is fuelwood from the forests, estimated at over 18 million cubic meters in 2018, and one in four German households is now heated with wood. Annually, about 28 million cubic meters of wood are used for heating in the form of logs (73%), pellets (10%), wood chips (4%), briquettes (2%), and, additionally, wooden residues and waste (9%) [23].

2. Materials and Methods

2.1. Methodical Framework

To answer the first research question, matter balances and land requirements within the available land area of the forests in Germany were compared. This approach uses the available statistical data from forest/greenhouse gas inventories [24] on timber logging and processing and calculations of the energy demand of typical houses. For the second research question, an ES approach is used to investigate land use impacts (in qualitative terms) by considering the forest and management types. To identify comprehensive spatial impacts and describe the trade-off between different land categories, the assessment methods of [14] were applied. Additional data were taken from [23] for different wood products and their use in Germany. Regarding the third question, based on the relevant types of fuel demands, the land requirement, in terms of the growing area, is characterized as the corresponding area to be considered. To quantify the availability of wood chips and pellets, the share of waste wood (from forestry) was calculated. Regarding solid wood logs, the forestry area, as a share against the timber, depending on the predominant tree type, is indicated.

2.2. Yields and Productivity for Biomass Supply

Wooden biomass can be supplied by several types of forest management (Figure 1). Its yield and productivity per hectare must first be calculated to obtain an estimate of the land requirements. Most of the wood biomass comes from forests. The most intensive management type (Figure 1a) is, of course, the complete harvest of all the trees to produce logs from the heartwood and chips from the forestry by-products, which is often carried out by small forest owners who do not participate in the timber production chain through their scattered forest parcels. It can be assumed that of a gross increment of about 66% (which is 80 million m^3 [20] of a total of 121.6 million m^3 [14]) is harvested and manufactured into fuelwood, while the rest remains in the forest to protect and fertilize the soil. The second management type (Figure 1b) is to use only the thinning wood as fuel and to include the heartwood harvest in the timber production. Here, the percentage is slightly different; while 66% of the growth (the same rate as above) is used for timber, a higher percentage of wood must be thinned and used for fuel due to the timber quality claims, (following statistics, this is 14.6% from the harvest). However, the prevalent type of German forestry, which is mainly carried out by the state forests and large private companies, is shown in Figure 1c. In the context of this type, the heartwood is used exclusively for timber production. Only 2% of the harvest in the form of harvesting by-products is recommended for fuel use. The remainder, including thinning wood, is left in the forest for soil protection and fertilization. Individuals can harvest small-diameter wood from the forest for a fee. Alternatively, this management type can be combined with the one shown in Figure 1b. Apart from this small percentage of self-extraction (in German "Eigenwerbung"), 40% [25] of the harvested wood becomes waste during processing and can be partially used for energy purposes. The average percentages are 26% wood chips, 12% sawdust, and 2% other residues [25]. Note that these by-products are also useful for covering the production plants' own energy needs and are used, in part, for composite wood and other woody materials (including paper and cellulose), which compete with the fuel market in terms of the raw wood sources. It has been shown statistically [26] that about 40% is used for wood-based materials, paper, and pulp production, while 60% is available for energy purposes.

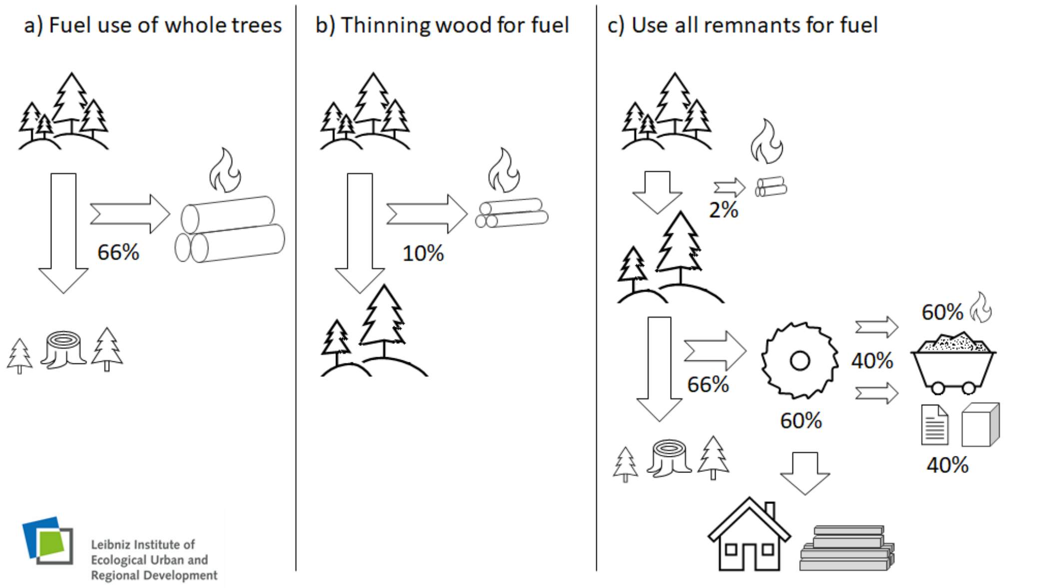

Figure 1. Several types of supply, from wood to fuel, with their average yields and shares (source: authors): (**a**) use of the heartwood of entire trees for fuel, (**b**) use of only the thinning wood for fuel, while the rest is used materially, (**c**) use of the forestry and saw-mill by-products for fuel.

These various proportions must be applied to the annual increment in German forests, which amounts to 121.6 million m^3 on 11.3 million ha of the forest area, corresponding to an average of 10.8 m^3 per ha and year.

2.3. ES Assessment and Trade-Off Analysis

Several forest ES were assessed qualitatively, the assessments are presented in Section 3.2. The methods described in [14,27] were used to assess the current situation and to identify possible synergies and trade-offs. The scheme of [27] enables a comparison of the threats and benefits of biomass energy use, although [27] did not consider woody biomass energy from forests (only that for biogas plants from arable land). For the individual groups of provisioning, regulating, and cultural ES, the framework addresses obvious impacts (as threats) and possible enhancements of ES (as benefits), together with the arguments for their validity, known from literature and forestry experience (see also Section 3.2). The comparison is useful but had to be adjusted to the content, as well as the gross GHG situation in Germany [28]. The considered ES were obtained from the selection of [14]. Impacts that may lead to changes in the forest ecosystem and its services were assumed to be more intensive use (i.e., a higher amount or more frequent removal of biomass, denser forest road network, more removal activities in otherwise unused parts of the forest) and an increasing trend towards more deciduous trees (due to higher deciduous firewood demands and prices).

The results are discussed in comparison with the findings of [15]. Following [27], the impacts of the extended use of biomass energy were analyzed in regard to the contrasting threats and benefits for the three ES groups (provisioning ES, regulating ES, cultural ES) and in comparison with the domestic demand [29].

3. Results

3.1. Land Demand for Woody Biomass Provision

From the forest increment, which is 10.7 m^3/ha*year on average in Germany, the area requirement of each management type from 2.1 can be derived (Table 1, Figure 2). All figures were converted into solid cubic meters (m^3) and hectares of forest, using the average weight of the firewood, 576 kg/m^3 (self-calculated average of the most frequent tree species in the state forests), and pellets, 650 kg/m^3 [30].

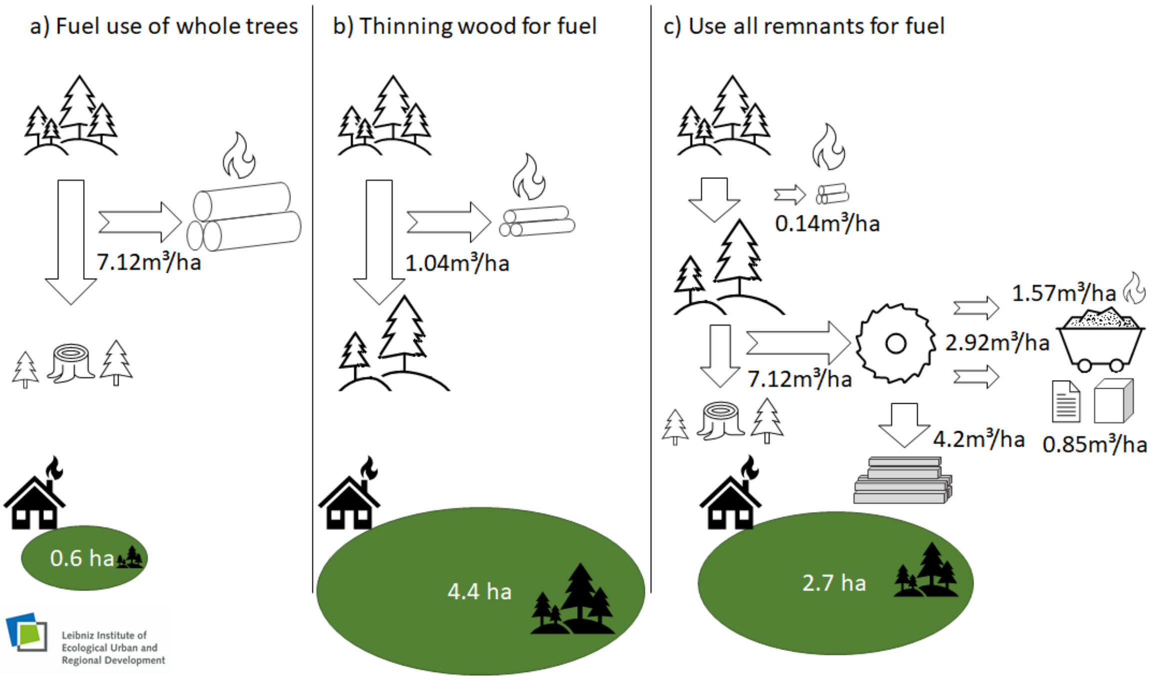

Figure 2. Land demands of wood fuel supply (source: authors) types: (**a**) when using the heartwood of entire trees for fuel, (**b**) when using the thinning wood for fuel, (**c**) when using only forestry and sawmill by-products for fuel and wooden materials proportionally.

For the first type, where the entire forest is used for energy purposes only (Figure 2a), the average hectare yield of 7.12 m^3 means that an average household (using 4.6 m^3 fuel [15]) requires 0.64 ha for heating, assuming that this management does not include thinning, as this would not be useful (Table 1). For the second type, most of the thinning wood is used for energy provision, and the main harvest is for material use (Figure 2b). The second type is mainly applicable to private forests that do not choose the first type. About 10% of the increment is used for heating, exactly 1.04 m^3 per hectare, which means that the average household needs 4.42 hectares of forest for fuel provision. The wood removed is sometimes sold for a small fee to different users, and they do it by themselves (see above). The third management type, using forest and production residues for energy purposes only (Figure 2c), is sometimes combined with the second one (Figure 2b), but in state-owned forests, the thinning wood is often left on site to improve the soil quality and maintain good ecosystem conditions. If small wood, wood chips, and sawdust are used, about 2.61 m^3 of fuel (not only logs) can be provided per hectare; thus, 1.76 ha of forest area is necessary to supply an average household. The third management type, without thinning wood, provides only 1.71 m^3/ha. In this case, 2.69 ha of forest is necessary to supply an average household (Table 1).

Table 1. Use cascade of timber and firewood from forestry or wood production residues.

Case of Demand: Annual Values	Total	Per Unit	Source/Remarks
Annual tree growth	121.6 million m^3	10.8 m^3/ha	[14] on forest area 11.3 Mill ha
Harvest timber 2020	80.4 million m^3	7.12 m^3/ha	[20] 66% logged
Stock accumulation	41.2 million m^3	3.59 m^3/ha	Difference of above
Thinning wood for fuel	11.8 million m^3	1.04 m^3/ha	6.78 million t * (0.576 t/m^3 density)
Harvest remnants for fuel	1.68 million m^3	0.14 m^3/ha	2% recommended for state forests
Sawmill timber production	48 million m^3	4.2 m^3/ha	60% timber, 40% remnants [31]
Remnants as wood chips	20.9 million m^3	1.85 m^3/ha	26% of the logged timber [31]
Wood chips for fuel	12.54 million m^3	1.11 m^3/ha	60% of the wood chips (statistics)
Remnants as sawn dust	9.65 million m^3	0.85 m^3/ha	14% of the logged timber [31]
Sawn dust for fuel (pellet production)	5.15 million m^3	0.46 m^3/ha	3.35 million t production [32] = 53% of resource potential
Total fuel potential from only remnants	19.37 million m^3	1.71 m^3/ha	Sum: harvest remnants, wood chips, sawn dust for fuel
Solid wooden fuel demand	33.9 million m^3	4.6 m^3/house	[33]
Land demand when using all harvested	Section 3.3	0.64 ha/house	Harvested timber/fuelwood demand
Land demand when using thinning wood	Section 3.3	4.42 ha/house	Thinning wood/fuelwood demand
Land demand when using only remnants	Section 3.3	2.69 ha/house	Sum remnants/fuelwood demand

* Can be enhanced up to 1.5 t/ha [33].

3.2. Ecosystem Service Trade-Offs and Synergies of Energy Biomass Provision from Forestry Land

The ES groups considered are provisioning, regulating, and cultural services [14]. Table 2 shows a qualitative assessment of the ecosystem services trade-offs and benefits of fuelwood production considered as threats and benefits of higher bioenergy use from the forest. Among the provisioning services, different services providing the energy supply are analyzed, mainly timber production and associated services such as water runoff, wild game, and mushrooms. In particular, the shift towards more deciduous tree species will result in a higher fuelwood proportion at the expense of a lower timber harvest, with the corresponding effects on the water balance and associated flora. Among the regulating and maintenance services, carbon sequestration is important, including soil carbon sinks, in addition to the different foliage types of deciduous trees, which are important for the results. Among the cultural services, recreation and health aspects are most relevant, but so are rare species' habitat conditions.

The comparison shows both beneficial and threatening effects in the case of all three ES groups, which almost balance each other out. Thus, special forest management determines whether the effect is positive or negative. Overall, more fuelwood removal does not equate to less ES in forests, but threats do occur when fuelwood removal is too intense and when the tree species composition is too far from the natural one.

Table 2. Qualitative comparison of the foreseeable threats and benefits of higher use of bioenergy from the forest, caused by intensified use and a reinforced trend towards more deciduous trees (due to higher deciduous firewood demands and prices).

Ecosystem Service Group	Threats	Benefits
Provisioning services, such as wild plants and animals; ground and surface water; fibers, timber, and genetic and other materials; energy.	No negative impacts on the water amount and quality nor on forest foods (fruits, mushrooms); competition with timber use and other tree products due to higher deciduous tree share, less edible mushrooms.	Use of otherwise abandoned forests and low-quality timber, unused areas, or resources; higher stability against forest pests and storm damage in the case of more deciduous trees; more fodder for game.

Table 2. *Cont.*

Ecosystem Service Group	Threats	Benefits
Regulating and maintenance services such as the removal of germs, nutrients and pollutants, flood protection, air refreshment, climate mediation, pollination, nurseries.	Soil organic matter content depletion; change in habitat quality in the case of land use intensification; changed transpiration rate and an altered interception during the non-leaf time, probably higher runoff in winter.	More resilient tree stands against storms and snow break of deciduous trees in winter; better balance of chemical and biological conditions of soils (less acidic) and tree health in the case of more native tree species; enhanced diversity.
Cultural services such as aesthetics, recreation, inspiration, education, science, spiritual heritage, and symbolic values.	Changing landscape character during the non-leaf time in winter; noise and fragmentation due to land use intensification.	Forests easier to walk through; more regional-typical forest scenery; older and bigger trees; easier to climb and play in the forest.

3.3. Demand for Energy Biomass and Associated Land Using Different Management Practices and Fuel Types

The German forest area of 11.3 million ha could not cover the national demand for wood logs if only thinning wood were used. However, since 5.49 million ha in Germany is formed of private forests (48%), which are partly used for wood log production, part of the demand is also met at the expense of timber production. As for the demands for wood pellets and chips, the forest sources are by far sufficient for meeting the domestic demand of 6.3 million ha, even if the 2.9 million ha used for the total fuelwood supply is subtracted from the total forest area (Table 3). A good combination would be reasonable, with a maximum share of timber production.

Table 3. Use cascade of timber and firewood from forestry or wood production residues in private households.

Case of Demand: Annual Values	Total	Per Unit	Source/Remarks
Private households' wood log demand	18.6 million m^3	4.6 m^3/house	[33,34] (2019)
Private households' wood pellet demand	2.90 million m^3	4.3 m^3/house	[23] 573,000 single + 108,000 multi-family houses 2018
Private households' wood chip demand	1.24 million m^3	6.1 m^3/house	[23] 182,000 single + 21,000 multi-family houses 2018
Forest land demand using all logs harvested	2.6 million ha	7.12 m^3/ha	ca. 70% wood logs from forest [33,34]
Forest land demand using only thinning	17.9 million ha	1.04 m^3/ha	S. above, this would be 158% of the German forest area
Land demand for pellet heating from remnants	6.30 million ha	9.26 ha/boiler	S. above (may overlap with previous and next)
Land demand for chip heating from remnants	1.12 million ha	5.52 ha/boiler	S. above (may overlap with two previous)

4. Discussion

A sustainable transformation of society and the economy to enable the use of renewable energies cannot consist of technological solutions alone. The limits set by the land, materials, energy, local conditions, ecosystems, climates, etc., have to be considered to define options for the future renewable energy infrastructure and to design energy systems with finite resources. Even though the domestic demand for round fuelwood products may be covered by only 2.9 of the total 11.3 million existing hectares of forest area, there is a strong need to use the maximum area for timber production, to ensure biodiversity, and to offset emissions [11]. Using the footprint method, a good estimation of the land requirements for different types of woody biomass use can be achieved [12], compared to other potential calculations methods, such as those described in [35,36], in the case of Germany, or in [37], for the EU-28 countries.

Thinning is a prerequisite for the production of high-quality timber. Through initially dense planting and later thinning, the trees form fewer branches and can thus produce knot-free or knot-poor wood, which is needed for construction, for the furniture industry, or even for veneer production. Therefore, thinning and the use of thinning wood for fuel purposes can be combined with timber production in the same area without losing the timber yield, but this would reduce the amount of deadwood in the forest available as a habitat for rare species and as fertilizer for forest soils. Therefore, the removal of thinning wood is only useful to a certain degree, and it has not been realized in some state forests. In addition, the provision of fuelwood from thinning alone is not sufficient, since it would require more land (158%) than that of the existing forest area in Germany, which can (and shall) be extended only to a small degree [15] (an approximately 3% forest increase is planned according to the forest strategies of different federal states, e.g., [38]). However, a smart combination of round fuelwood provision from forests that cannot be used for timber production, along with thinning wood and round wood from other land uses, such as parks, gardens, and orchards, and with several by-products, will surely cover the demands in Germany [36], as the above calculations can prove. Uncertainties about the accuracy of the figures and land requirements exist with respect to the actual applied management types and the changing tree species composition of forests in the future, which would be possible to calculate only by working with different scenarios [15,37].

The trade-off between fuelwood consumption and forest carbon sequestration needs to be discussed in the context of the climate-protective effects of increasing wood extraction for bioenergy. Recently, the combustion of raw wood and, to an even greater extent, waste wood has come under criticism in Germany for air quality reasons (fine dust pollution) [21]. It has been shown that the use of entire trees for fuel would exceed the land resources if timber production were to be considered the main aim of forestry. This also applies to the requirement for maximum carbon storage in forests, as well as in wood-based materials, which is best provided by long-lasting wood products [29]. If wood logs are used for fuel, they should come, to a greater extent, from gardening, landscape management, and urban green pruning. In common with [15,27], the evaluations of this paper show that changing management strategies for adapting forests to climate change will enhance the provision of woody biomass for heating purposes but not damage the ES in turn. The effects on ES can be both positive and negative depending on the management strategy and should be optimized considering the local potential and situation.

Of the various biomass fuel sources, only a small fraction can be used in single-house furnaces for residential heating. With about 13 million units, log stoves are the most widely used, consuming a total of 14 million tons of fuel per year, with an energy content of 250 PJ/y [29], most of which comes from private forests, gardens, or other greenery, while only a smaller proportion comes from the fuelwood market. These stoves can also burn briquettes from wood residues and coal, although the latter is not considered here. Other fuels, such as wood chips and pellets, are technically not applicable to normal stoves, while wood waste and herbaceous plant residues are not recommended for use in these facilities, since they cause enormous emissions and ash and slag handling problems.

An emerging type of heating system, with 884,000 units in 2018 [23], are boilers and heaters designed to consume pellets and wood chips because, as automated systems, they require minimal maintenance and are as convenient when used as oil or gas boilers. From the availability of resources, climate, and energy points of view, they mainly use residues from forestry and the wood industry, which can rarely be used in any other way, except for low-grade wood materials, paper, or cellulose. Even though these boilers compete with the material use of wood, they are a better choice among the wood-based heaters, because they allow for the use of low-grade wood residues, operate more easily, and have less impact on the environment. Once installed, the boilers must be maintained, as they are usually the only heat source of the respective buildings. Boilers' demand is about 1.7 million tons of fuel, with 30 PJ per year [29]. However, the calculations show that the supply of all the boilers in Germany can be ensured without limiting the supply of wood materials or exceeding the national land resources. This is true even if the number of these fireplaces were to be increased, which can be recommended herein.

Future research should concentrate on the actual used management types (i.e., the actual forest area that is used for fuelwood only, where is thinning applied and used for energy), on the changing tree species composition (mainly regarding deciduous or coniferous trees) of forests, and on different regions with specific growing and climate conditions [35]. As soon as data from the forest inventory [24], which is under development in Germany at present, is available, this kind of analysis will be possible, with higher precision.

5. Conclusions

The German forest area is large enough to cover the national demand for timber, fuelwood, and other wooden materials if it is used based on a sound combination of management types and with respect to environmental issues. Even though thinned wood cannot meet the domestic demand alone, it is not reasonable to use whole trees for firewood production that could be used for material purposes. Instead, only those forests and trees that are not usable for material purposes should be used for energy. Thinned wood is also not optimal for use as a fuel supply because there is not enough of it, and this use competes with sustainability issues. A good combination of whole-tree use, thinning wood, and woody residues can meet national needs and does not limit the material supply of wood or the provision of ecosystem services in forests. The qualitative consideration of forest ecosystem services shows that changing the forest composition or management may increase the fuelwood supply but does not necessarily decrease forest ES.

In comparison, wood pellets and chips are preferable to wood logs because their sources are far from being exhausted, and these fuels do not compete with quality timber, as can be concluded by the above-shown calculations. In addition, the air pollution caused by modern pellet and chip boilers is much lower than that caused by wood-log-consuming fireplaces.

Finally, there is not enough land to offset emissions by planting forests and replacing our current energy consumption with bioenergy (see also [15]). Research examining ecological footprint analysis is needed to measure the land area required to provide heat for Germany using different types of woody biomasses. A finer distribution of tree species and user types for both timber and fuelwood is already planned for our own future research.

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