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European Hophornbeam Biomass for Energy Application: Influence of Different Production Processes and Heating Devices on Environmental Sustainability

Alessio Ilari, Sara Fabrizi and Ester Foppa Pedretti *

Department of Agricultural, Food and Environmental Sciences, Università Politecnica delle Marche, Via Brecce Bianche 10, 60131 Ancona, Italy; a.ilari@univpm.it (A.I.); s.fabrizi@univpm.it (S.F.)
* Correspondence: e.foppa@univpm.it; Tel.: +39-0712-204-918

Abstract: Environmental sustainability has recently shifted towards biodiversity protection via governmental and intergovernmental initiatives (e.g., the UN Millennium Ecosystem Assessment, MA). The life cycle assessment, the widespread method for assessing environmental sustainability, was not created to evaluate impacts on biodiversity. However, several authors recognize its ability to estimate biodiversity loss drivers (impact indices on land use change and ecosystem). The study aims to apply LCA to the forest sector, precisely to the wood–energy chain of Hophornbeam, to cover suggestions of the MA for the biodiversity impact assessment. Six different scenarios for stove (3) and fireplace (3) wood production were analyzed, evaluating two baselines and four alternative scenarios, including sensitivity analyses related to transport distances for the raw materials. The functional unit is 1 MJ of energy. The fireplace combustion scenarios are relatively more sustainable than the stove ones are (2.95–3.21% less). The global warming potential (around 3 g CO_2 eq/MJ) is consistent with current European directives on the sustainability of biofuels and scientific literature. The scenarios showed similarities regarding the impact of the categories related to MA drivers. Although biodiversity is protected by limiting forest management, some authors argue that for some species (e.g., Hophornbeam), a rational tree felling could produce biofuels, increasing biodiversity.

Keywords: *Ostrya carpinifolia*; ecosystem assessment; life cycle assessment; stove; fireplace; bioenergy

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1. Introduction

The term sustainability is still highly controversial, and although it is believed that this concept has been defined independently, it is closely linked to ideas of an economic nature. Over the years, the attention paid to the definition of sustainable development and sustainability has materially shifted the choices of human activities towards radically different approaches. Consider the application of the Hartwick–Solow criterion [1–3], which justified the exploitation of natural capital based on the criterion of substitutability with economic and artificial capitals. The Hartwick–Solow criterion can be described through the concept of weak sustainability. Weak sustainability has been partially overcome by strong sustainability, which presupposes the nonsubstitutability of natural capital. More simply, strong sustainability supports the need to guarantee natural resources stocks.

Over the past forty years, the paradigm shift towards strong sustainability has generated an increasingly present public opinion on comparing ecosystems and relative biodiversity preservation. Apparently, the interruption of resources exploitation promotes stock growth, but if this is true for abiotic resources, it is more complex for biotic resources. The SMS theory (Safe Minimum Standard) states that below a specific threshold, the restoration of natural capital through artificial capital is unsustainable, and the natural capital is hopelessly compromised [4–6]. Wood is one of the biotic resources that highlight these aspects well and has been of interest in preservation for years. Wood production chain and land use change (LUC) have been considered bad practices for conserving woods and biodiversity.

From the second half of the last century, the area covered by woods in Italy and Europe has increased [7], and the biodiversity has remained almost stable [8]. The Millennium Ecosystem Assessment (MA) in 2005 established the main drivers for biodiversity loss and ecosystem changes: habitat change (land use changes, physical modification of rivers or water withdrawal from rivers, loss of coral reefs, and damage to sea floors due to trawling), climate change, invasive alien species, overexploitation, and pollution. However, behind the definition of the key impact factors is the calculation of the impact itself.

Land use change is considered the most significant driver of loss in nature and biodiversity [9]. LUC directly impacts the survival and proliferation of species through the potential destruction of habitats and modification of the environment. However, evaluating the effect of LUC on biodiversity can be challenging due to the elusive nature of the biodiversity concept and the inter-relation between LUC and other global drivers such as climate change. Moreover, some ecological impacts can either be small but cumulative, spatially removed, or be difficult to detect by methods used or spatiotemporal scales [10]. Estimating the impacts of LUC on biodiversity largely depends on location, research methods, and taxonomic focus [11]. Thus, advocating for adopting relevant mitigation strategies requires using interdisciplinary, inclusive, comprehensive, and replicable methods for biodiversity loss assessment [12].

The life cycle assessment (LCA) is a universally accepted tool that can meet these criteria for good biodiversity metrics. LCA is a standardized scientific methodology for assessing the environmental impact of products and services related to human activities. This tool has been applied to determine indices based on resources exploitation, substances emission on the different environments (air, water, soil), and the impact on biodiversity throughout the evaluation of species reduction (considering a damage impact category). In LCA, biodiversity is mainly introduced as an endpoint category modeled as a loss in species richness related to the conversion and use of land over time and space. Due to biodiversity assessment's complexity, the present land use models that use biodiversity indicators tend to significantly simplify the transient dynamics and intricate interactions among and between species and their habitats [12]. Several studies linked LCA studies with biodiversity assessments [13–15]. Matching this last aspect with the MA declaration, it appears clear that the LCA method is still not exhaustive because it cannot determine the habitat change and the presence of invasive species. Souza et al. (2015) [12] highlighted several limitations in existing models relating to concepts, inventory analysis, definition of indicators, and impact assessment methods. However, considering that soil and its transformations are one of the main drivers of biodiversity loss [16], all relative indices are deemed valid in the indirect assessment of biodiversity loss. Regarding this aspect, several indices have been tested to be included as impact categories for the LCA method. Neglecting the issues of the millennium assessment, the method has been applied to the forestry and biomass sector in numerous studies [17–27], as reported in Table 1. However, few of the case studies analyzed dealt with broadleaf species (rarely used for heat production and sometimes reporting unusual functional units) with different physiological characteristics, growth (related to forest management), and interaction with the environmental compartments (air, water, soil) that host biodiversity.

This paper aims to assess the impact of hophornbeam wood production for energy purposes using the LCA and includes specific indices to cover MA suggestions for biodiversity assessment. The hypothesis underlying the study is to test the ability of the classical indices of the LCA (suitably related to the MA drivers as described in the following chapters) in estimating the effects on the drivers identified by the Millennium Ecosystem Assessment. In particular, it is intended to identify any differences relating to the various scenarios tested. Considering the scarcity of specific studies on the forest sector, for temperate broad-leaved forests, the novelty of the study lies in providing primary information about material and energy flows of forest management operations and in analyzing the environmental impact of a widespread supply chain in central Italy and the Balkans.

Table 1. Life cycle inventory table for baseline scenario (BS1).

Reference	Paper Type	Focus	Wood Species	System Boundaries	Note
[17]	Review	LCA forestry sector	Softwood, Hardwood	cradle to gate (only 1 cradle to grave for softwood)	5 studies reported impacts on energy unit all related to softwood species
[18]	Review	LCA renewable energy	Poplar (SRF), Straw	cradle to grave	Systems mainly intended for electricity production
[19]	Review	LCA sustainable regional development	Not specified	Not specified	The studies reported mainly analyze forest management from the point of view of CO_2 storage and production of renewable fuels
[20]	Article	LCA and ecosystem quality	Spruce	cradle to gate	Data refers to 1 m^3 of wood
[21]	Article	LCA and biodiversity	Boreal forest	cradle to gate	1 m^3 wood for sawmills or papermill
[22]	Review	LCA of wood for automotive	Not specified	various	Only 1 case study highlighted for energy focusing on social aspects
[23]	Article	LCA of biomass utilization	Softwood and Hardwood unspecified woodchips	Not applicable	Data refers to annual final energy demand (not well specified) foreseen for 2035
[24]	Article	LCA and biodiversity	Eucalyptus and Softwood	cradle to gate	The case study reports an approach to include biodiversity in LCA framework
[25]	Article	LCA for eco-design	Birch plywood	cradle to gate	Eco-design of wood furniture
[26]	Article	Consequential LCA	Softwood	cradle to grave	Consequential analysis on pyrolysis related to forest residue (FU)
[27]	Article	Comparative LCA	Hardwood (not specified)	cradle to grave	FU 1 Mg (wet basis) of logs for energy or structural element

2. Materials and Methods

2.1. LCA

LCA analysis has been conducted considering a typical forestry site for firewood production as a representative of central Italy. The forest management system analyzed is the coppice with standards, the most common in the Apennines.

2.1.1. Goal

The goal of the analysis is to assess the impact on the environment using impact categories and characterization factors of CML_IA baseline V3.01/EU25 for hophornbeam firewood production. The results are intended for operators in the forestry sector, academics in the forestry and biomass sector, and policymakers mainly of the mountain municipalities of Italy and the Balkans.

2.1.2. Scope

The functional unit (FU) selected is 1 MJ (Mega Joule) of thermal energy produced. The reference standard establishes that the functional unit must reflect the system functions. In this case, the objective of the supply chain is to produce energy. Therefore, the choice of the MJ of energy is the most appropriate FU. However, from a logistical point of view, the timber is sold based on the mass necessary for residential heating, which on average in central Italy corresponds to 4.5 t. Therefore, to allow easier reading of the results by operators of the supply chain and end-users of the wood, an alternative FU has been selected corresponding to the energy produced by average mass burned by a family for heating in one year (equivalent to 4.5 t of wood). The final product both for fireplace and for stove has 30% moisture content, gross calorific value of 19,266 kJ/kg, and a low calorific value of 17,996 kJ/kg, ash content, carbon, nitrogen, and hydrogen have been measured and equal to 2.2%, 49.6%, 0.2%, and 5.8% respectively. All the values reported are expressed on dry matter, and the methodology followed for wood characterization is the same reported by other studies [28]. In detail, the analysis of the gross calorific value was carried out using an isoperibolic calorimeter (IKA Werke GmbH & CO, Staufen, Germany, model C2000 Basic); carbon (C), hydrogen (H), and nitrogen (N) were analyzed using an elemental analyzer (Perkin Elmer Italia SpA, Milano, Italy, model Series II 2400). Low calorific value was calculated considering the gross calorific value and the elemental analysis (CHN); ash content has been measured using a thermogravimetric analyzer (LECO Italy Srl, Milano, Italy, model TGA701). Between the retail phase and the combustion phase, a reduction of the moisture content of a further 10% (final 20%) was considered. This reduction is due to the storage that runs between the purchase and the combustion of the wood. The latter being carried out manually does not consider any additional data other than reducing humidity. Production steps consist of 5 phases in baseline scenario number 1 (BS1), as described in Figure 1. The first phase includes the operations of felling, delimbing, and sizing (FDS); the second phase includes processing and extraction of wood from the forest (PE); the third phase includes sizing of the wood to final dimensions (S); the fourth phase is retail to end-user (R); the fifth phase is combustion in stove or fireplace (C). The baseline scenario (BS2) and alternative scenario (AS) phases are 6 with an intermediate transport to forecourt (FT), near to the felling point for BS2 or faraway for AS. The choice to insert two basic scenarios and only one alternative scenario arises from the fact that the basic scenarios are both under the company's direct control. The alternative scenario instead depends on competing companies from the extraction phase onwards. All the phases with relative operations are described afterward.

2.1.3. System Description

The data provided below have been collected based on the activities of the Bartocci Enrico company based in Poggio San Vicino (Macerata), Italy. These data can represent a standard supply chain for wood production for central Italy. BS1 is characterized by five phases. First, felling, delimbing, and first sizing are performed in woodland at the same time using a standard chainsaw with 50 cm blade and 50 cm^3 engine size. With a full tank, 0.68 L of fuel blend (2% of mineral oil), and 0.38 l of chainsaw oil, the fresh firewood (120 cm size) produced is around 2.25 t. The second phase consists of the processing and extraction of wood. Typically, wood logs are concentrated near the felling place and roughly piled. The movement takes place by tractor for distances not exceeding 300 m. After five months, the logs reach about 30% moisture (half-dry logs), and they are then sectioned and split on-site in two different formats: 40–45 cm for fireplace logs and 25–30 cm for stove logs. Pieces are finally manually piled and sent to the final user within a 100 km radius from the company center. The quantity normally transported is 4.5 t, corresponding to 5 pallets of just under one ton each. This quantity also corresponds to the average annual consumption for a typical family in the distribution area. BS2 differs from the previous scenario only for an additional step included between processing/extraction and sizing. This phase consists of a transport with 26 t truck (payload 15 t) from the extraction site to the central forecourt. This phase begins at the end of the drying period of the timber and occurs if sectioning on site is not possible. The average distance between the extraction site and the forecourt area is 10 km (base distance used in the study). Shorter distances normally do not allow a biomass concentration useful for reaching a critical mass for processing. Longer distances are generally avoided for economic reasons. AS is quite like BS2; the differences between the two start from the forecourt transport phase. For AS, the transport means used for forecourt transport is a 28–30 t payload truck not by the company but from raw material buyers. This scenario was selected as it represents the supply chain of companies that distribute firewood for medium–large towns in the Marche region that do not carry out felling and extraction operations but only final cutting and sale to the consumer. These companies minimize costs by using higher-payload trucks than those described in the BS2 scenario, though distances are similar to those in BS2. The last phase considered is heat production. Two different biomass thermal processes have been selected based on burnt biomass type and the respective devices for which they are intended. Considering BS1, BS2, and AS for stove, a combustion process for a 6 kW wood heater has been selected considering that for Italy, a wood-burning stove with manual loading has a power between 2 and 10 kW [29]. For the same processes referred to firewood, a secondary 30 kW fireplace combustion process was selected considering that the power of such devices is between 5 and 50 kW [29]. Although the combustion scenario for solid biomass may involve different devices (fireplaces, stoves, boilers) and biofuel (pellets, wood, wood chips), according to an analysis by the Italian Association of Agroforestry Energies (AIEL), the devices that use wood (fireplaces, stoves, and small log boilers) represent 74.1% of the devices surveyed (about 8 million) [30]. In addition, the combustion phase was included using secondary data, in particular from the Ecoinvent 3 database; for both combustion processes (stove or fireplace), the efficiency in the production of thermal energy corresponds to 83.5% assuming the total combustion of the wood.

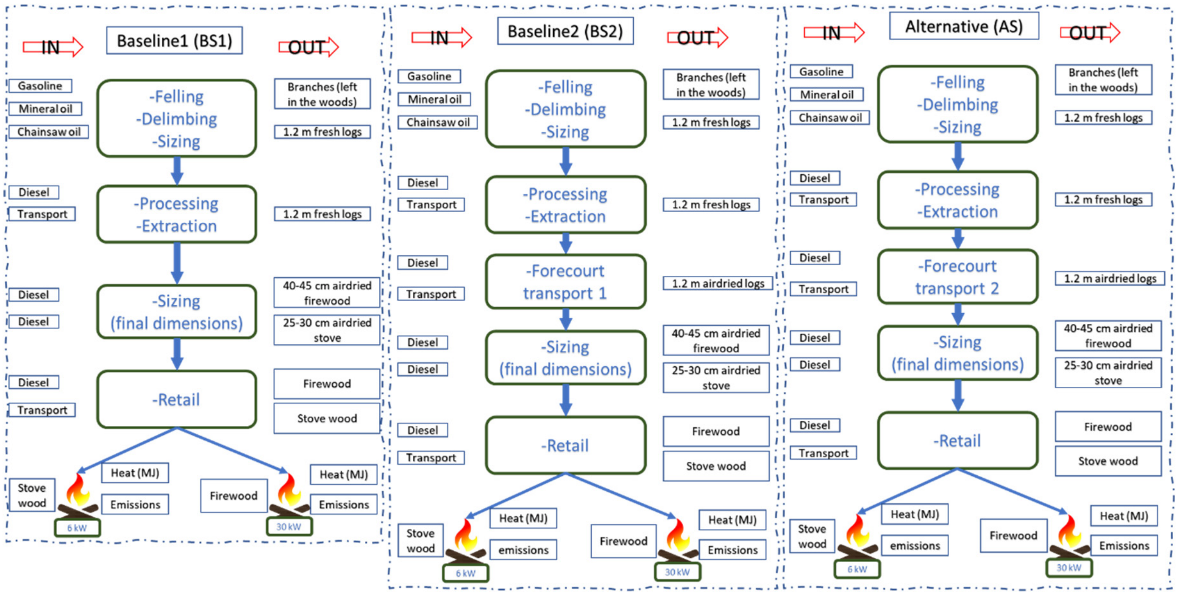

Figure 1. System boundary for BS1, BS2, and AS considering two different heat production scenarios.

2.1.4. System Boundary

The system boundary can be considered second-order (it includes material and energy flows together with operation), and the wood production has to be considered part of the natural system. Therefore, the analysis performed can be classified as a "cradle to grave" and cover all the phases from raw material extraction to heat production. Wood ash disposal has not been modelled considering that low-power devices (less than 50 kW) are typically carried out by distributing directly on the ground. The biogenic CO_2 emission from combustion has not been considered as the growing forest absorbs them in a much shorter time frame than shown in the GWP (baseline) calculation horizon.

2.1.5. Allocation Procedures

The system under analysis produces two different products: fireplace wood and stove wood. These products are entirely independent of one another even if produced by the same production chain because they are not simultaneously produced. All the data specifically related to fireplace wood or stove wood have been provided separated, and for this reason, no allocation procedure was necessary.

2.1.6. Data Quality, Time Reference, and Technology

Primary data gathered are specific for the case study. Data collected regards raw production fuel and lubricants used for felling, delimbing and first sizing, moisture reduction (necessary for mass balance calculations), diesel for transports, and final sizing (band saw powered by tractor power take-off). All the data do not refer to a specific year but are an average of information collected by the company in the last few years. The technology adopted can be considered average considering the specific geographic area (Marche region), but considering a larger area, such as the whole of Italy, the technology should be considered quite obsolete. Secondary data regard mainly transportation means selected from Ecoinvent 3 database and combustion process.

2.1.7. Inventory

Tables 2–4 report the life cycle inventory (LCI) tables with main input referring to FU selected for BS1, BS2, and AS, respectively.

Table 2. Life cycle inventory table for baseline scenario (BS1).

Unit Process	Input/Output	Amount	Unit
Felling/delimbing/sizing	Petrol	8.55×10^{-5}	L
	Oil 2-stroke engines	1.69×10^{-6}	L
	Chainsaw oil	4.87×10^{-5}	L
	Fresh firewood logs	2.89×10^{-1}	kg
Processing/extraction	Diesel	1.54×10^{-4}	L
	Tractor	8.67×10^{-2}	tkm
	Extracted fresh firewood	2.89×10^{-1}	kg
Sizing (firewood)	Diesel	6.05×10^{-5}	L
	Sized firewood	6.35×10^{-2}	kg
Sizing (stove wood)	Diesel	8.76×10^{-5}	L
	Sized stove wood	6.35×10^{-2}	kg
Retail	Diesel	2.47×10^{-4}	L
	Truck	6.35×10^{-3}	tkm
Combustion	Stove/fireplace	1	MJ
	Range min	9.93×10^{-1}	MJ
	Range max	1.01	MJ

Table 3. Life cycle inventory table for baseline scenario n 2 (BS2).

Unit Process	Input/Output	Amount	Unit
Felling/delimbing/sizing	Petrol	8.55×10^{-5}	L
	Oil 2-stroke engines	1.69×10^{-6}	L
	Chainsaw oil	4.87×10^{-5}	L
	Fresh firewood logs	2.89×10^{-1}	kg
Processing/extraction	Diesel	1.54×10^{-4}	L
	Tractor	8.67×10^{-2}	tkm
	Extracted fresh firewood	2.89×10^{-1}	kg
Forecourt transport 1	Diesel	1.62×10^{-4}	L
	Transported wood	1.15×10^{-1}	kg
Sizing (firewood)	Diesel	6.05×10^{-5}	L
	Sized firewood	6.35×10^{-2}	kg
Sizing (stove wood)	Diesel	8.76×10^{-5}	L
	Sized stove wood	6.35×10^{-2}	kg
Retail	Diesel	2.47×10^{-4}	L
	Truck	6.35×10^{-3}	tkm
Combustion	Stove/fireplace	1	MJ
	Range min	9.93×10^{-1}	MJ
	Range max	1.01	MJ

Table 4. Life cycle inventory table for alternative scenario (AS).

Unit Process	Input/Output	Amount	Unit
Felling/delimbing/sizing	Petrol	8.55×10^{-5}	L
	Oil 2-stroke engines	1.69×10^{-6}	L
	Chainsaw oil	4.87×10^{-5}	L
	Fresh firewood logs	2.89×10^{-1}	kg
Processing/extraction	Diesel	1.54×10^{-4}	L
	Tractor	8.67×10^{-2}	tkm
	Extracted fresh firewood	2.89×10^{-1}	kg
Forecourt transport 2	Diesel	1.92×10^{-4}	L
	Transported wood	2.23×10^{-1}	kg
Sizing (firewood)	Diesel	6.05×10^{-5}	L
	Sized firewood	6.35×10^{-2}	kg
Sizing (stove wood)	Diesel	8.76×10^{-5}	L
	Sized stove wood	6.35×10^{-2}	kg
Retail	Diesel	2.47×10^{-4}	L
	Truck	6.35×10^{-3}	tkm
Combustion	Stove/fireplace	1	MJ
	Range min	9.93×10^{-1}	MJ
	Range max	1.01	MJ

2.1.8. Life Cycle Impact Assessment

Several impact indices have been selected according to the Hophornbeam wood production chain and MA drivers of biodiversity loss. Table 5 details the indices and relative characterization models.

Table 5. Impact categories and characterization models selected (method ReCiPe Midpoint (H) V1.10).

Impact Category [1]	Acronym	Unit	Characterization Model	MA Driver Reference
Climate change	GWP	kg CO_2 eq	[31]	Climate change
Terrestrial acidification	TAP	kg SO_2 eq	[32]	Habitat change
Human toxicity	HTP	kg 1,4-DB eq	[33,34]	Pollution
Freshwater ecotoxicity	FETP	kg 1,4-DB eq		Pollution
Marine ecotoxicity	METP	kg 1,4-DB eq		Pollution
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq		Pollution
Natural land transformation	NLTP	m^2	[35]	Habitat change
Water depletion	WCP	m^3	[36]	Overexploitation
Metal depletion	MCP	kg Fe eq	[37,38]	Overexploitation
Fossil depletion	FCP	kg oil eq	[39]	Overexploitation
Particulate matter formation	PMFP	kg PM 10 eq	[40]	Pollution

[1] Impact categories are intended for a problem-oriented approach (midpoint) and are expressed as a potential impact.

3. Results

3.1. LCA

As reported in Table 6a,b, and Figure 2, BS2 stove shows the higher impact for all the impact categories selected except for NLTP, which remains constant (considering three decimal places).

Table 6. (**a**) Results of LCIA phase using selected impact categories; functional unit is 1 MJ of energy. (**b**) Results of LCIA phase using selected impact categories; functional unit is 4.5 t of dried logs (included combustion).

(a)							
Impact Category	**Unit**	**BS1 Stove**	**BS2 Stove**	**AS Stove**	**BS1 Firewood**	**BS2 Firewood**	**AS Firewood**
GWP	kg CO_2 eq	2.72×10^{-3}	2.95×10^{-3}	2.87×10^{-3}	2.64×10^{-3}	2.87×10^{-3}	2.78×10^{-3}
TAP	kg SO_2 eq	2.09×10^{-5}	2.21×10^{-5}	2.16×10^{-5}	2.07×10^{-5}	2.19×10^{-5}	2.14×10^{-5}
HTP	kg 1,4-DB eq	1.02×10^{-3}	1.02×10^{-3}	1.02×10^{-3}	1.02×10^{-3}	1.02×10^{-3}	1.02×10^{-3}
FETP	kg 1,4-DB eq	1.23×10^{-5}	1.23×10^{-5}	1.23×10^{-5}	1.23×10^{-5}	1.23×10^{-5}	1.23×10^{-5}
METP	kg 1,4-DB eq	1.43×10^{-5}	1.45×10^{-5}	1.44×10^{-5}	1.43×10^{-5}	1.45×10^{-5}	1.44×10^{-5}
TETP	kg 1,4-DB eq	5.10×10^{-7}	5.24×10^{-7}	5.18×10^{-7}	5.08×10^{-7}	5.22×10^{-7}	5.17×10^{-7}
NLTP	m^2	8.01×10^{-6}	8.01×10^{-6}	8.01×10^{-6}	8.01×10^{-6}	8.01×10^{-6}	8.01×10^{-6}
WCP	m^3	2.75×10^{-3}	2.75×10^{-3}	2.75×10^{-3}	2.74×10^{-3}	2.74×10^{-3}	2.74×10^{-3}
MCP	kg Fe eq	1.38×10^{-4}	1.38×10^{-4}	1.38×10^{-4}	1.37×10^{-4}	1.37×10^{-4}	1.37×10^{-4}
FCP	kg oil eq	7.62×10^{-4}	8.36×10^{-4}	8.08×10^{-4}	7.35×10^{-4}	8.09×10^{-4}	7.81×10^{-4}
PMFP	kg PM10 eq	1.55×10^{-5}	1.60×10^{-5}	1.58×10^{-5}	1.55×10^{-5}	1.59×10^{-5}	1.58×10^{-5}
(b)							
Impact Category	**Unit**	**BS1 Stove**	**BS2 Stove**	**AS Stove**	**BS1 Firewood**	**BS2 Firewood**	**AS Firewood**
GWP	kg CO_2 eq	1.93×10^{2}	2.09×10^{2}	2.03×10^{2}	1.87×10^{2}	2.03×10^{2}	1.97×10^{2}
TAP	kg SO_2 eq	1.48	1.56	1.53	1.47	1.55	1.52
HTP	kg 1,4-DB eq	7.23×10^{1}	7.26×10^{1}	7.25×10^{1}	7.22×10^{1}	7.24×10^{1}	7.23×10^{1}
FETP	kg 1,4-DB eq	8.70×10^{-1}	8.71×10^{-1}	8.71×10^{-1}	8.68×10^{-1}	8.69×10^{-1}	8.69×10^{-1}
METP	kg 1,4-DB eq	1.02	1.03	1.02	1.01	1.02	1.02
TETP	kg 1,4-DB eq	3.61×10^{-2}	3.71×10^{-2}	3.67×10^{-2}	3.60×10^{-2}	3.70×10^{-2}	3.66×10^{-2}
NLTP	m^2	5.68×10^{-1}	5.68×10^{-1}	5.68×10^{-1}	5.68×10^{-1}	5.68×10^{-1}	5.68×10^{-1}
WCP	m^3	1.95×10^{2}	1.95×10^{2}	1.95×10^{2}	1.94×10^{2}	1.94×10^{2}	1.94×10^{2}
MCP	kg Fe eq	9.75	9.75	9.75	9.73	9.73	9.73
FCP	kg oil eq	5.40×10^{1}	5.92×10^{1}	5.72×10^{1}	5.21×10^{1}	5.73×10^{1}	5.53×10^{1}
PMFP	kg PM 10 eq	1.10	1.13	1.12	1.10	1.13	1.12

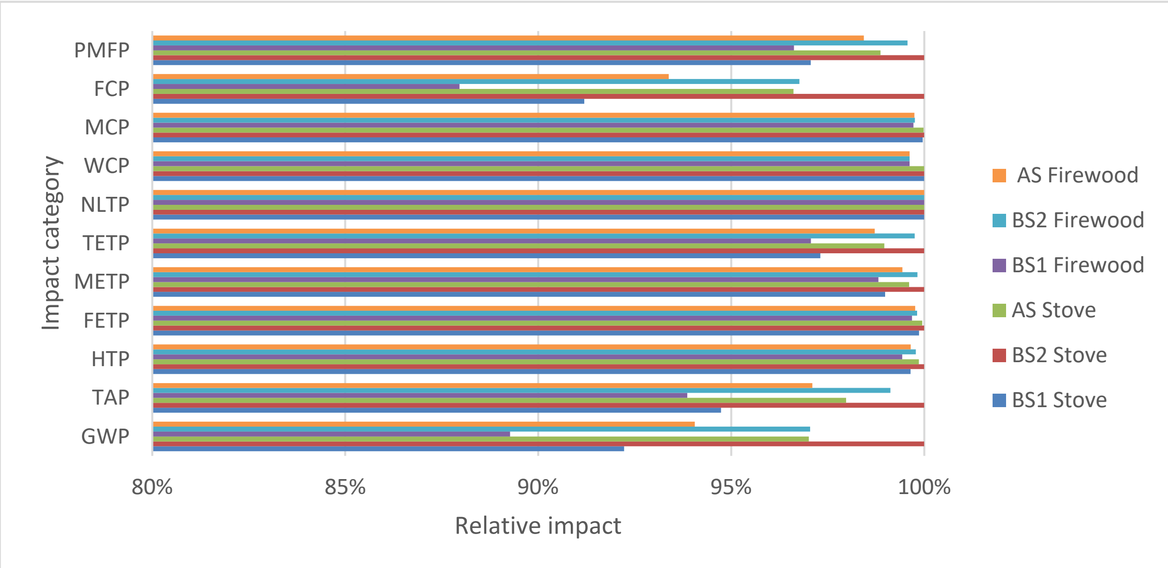

Figure 2. The relative impact of different scenarios compared. The *y*-axis scale was deliberately set between 80% and 100% to magnify the impact difference.

The contribution analysis conducted is reported in Tables 7 and 8, and to ease its readability, it is presented in graphic form in Figure 3. As is evident from the results, the distribution phase shows a high impact for many of the selected categories, except for NLTP, WCP, and MCP. The major contributor is processing and extraction for NLTP, sizing for WCP and MCP.

Table 7. Contribution analysis for baseline scenario 1 (BS1), baseline scenario 2 (BS2), and AS for stove.

Impact Category	FDS	PE	S	FT	R	C
			BS1 Stove			
GWP	7.2%	5.7%	10.3%		24.9%	51.9%
TAP	3.7%	2.2%	78.9%		0.3%	14.9%
HTP	1.1%	1.5%	2.9%		16.4%	78.1%
PMFP	0.2%	0.3%	0.1%		0.4%	99.1%
TETP	0.2%	1.1%	3.2%		15.0%	80.5%
FETP	0.3%	0.2%	0.7%		1.0%	97.7%
METP	0.3%	2.2%	6.0%		11.4%	80.0%
NLTP	0.4%	0.7%	1.4%		8.9%	88.5%
WCP	0.6%	0.3%	0.8%		8.1%	90.2%
MCP	0.3%	0.6%	0.6%		0.4%	98.1%
FCP	0.7%	0.9%	0.6%		3.0%	94.8%
			BS2 Stove			
GWP	6.7%	5.3%	9.5%	7.7%	23.0%	47.9%
TAP	1.1%	1.4%	2.8%	5.2%	15.5%	74.0%
HTP	0.3%	0.2%	0.7%	0.3%	1.0%	97.4%
PMFP	0.4%	0.7%	1.4%	2.9%	8.7%	86.0%
TETP	0.6%	0.3%	0.8%	2.7%	7.9%	87.8%
FETP	0.3%	0.6%	0.6%	0.1%	0.4%	98.0%
METP	0.7%	0.9%	0.6%	1.0%	3.0%	93.8%
NLTP	0.3%	0.6%	0.0%	0.0%	0.0%	99.2%
WCP	0.9%	0.6%	1.2%	0.0%	0.0%	97.3%
MCP	0.3%	0.4%	0.8%	0.0%	0.1%	98.4%
FCP	3.6%	6.2%	10.4%	8.8%	26.0%	45.0%
			AS Stove			
GWP	6.9%	5.4%	9.8%	4.9%	23.7%	49.3%
TAP	1.1%	1.4%	2.9%	3.3%	15.8%	75.5%
HTP	0.3%	0.2%	0.7%	0.2%	1.0%	97.5%
PMFP	0.4%	0.7%	1.4%	1.8%	8.8%	86.9%
TETP	0.6%	0.3%	0.8%	1.7%	8.0%	88.7%
FETP	0.3%	0.6%	0.6%	0.1%	0.4%	98.0%
METP	0.7%	0.9%	0.6%	0.6%	3.0%	94.2%
NLTP	0.3%	0.6%	0.0%	0.0%	0.0%	99.2%
WCP	0.9%	0.6%	1.2%	0.0%	0.0%	97.3%
MCP	0.3%	0.4%	0.8%	0.0%	0.1%	98.4%
FCP	3.8%	6.4%	10.7%	5.6%	26.9%	46.6%

FDS: felling, delimbing, sizing. PE: processing, extraction. S: sizing to final dimensions. FT: forecourt transport. R: retail, C: combustion.

From the data obtained, combustion is the major contributor to impact for all the categories and all the scenarios selected. The share of combustion ranges from 14.9% to 99.1% for BS1 stove and from 19.7% to 99.1% for BS1 fireplace. Similar behavior is reported for BS2 stove and fireplace, where the share is lower due to the additional transport phase, ranging from 45.0% to 99.2% and 46.5% to 99.2%, respectively. For AS scenarios, a similar percentage to BS2 is detected, just slightly higher due to the more efficient forecourt transport that lowers the share of transportation for combustion (the lower impact of AS scenario lies in the greater quantity transported over the same distance as that in the BS2 scenario). A significant impact is also detected for the retail phase with a relevant contribution on GWP, HTP, TETP, and METP for BS1 scenarios. For BS2 and AS scenarios, the retail phase has a relevant contribution to FCP due to fossil fuels for transport. The contribution analysis for BS2 and AS shows an increasing impact related to the higher distance for forecourt transport.

In contrast to what was previously written in the case of the TAP impact category, the sizing phase contributes the most, as far as the BS1 scenarios are concerned. For GWP, HTP, TAP, and FCP, the impact is more balanced between the different phases than in all the other categories in which combustion predominates. In Figure 4 is reported the sensitivity analysis relative to an increasing distance for transport from the forecourt to final processing. Looking at the chart, it is clear that this impact is always lower than the reference impact of wood chips from annex C of RED II standard. From a standard distance of 10 km (baseline) to a maximum of 100 km, the impact increases until reaching the impact of wood chips as indicated in Annex C of the RED II regulation (BS2 scenarios with forecourt transport of 100 km).

Table 8. Contribution analysis for baseline scenario 1 (BS1), baseline scenario 2 (BS2), and AS for fireplace.

Impact Category	FDS	PE	S	FT	R	C
				BS1 Fireplace		
GWP	7.5%	5.9%	7.3%		25.7%	53.6%
TAP	5.0%	2.9%	72.1%		0.4%	19.7%
HTP	1.1%	1.5%	2.1%		16.5%	78.8%
PMFP	0.2%	0.3%	0.0%		0.4%	99.1%
TETP	0.3%	1.1%	2.2%		15.1%	81.3%
FETP	0.3%	0.2%	0.5%		1.0%	97.9%
METP	0.3%	2.3%	4.2%		11.6%	81.6%
NLTP	0.4%	0.7%	1.0%		9.0%	88.9%
WCP	0.6%	0.3%	0.6%		8.2%	90.4%
MCP	0.3%	0.6%	0.4%		0.4%	98.3%
FCP	0.7%	0.9%	0.4%		3.0%	95.0%
				BS2 Fireplace		
GWP	6.9%	5.4%	6.7%	8.0%	23.7%	49.3%
TAP	1.1%	1.4%	1.9%	5.3%	15.6%	74.7%
HTP	0.3%	0.2%	0.5%	0.3%	1.0%	97.6%
PMFP	0.4%	0.7%	1.0%	2.9%	8.7%	86.3%
TETP	0.6%	0.3%	0.5%	2.7%	7.9%	88.0%
FETP	0.3%	0.6%	0.4%	0.1%	0.4%	98.2%
METP	0.7%	0.9%	0.4%	1.0%	3.0%	94.0%
NLTP	0.3%	0.6%	0.0%	0.0%	0.0%	99.2%
WCP	0.9%	0.6%	0.8%	0.0%	0.0%	97.7%
MCP	0.3%	0.4%	0.5%	0.0%	0.1%	98.6%
FCP	3.7%	6.4%	7.4%	9.1%	26.9%	46.5%
				AS Fireplace		
GWP	7.1%	5.6%	6.9%	5.1%	24.4%	50.9%
TAP	1.1%	1.4%	2.0%	3.3%	16.0%	76.2%
HTP	0.3%	0.2%	0.5%	0.2%	1.0%	97.7%
PMFP	0.4%	0.7%	1.0%	1.8%	8.8%	87.3%
TETP	0.6%	0.3%	0.5%	1.7%	8.0%	88.9%
FETP	0.3%	0.6%	0.4%	0.1%	0.4%	98.2%
METP	0.7%	0.9%	0.4%	0.6%	3.0%	94.4%
NLTP	0.3%	0.6%	0.0%	0.0%	0.0%	99.2%
WCP	0.9%	0.6%	0.8%	0.0%	0.0%	97.7%
MCP	0.3%	0.4%	0.5%	0.0%	0.1%	98.6%
FCP	3.9%	6.6%	7.7%	5.8%	27.9%	48.2%

FDS: felling, delimbing, sizing. PE: processing, extraction. S: sizing to final dimensions. FT: forecourt transport. R: retail, C: combustion.

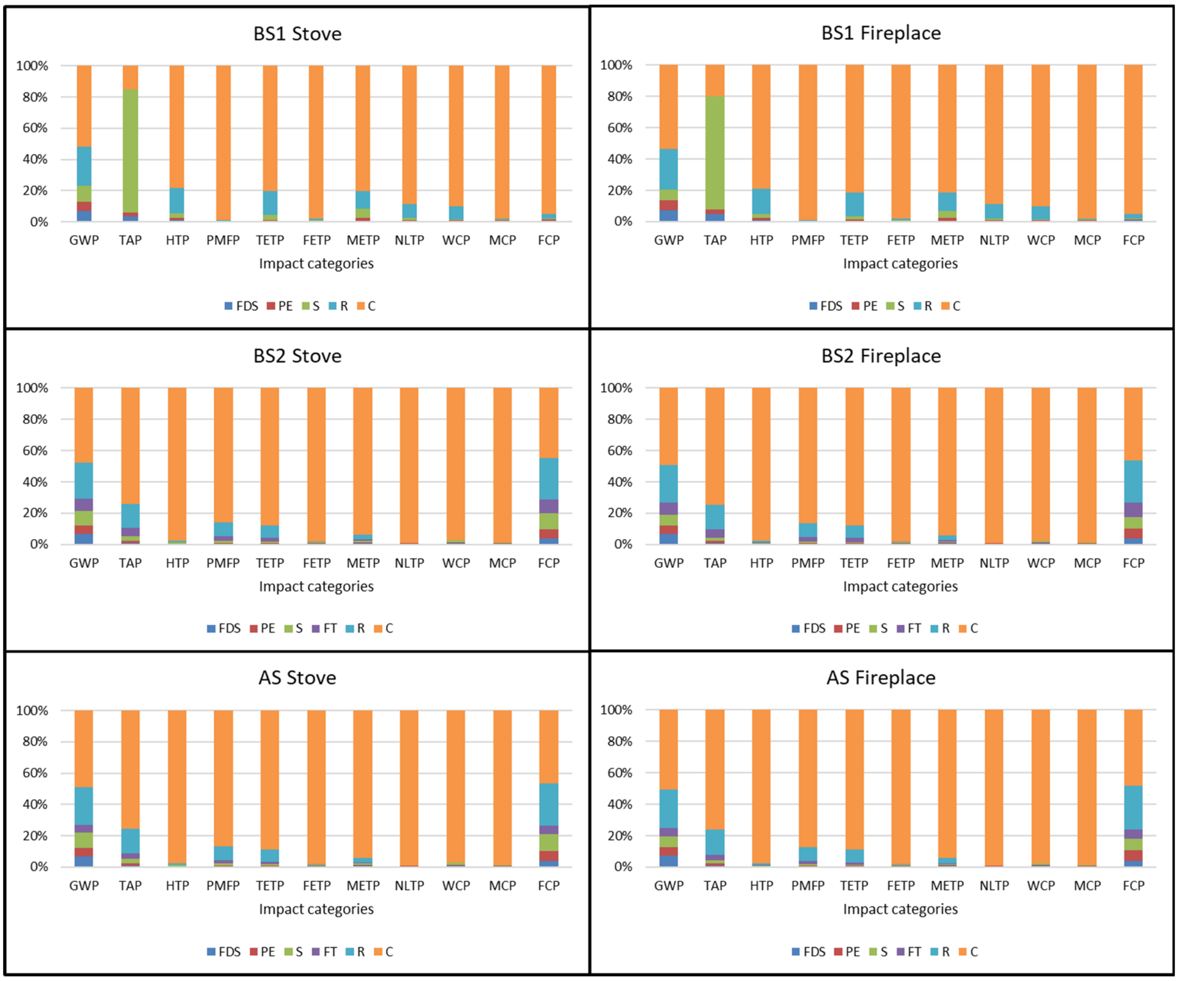

Figure 3. Contribution analysis relative to all the scenarios analyzed (raw data are reported in Tables 6 and 7).

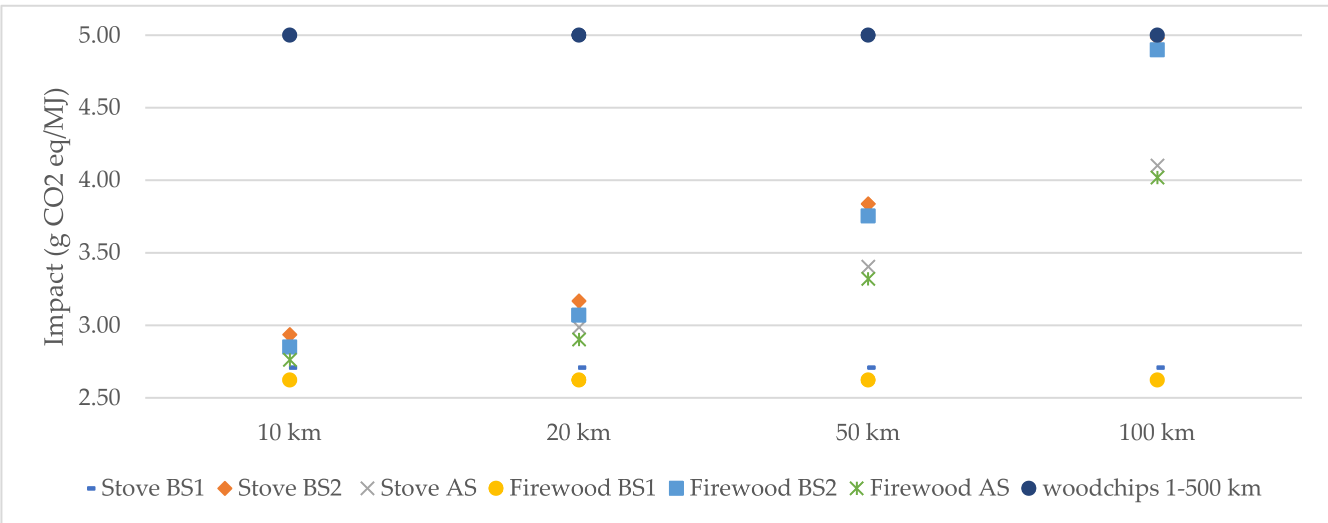

Figure 4. Global warming potential (GWP) impact behavior of all scenarios related to transport increasing distance from forecourt to final processing, with reference to RED II impact for wood chips.

The sensitivity analysis conducted on transportation from extraction location and sizing location (forecourt transport) for BS2 and AS (both stove and fireplace) shows a significant increase. By default, the distance set for this phase is 10 km considering that most of the forestry companies stay close to the production areas. However, it is not uncommon for some companies to set up processing areas closer to larger population centers to reduce the burden of the retail phase. Results show that increasing transportation distance by 100% (10 to 20 km) for forecourt transport will increase the final impact from 8% to 17% for BS2 stove and from 9% to 17% BS2 firewood. Similar results were found for AS. In this case, the final impact increased from 5% to 10% for AS stove and from 5% to 11% for AS firewood. Increasing the transportation distance to 50 km and 100 km also increased impact by 42% and 84%, respectively (BS2 stove), 43% and 87% (BS2 firewood), 26% and 52% (AS stove), and 27% and 53% (AS firewood).

3.2. Indirect Impact on Biodiversity

In Table 9 is reported the impact for BS1, BS2, and AS considering the standard forecourt transport of 10 km, applying an endpoint approach for impact assessment (method used ReCiPe Endpoint (H) v1.10/Europe ReCiPe H/A).

Table 9. Damage assessment for the scenarios tested (ReCiPe Endpoint (H)/Europe H/A).

Damage Category	Unit	BS1 Stove	BS2 Stove	AS Stove	BS1 Fireplace	BS2 Fireplace	AS Fireplace
Human Health	DALY	8.57×10^{-9}	9.02×10^{-9}	8.85×10^{-9}	8.43×10^{-9}	8.88×10^{-9}	8.71×10^{-9}
Ecosystems	Species.yr	1.81×10^{-9}	1.81×10^{-9}	1.81×10^{-9}	1.81×10^{-9}	1.81×10^{-9}	1.81×10^{-9}
Resources	$	1.36×10^{-4}	1.48×10^{-4}	1.43×10^{-4}	1.31×10^{-4}	1.44×10^{-4}	1.39×10^{-4}

It is possible to note that the impact categories linked to ecosystem damage and thus indirectly linked to biodiversity do not show a significant variation. On the other hand, the category of human health and resources damage shows an increasing impact starting from BS1 (lowest impact) to BS2 (highest impact) for both stove and fireplace scenarios.

4. Discussion

The results highlight the impact of heat production from the wood of a given tree species widely spread in Italy and the Balkans, which forms populations that are often dense and with few other species of silvicultural interest. The scenarios analyzed that represent the normal supply chains present in Italy show how the impact of the scenarios for firewood is less than that for wood for stoves. Although there are differences in the combustion processes, they do not show substantial differences in impact. The greater impact of the woodstove scenarios is entirely attributable to the increased use of fuels, lubricants, and machines for the wood splitting and cutting phases, which require more inputs as the material is reduced into smaller pieces. On the contrary, in the firewood scenarios, the impact for cutting and splitting is lower as the load capacity of the combustion devices is greater, and they can therefore handle longer logs with a greater diameter than those used stoves. The comparison between short chain (BS1) and medium chains (BS2 and AS) shows a foreseeable lower impact for short chain than for the two medium chains. AS shows better environmental performances due to the more efficient transport means employed compared to BS2. In all cases, combustion contributes to a higher impact in all the categories except TAP for BS1 stove and fireplace.

We compared our results to the impacts of similar supply chains included in technical standards such as the RED II regulation and the EU directive 2018/2001 [41], which report the impact of different energy chains (for the production of electricity and heat) from solid biofuels such as wood. It is evident that the present case study presents lower but comparable values, 3 g CO_2 eq/MJ of the present study (baseline) against 5 g CO_2 eq/MJ of the 2018/2001 regulation (referring to wood chips from wood logs with transport distance 0–500 km). For this last case, the same legislation reports a contribution of 0.3 g CO_2 eq/MJ for the wood chips processing phase. For the scenarios tested with the forecourt transport distance of 100 km, the impact is very close to that reported by the legislation net of chipping (4.1–4.9 g CO_2 eq/MJ). Similar results can be found in the literature. Pierobon et al. 2015 [42] reported an impact on GWP for firewood production that ranged from

4.3 and 9.7 g CO_2 eq/MJ (the study avoided the emission of biogenic CO_2) for short and long production chains. The other few studies focusing on energy conversion reported values of 1.5–3.5 g CO_2 eq/MJ [43], 18–53 g CO_2 eq/MJ (the study considers managed and fertilized systems) [44], 7.5–8 g CO_2 eq/MJ [45], and 2.1–2.9 g CO_2 eq/MJ [46].

The present study aims to increase multidisciplinary knowledge in the forestry field to objectively evaluate the best choices in terms of management of both Italian and broader geographic forest heritage. Specifically, for the Hophornbeam, scientific evidence [47] demonstrates that coppice management favors a greater level of biodiversity right after cutting. This appears to contrast the requests of the ecological movements that support the need to stop all felling activities in the woods. Obviously, what is true for the cenosis in which the Hophornbeam predominates may not be true for other forest formations. However, considering the carbon neutrality of biological systems (limited to biogenic carbon emissions from wood-burning and in the absence of land use change), the advantage of rational forest cutting appears clear if this guarantees greater biodiversity and resilience.

Concerning the high contribution of the combustion phase of the present case study, a possible mitigation measure could be transforming the material into densified materials such as pellets or briquettes that would be valorized in devices with better energy performance and lower emissions of unburnt and particulate matter. This measure would generate a greater impact of the transformation phase (generated by the greater energy consumption to dry and densify the wood) regarding the GWP (as reported by the RED II reference values) against a reduced impact for categories such as human toxicity. The possible opportunity and advantage of the production of densified products is not certain and should be investigated on a case-by-case basis.

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References

1. Ayres, R.U.; Van Den Bergh, J.C.J.M.; Gowdy, J.M. Strong versus weak sustainability: Economics, natural sciences, and "consilience". *Environ. Ethics* **2001**, *23*, 155–168. [CrossRef]
2. John, M. Hartwick Intergenerational Equity and the Investing of Rents from Exhaustible Resources. *Am. Econ. Rev.* **1977**, *67*, 972–974.
3. Solow, R.M. On the Intergenerational Allocation of Natural Resources. *Scand. J. Econ.* **2016**, *88*, 141–149. [CrossRef]
4. Haight, R.G. Decision models for forest and wildlife management. *NCASI Tech. Bull.* **1999**, *781*, 212.
5. Narloch, U.; Drucker, A.G.; Pascual, U. Payments for agrobiodiversity conservation services for sustained on-farm utilization of plant and animal genetic resources. *Ecol. Econ.* **2011**, *70*, 1837–1845. [CrossRef]
6. Crowards, T.M. Safe Minimum Standards: Costs and opportunities. *Ecol. Econ.* **1998**, *25*, 303–314. [CrossRef]
7. FAO. The State of World's Forests. 2020. Available online: https://www.fao.org/publications/sofo/en/#:~{}:text=The%20State%20of%20the%20World%E2%80%99s%20Forests%202020%20assesses,terms%20of%20both%20conservation%20and%20sustainable%20development%20outcomes (accessed on 20 October 2021).
8. Pilotto, F.; Kühn, I.; Adrian, R.; Alber, R.; Alignier, A.; Andrews, C.; Bäck, J.; Barbaro, L.; Beaumont, D.; Beenaerts, N.; et al. Meta-analysis of multidecadal biodiversity trends in Europe. *Nat. Commun.* **2020**, *11*, 3486. [CrossRef]
9. Bongaarts, J. IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. *Popul. Dev. Rev.* **2019**, *45*, 680–681. [CrossRef]

10. Raiter, K.G.; Possingham, H.P.; Prober, S.M.; Hobbs, R.J. Under the radar: Mitigating enigmatic ecological impacts. *Trends Ecol. Evol.* **2014**, *29*, 635–644. [CrossRef]
11. Davison, C.W.; Rahbek, C.; Morueta-Holme, N. Land-use change and biodiversity: Challenges for assembling evidence on the greatest threat to nature. *Glob. Chang. Biol.* **2021**, *27*, 5414–5429. [CrossRef]
12. Souza, D.M.; Teixeira, R.F.M.; Ostermann, O.P. Assessing biodiversity loss due to land use with Life Cycle Assessment: Are we there yet? *Glob. Chang. Biol.* **2015**, *21*, 32–47. [CrossRef]
13. Myllyviita, T.; Sironen, S.; Saikku, L.; Holma, A.; Leskinen, P.; Palme, U. Assessing biodiversity impacts in life cycle assessment framework—Comparing approaches based on species richness and ecosystem indicators in the case of Finnish boreal forests. *J. Clean. Prod.* **2019**, *236*, 117641. [CrossRef]
14. Winter, L.; Lehmann, A.; Finogenova, N.; Finkbeiner, M. Including biodiversity in life cycle assessment—State of the art, gaps and research needs. *Environ. Impact Assess. Rev.* **2017**, *67*, 88–100. [CrossRef]
15. Asselin, A.; Rabaud, S.; Catalan, C.; Leveque, B.; L'Haridon, J.; Martz, P.; Neveux, G. Product Biodiversity Footprint—A novel approach to compare the impact of products on biodiversity combining Life Cycle Assessment and Ecology. *J. Clean. Prod.* **2020**, *248*, 119262. [CrossRef]
16. Teillard, F.; Anton, A.; Dumont, B.; Finn, J.A.; Henry, B.; Souza, D.M.; Manzano, P.; Milà i Canals, L.; Phelps, C.; Said, M.; et al. A review of indicators and methods to assess biodiversity. Livestock Environmental Assessment and Performance (LEAP) Partnership. 2016, p. 150. Available online: https://www.fao.org/3/av151e/av151e.pdf (accessed on 10 October 2021).
17. Klein, D.; Wolf, C.; Schulz, C.; Weber-Blaschke, G. 20 years of life cycle assessment (LCA) in the forestry sector: State of the art and a methodical proposal for the LCA of forest production. *Int. J. Life Cycle Assess.* **2015**, *20*, 556–575. [CrossRef]
18. Varun; Bhat, I.K.; Prakash, R. LCA of renewable energy for electricity generation systems—A review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1067–1073. [CrossRef]
19. Balkau, F.; Bezama, A.; Leroy-Parmentier, N.; Sonnemann, G. A review on the use of life cycle methodologies and tools in sustainable regional development. *Sustainability* **2021**, *13*, 10881. [CrossRef]
20. Côté, S.; Beauregard, R.; Margni, M.; Bélanger, L. Using naturalness for assessing the impact of forestry and protection on the quality of ecosystems in life cycle assessment. *Sustainability* **2021**, *13*, 8859. [CrossRef]
21. Rossi, V.; Lehesvirta, T.; Schenker, U.; Lundquist, L.; Koski, O.; Gueye, S.; Taylor, R.; Humbert, S. Capturing the potential biodiversity effects of forestry practices in life cycle assessment. *Int. J. Life Cycle Assess.* **2018**, *23*, 1192–1200. [CrossRef]
22. Mair-Bauernfeind, C.; Zimek, M.; Lettner, M.; Hesser, F.; Baumgartner, R.J.; Stern, T. Comparing the incomparable? A review of methodical aspects in the sustainability assessment of wood in vehicles. *Int. J. Life Cycle Assess.* **2020**, *25*, 2217–2240. [CrossRef]
23. Vadenbo, C.; Tonini, D.; Burg, V.; Astrup, T.F.; Thees, O.; Hellweg, S. Environmental optimization of biomass use for energy under alternative future energy scenarios for Switzerland. *Biomass Bioenergy* **2018**, *119*, 462–472. [CrossRef]
24. Turner, P.A.M.; Ximenes, F.A.; Penman, T.D.; Law, B.S.; Waters, C.M.; Grant, T.; Mo, M.; Brock, P.M. Accounting for biodiversity in life cycle impact assessments of forestry and agricultural systems—the BioImpact metric. *Int. J. Life Cycle Assess.* **2019**, *24*, 1985–2007. [CrossRef]
25. Bianco, I.; Thiébat, F.; Carbonaro, C.; Pagliolico, S.; Blengini, G.A.; Comino, E. Life Cycle Assessment (LCA)-based tools for the eco-design of wooden furniture. *J. Clean. Prod.* **2021**, *324*, 129249. [CrossRef]
26. Brassard, P.; Godbout, S.; Hamelin, L. Framework for consequential life cycle assessment of pyrolysis biorefineries: A case study for the conversion of primary forestry residues. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110549. [CrossRef]
27. Lu, H.R.; El Hanandeh, A. Energy conversion vs. structural products: A novel multi-objective multi-period linear optimisation with application to the Australian hardwood plantation thinned logs. *J. Clean. Prod.* **2019**, *224*, 614–625. [CrossRef]
28. Ilari, A.; Foppa Pedretti, E.; De Francesco, C.; Duca, D. Pellet Production from Residual Biomass of Greenery Maintenance in a Small-Scale Company to Improve Sustainability. *Resources* **2021**, *10*, 122. [CrossRef]
29. ENEA Scheda Tecnologica: BIOMASSE TERMICHE. 2010, pp. 153–164. Available online: https://energia.regione.emilia-romagna.it/low-carboneconomy/fer/documenti/copy2_of_ENEA-2010-FontiRinnovabili-Biomasse%20termiche-pp.153-164.pdf (accessed on 10 October 2021).
30. Francescato, V. Manuale Apparecchi e Caldaie a Biocombustibili Agroforestali. 2012. Available online: https://www.aielenergia.it/pubblicazioni-manuali (accessed on 10 October 2021).
31. Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; 1535p.
32. Roy, P.O.; Azevedo, L.B.; Margni, M.; van Zelm, R.; Deschênes, L.; Huijbregts, M.A.J. Characterization factors for terrestrial acidification at the global scale: A systematic analysis of spatial variability and uncertainty. *Sci. Total Environ.* **2014**, *500–501*, 270–276. [CrossRef]
33. van Zelm, R.; Stam, G.; Huijbregts, M.A.J.; van de Meent, D. Making fate and exposure models for freshwater ecotoxicity in life cycle assessment suitable for organic acids and bases. *Chemosphere* **2013**, *90*, 312–317. [CrossRef]
34. Van Zelm, R.; Huijbregts, M.A.J.; Van De Meent, D. USES-LCA 2.0-a global nested multi-media fate, exposure, and effects model. *Int. J. Life Cycle Assess.* **2009**, *14*, 282–284. [CrossRef]
35. De Baan, L.; Alkemade, R.; Koellner, T. Land use impacts on biodiversity in LCA: A global approach. *Int. J. Life Cycle Assess.* **2013**, *18*, 1216–1230. [CrossRef]

36. Hanafiah, M.M.; Xenopoulos, M.A.; Pfister, S.; Leuven, R.S.E.W.; Huijbregts, M.A.J. Characterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction. *Environ. Sci. Technol.* **2011**, *45*, 5272–5278. [CrossRef] [PubMed]
37. Vieira, M.D.M.; Ponsioen, T.C.; Goedkoop, M.J.; Huijbregts, M.A.J. Surplus Ore Potential as a Scarcity Indicator for Resource Extraction. *J. Ind. Ecol.* **2017**, *21*, 381–390. [CrossRef]
38. Vieira, M.D.M.; Ponsioen, T.C.; Goedkoop, M.J.; Huijbregts, M.A.J. Surplus cost potential as a life cycle impact indicator for metal extraction. *Resources* **2016**, *5*, 2. [CrossRef]
39. Ponsioen, T.C.; Vieira, M.D.M.; Goedkoop, M.J. Surplus cost as a life cycle impact indicator for fossil resource scarcity. *Int. J. Life Cycle Assess.* **2014**, *19*, 872–881. [CrossRef]
40. van Zelm, R.; Preiss, P.; van Goethem, T.; Van Dingenen, R.; Huijbregts, M. Regionalized life cycle impact assessment of air pollution on the global scale: Damage to human health and vegetation. *Atmos. Environ.* **2016**, *134*, 129–137. [CrossRef]
41. European Parliament Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Off. J. Eur. Union* **2018**, *2018*, 82–209.
42. Pierobon, F.; Zanetti, M.; Grigolato, S.; Sgarbossa, A.; Anfodillo, T.; Cavalli, R. Life cycle environmental impact of firewood production—A case study in Italy. *Appl. Energy* **2015**, *150*, 185–195. [CrossRef]
43. Lindholm, E.L.; Berg, S.; Hansson, P.A. Energy efficiency and the environmental impact of harvesting stumps and logging residues. *Eur. J. For. Res.* **2010**, *129*, 1223–1235. [CrossRef]
44. Routa, J.; Kellomäki, S.; Kilpeläinen, A.; Peltola, H.; Strandman, H. Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. *GCB Bioenergy* **2011**, *3*, 483–497. [CrossRef]
45. Whittaker, C.; Mortimer, N.; Murphy, R.; Matthews, R. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass Bioenergy* **2011**, *35*, 4581–4594. [CrossRef]
46. Alam, A.; Kilpeläinen, A.; Kellomäki, S. Impacts of initial stand density and thinning regimes on energy wood production and management-related CO 2 emissions in boreal ecosystems. *Eur. J. For. Res.* **2012**, *131*, 655–667. [CrossRef]
47. Mei, G.; Pesaresi, S.; Corti, G.; Cocco, S.; Colpi, C.; Taffetani, F. Changes in vascular plant species composition, top-soil and seed-bank along coppice rotation in an *Ostrya carpinifolia* forest. *Plant Biosyst. Int. J. Deal. All Asp. Plant Biol.* **2020**, *154*, 259–268. [CrossRef]