energies

MDPI

Article

Identification of Suitable Areas for Biomass Power Plant Construction through Environmental Impact Assessment of Forest Harvesting Residues Transportation

Maria Pergola [1], Angelo Rita [2], Alfonso Tortora [2], Maria Castellaneta [2], Marco Borghetti [2], Antonio Sergio De Franchi [2], Antonio Lapolla [2], Nicola Moretti [2], Giovanni Pecora [2], Domenico Pierangeli [2], Luigi Todaro [2] and Francesco Ripullone [2,*]

[1] Ages s.r.l. s—Academic Spin-off, University of Basilicata, Viale dell'Ateneo Lucano, 10-85100 Potenza, Italy; mariateresa_pergola@virgilio.it

[2] School of Agricultural, Forestry, Food and Environmental Sciences, University of Basilicata, viale dell'Ateneo Lucano, 10. I-85100 Potenza, Italy; angelo.rita@unibas.it (A.R.); alfonso.tortora@unibas.it (A.T.); maria.castellaneta@unibas.it (M.C.); marco.borghetti@unibas.it (M.B.); sergio.defranchi@unibas.it (A.S.D.F.); antonio.lapolla@unibas.it (A.L.); nicola.moretti@unibas.it (N.M.); giov.pecora@gmail.com (G.P.); domenico.pierangeli@unibas.it (D.P.); luigi.todaro@unibas.it (L.T.)

* Correspondence: francesco.ripullone@unibas.it; Tel.: +39-097-120-5354

Received: 3 April 2020; Accepted: 26 May 2020; Published: 28 May 2020

check for updates

Abstract: In accordance with European objectives, the Basilicata region intends to promote the use of energy systems and heat generators powered by lignocellulosic biomass, so the present study aimed to investigate the availability of logging residues and most suitable areas for the construction of bioenergy production plants. The life cycle assessment (LCA) methodology was employed to conduct an environmental impact assessment of the biomass distribution and its transport, and spatial LCA was used to evaluate the impact of regional transport. One cubic meter kilometer (m^3 km^{-1}) was used as the functional unit and a small lorry was considered for the transport. The results showed that the available harvesting residues amounted to 36,000 m^3 and their loading environmental impact accounted for 349 mPt m^{-3}. The impacts of transport (4.01 mPt m^{-3}) ranged from 3.4 to 144,400 mPt km^{-1} forest parcel^{-1}, mainly affecting human health (95%) and, second, the ecosystem quality (5%). Three possible sites for bioenergy plant location were identified considering the environmental impact distribution due to feedstock transport. Findings from this research show the importance of considering the LCA of biomass acquisition in site selection and can fill the knowledge gaps in the available literature about spatial LCA.

Keywords: bioenergy; life cycle assessment; geographic information system (GIS); harvesting residues

1. Introduction

Harvesting residues are the biomass left on fields after wood harvesting (tops, branches, and little non-marketable trunks) [1]. On average, 10% to 15% of this biomass is left on site as forest residues following harvesting operations [2] because it is expensive to harvest and transport and there are few markets for this wood material. Occasionally, some of the larger logging wood is removed as firewood for domestic consumption [3].

At the same time, the use of wood biomass is believed to be an important component of renewable energies, particularly for producing thermal energy or joint thermal and electrical energy with a view to creating smart energy cities. Bailey et al. [4], Perez-Verdin et al. [5], and Moon et al. [6] argued that the use of wood biomass residues to produce energy or fuel can encourage the rise of regional economies and the creation of new employment opportunities. In the last decade, there has been increased awareness in using this residual biomass as a raw material for renewable energy as a response to the standards for renewable fuels and energy markets [7]. This is because the production of forest biomass energy has the potential to reduce carbon emissions when replacing fossil fuels, although several authors have reported contrasting evidence [8]; retrieve waste that would otherwise be disposed of in landfills or be incinerated; create jobs (especially in rural areas); and supply local and sustainable energy for communities, reducing their dependence on the international fuel market, as affirmed by Shabani et al. [9], Saidur et al. [10], and Ahtikoski et al. [11]. However, these residues are often not fully utilized due to the lack of demand within the immediate vicinity of the processing plant. Furthermore, transporting residues to an area with high demand is considered uneconomical [12], and significant costs are associated with the supply of forest residues from the forest. Transport also constitutes one of the major sources of air pollution, in particular, due to emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile non-methane organic compounds (NMVOC), primary particulate matter (PM 2.5), and carbon monoxide (CO). The latter are produced during fuel combustion, but other non-exhaust emissions of particulates, are produced during road and rail transport due to the abrasion of brakes, wheels, etc. [13]. Thus, the inclusion of some collection sites is out of the question due to long distances, harsh topographic conditions, or ecological restrictions. In any case, it is advised that 30% of the harvesting wood residues are left in place in order to restore the fertility of the forest soil [14–17].

When analyzing the whole life cycle of the product, Law and Harmon [18] and Schulze et al. [19] highlighted the fact that some aspects of production could worsen rather than contribute to mitigating climate change such as long-distance lumber transport. Farkavcova et al. [20] stated that in Europe, transport represents 22% of the total emissions, and that these emissions are constantly increasing. In addition, urban transport is responsible for around 25% of the CO_2 emissions produced by all transport [21]. Referring to the forestry sector, cradle-to-grave life cycle assessment (LCA) studies have shown that transport significantly contributes to the overall results by representing 60%–70% of the overall environmental impact [20,22]. In this regard, LCA is very useful, since it is a useful tool for evaluating all environmental impacts linked with a product, process, or activity as well as the consumption and emissions of resources [23]. LCA is constantly evolving, and its application to bioenergy systems has been a key factor for the development of the process in the last few years. In the literature, bioenergy production chains have been evaluated from an environmental and energy point of view by several authors [24–30]. Particular attention has been paid to saving greenhouse gas (GHG) emissions and energy balances for the production of liquid biofuels [31]. Some reviews have considered electricity, while only one study has included heat in addition to generating electricity [24]. Referring to transportation systems, an LCA study includes the identification of direct, indirect, and supply chain emissions affecting the system. In particular, direct emissions refer to energy consumption and emissions associated with vehicle movement, namely, air emissions (CO_2, CO, SO_x, NO_x, PM, etc.) from diesel combustion. In LCA transport, fuel use and the related produced emissions are called direct emissions because they are associated with the direct objective of the system to ease the movement of residues. Indirect processes are those that must exist for the direct process to exist, in this case, vehicles, infrastructure, and energy production services; vehicle production; infrastructure construction, management, and maintenance; and fuel and electricity production. Additionally, these indirect processes depend on a supply chain to produce materials, services, and other activities, probably far from where the vehicle acts [32]. Similarly, the direct energy input represents the energy effectively used to sustain a process (fuel and oil consumption of machineries, and energy consumption of humans during the work), while the indirect energy input stands for the energy stored in the materials used in the process (the energy value for the production of machinery and tools) [33,34].

Wood biomass residues are geographically allocated, with alterations in space–time availability. Therefore, energy and environmental evaluation requires a decision support system for efficient planning [35,36]. To plan a biomass facility, a preliminary and precise database including the distribution of residues and the seasonal variation (peak period and decreased availability period) is essential. Logistics such as the harvesting, storage, and transport of residues are spatially interconnected and require accurate planning. A geographic information system (GIS) is an important territorial decision-making tool that allows for a precise evaluation of distributed resources for renewable energy [37–39]. The joint use of LCA and GIS, also known as spatial LCA [35], can be useful for estimating the biomass potential in a region, and enhancing the results of environmental impact assessment by counting spatial variations and considering power plant design.

According to the European commitment of the last few years, which is aimed at solving the international economic and environmental problems linked to the climate and energy supply, the Basilicata region has highlighted the importance of the agricultural and forestry sector in the development and diffusion of renewable agro-energy sources [40]. The regional commitment aims at strengthening the financial instruments to support research and experimentation as well as the involvement of interested companies in implementing pilot projects in the regional territory. In 2012, the potential supply of forest wood biomass for bioenergy production in the Basilicata region was estimated to be around 500,000 tons per year [41]. Of this quantity, the same authors identified a mean annual production of about 22,000 tons of residual biomass of forestry origin and an average annual production of about 400,000 tons of residual biomass of agricultural origin as well as an average annual unitary production of dry biomass from dedicated crops, consisting of approximately 60,000 tons on private fields and approximately 57,000 tons on public fields [41]. Thus, the regional administration has assigned a strategic role to the energy sector to relaunch the territories with the aim of creating new and qualified job opportunities and environmentally friendly development [40]. Hence, the present research is part of the "Smart Basilicata Research and Development" project. This project aims to develop innovative techniques for the management of wood biomass including their use for energy purposes. The aim of the present research was the selection of co- and trigeneration plant construction sites and the optimal residual forest woody material collection areas in the regional territory after first investigating the availability and amount of harvesting residues through an analysis of forest management plans (FMPs) still in force. GIS was used as a decision-making spatial tool for the accurate assessment of spatially logging residues for lignocellulosic bioenergy production. Additionally, the LCA methodology was employed for an environmental impact assessment of the biomass load and transport and spatial LCA was used to investigate the distribution of the impact on the regional territory.

2. Materials and Methods

2.1. Case Study Description

The study was performed in the Basilicata region, one of the most forested areas in southern Italy (356,426 hectares) in which the forest sector is governed by Regional Law No. 42 of the 30th November 1998 "Rules on Forestry" [42]. The objective of forest management planning in this region is to apply sustainable forest management guidelines, which are carried out through FMPs. In the present study, only wood biomass produced directly from forest plans was taken into consideration (i.e., the logging residues estimated as percentages of forest utilization), according to the guidelines developed by the Basilicata region for the reduction of FMPs [42].

Considering the forestry sector and despite the benefits of forest management, in the Basilicata region, as in other Mediterranean areas and South-East Europe, the seasonality in the demand for wood products such as firewood, the substantial investments required to purchase woodland lots by forest companies, and the high cost of transactions due to the slowness of the administrative and authorization procedures, has resulted in an excessive bureaucracy [43,44], which significantly reduces the gross operating margins of companies. All this does not incentivize the purchase and consequent management of woods, especially in terms of public ownership. This leads to the abandonment of forests and sometimes to the degradation phenomena that affects the capacity of forest ecosystems [45].

Therefore, in Basilicata, there are currently 83 FMPs, 35 of which are still in force. Consequently, the study was performed in these latter municipalities (Figure 1).

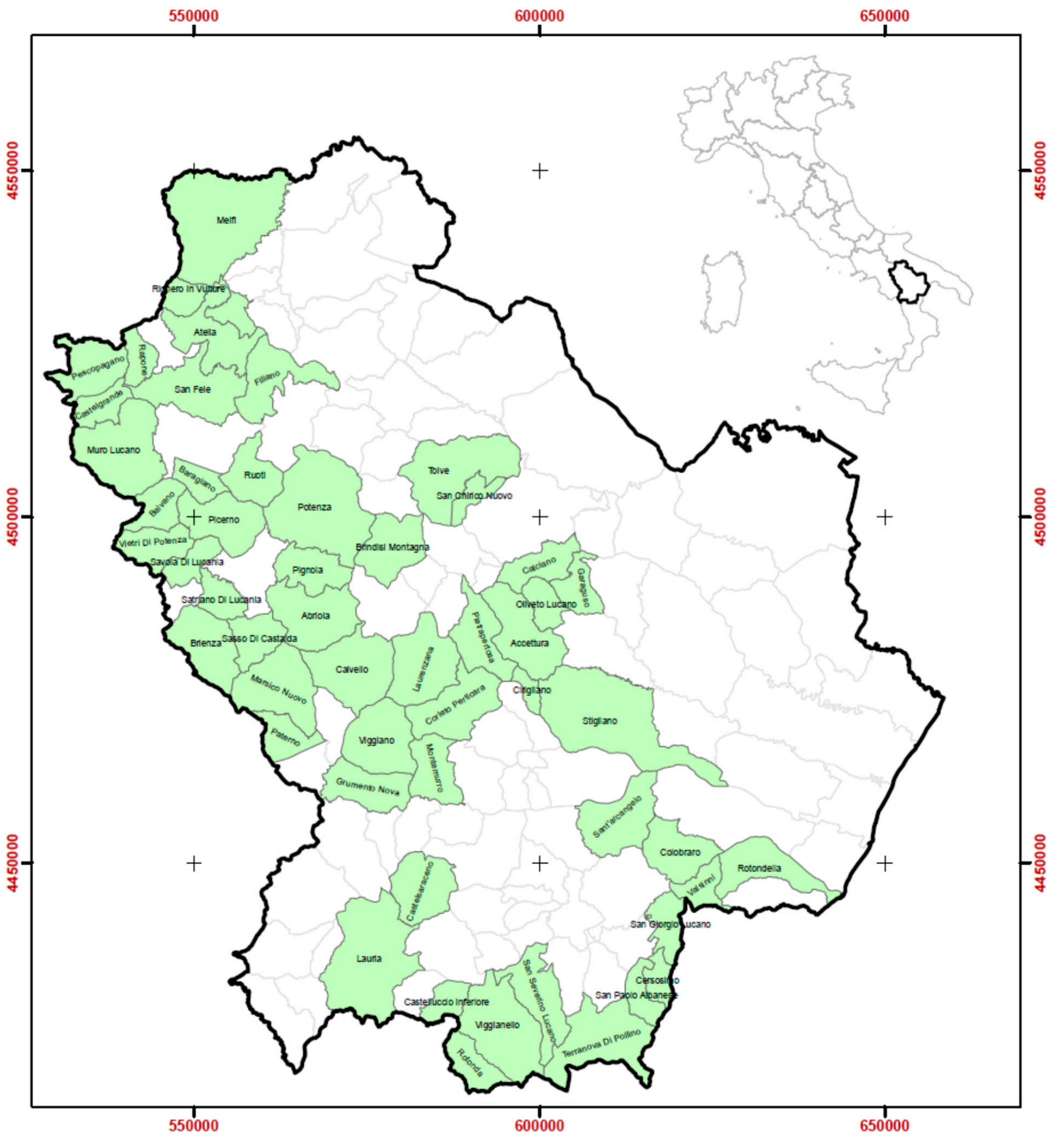

Figure 1. Study area: municipalities of the Basilicata region in which forest management plans (FMPs) are still in force.

2.2. *The Life Cycle Assessment (LCA) Approach*

The present study was designed to investigate the optimization of biomass supply distances in order to designate suitable sites for the implementation of cogeneration or trigeneration plants powered by biomass in the Basilicata region. An LCA analysis was performed according to the ISO 14040/44 (2006) [23,46].

The objective of the present analysis was to address the movement of the harvesting residues, by road, from the production forest parcels in the regional territory. Therefore, the system boundaries include the environmental impacts during all phases of the transport (transport operation and infrastructure), from raw material extraction to their use and, finally, disposal. Moreover, through the LCA methodology, all important emissions were quantified as well as their related environmental and health impacts and the issue of the resource consumption combined with transport.

In order to estimate the environmental impact of transport services and correlate transport datasets with other product life cycles, environmental loads are determined using the functional unit of one cubic meter kilometer (m^3 km^{-1}). A cubic meter kilometer is defined as the transport of a cubic meter of harvesting waste from a given transport service over a kilometer [47].

Data on the available harvesting residues and their distribution in the regional territory were gathered from an analysis of the 35 FMPs still in force. In particular, these residues were estimated as percentages of forest utilization, according to the guidelines developed by the Basilicata region for the redaction of FMPs. These percentages reflect the share of residues in the mean annual cut, as indicated by Cozzi et al. [48]. In order to ensure sustainable harvesting levels (max 60% of the annual increment for high forest and 90% for coppice forest), the percentage of forest utilization was between 5% and 50% of the total wood mass in the examined FMPs, and the relative percentage of residues available ranged from 9% to 20%. Data related to harvesting residues (tops, branches, and little non-marketable trunks usually left on sites) and load (forestry machines used, duration of the operation and fuel consumed) were taken from information reported in Pergola et al. [49], while data on the transportation were extrapolated from SimaPro's Life Cycle Inventory (LCI) databases and, in particular, from databases of scientific relevance and accuracy such as Ecoinvent 3 [50]. Since one of the objectives of this research was to investigate the regional distribution of the environmental impacts of the transport of woody residues, the item "Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7.5 ton total weight, 3.3 ton max payload RER S" was employed, whose emissions calculation was obtained from the literature [51] based on measurements [52].

Environmental assessment was performed using the SimaPro 8.0.4.30 (copyright PRé Consultants bv 2014) software by means of the LCA Eco-indicator 99 endpoint method, in which "environment" was defined as being affected by three types of damage [53]:

(1) Human health, which encompasses the number and duration of illnesses and years of life lost because of early death from environmental impacts. These latter comprise global warming, ozone layer reduction, carcinogenic and respiratory effects, etc. The measurement unit is the disability-adjusted life year (DALY);
(2) Ecosystem quality, which encompasses the effect on animal and plant biodiversity, particularly related to issues linked to acidification, ecotoxicity, and land use including the reduction of agricultural resources such as sand and gravel. Its indicator unit is the potentially disappeared fraction (PDF) of species for a given area and for a precise period (PDF m^{-2} $year^{-1}$); and
(3) Resources, which include the excess energy needed in the future to extract lower-quality mineral and fossil resources. Its indicator unit is the surplus of MJ.

In addition, the impact assessment was performed following the endpoint approach, which expresses the total environmental impact in a single score using the point (Pt) or millipoint (mPt) as the standard unit [53].

2.3. The Geographic Information System (GIS) Analysis

The ability to analyze the environment and understand all the factors that characterize it is a prerequisite for carrying out a study on a territory's suitability, and the main tools are often represented by the GIS. The latter is itself a system of tools designed to acquire, extract, archive, manipulate, analyze, manage, visualize, and present all types of geographically referenced data, which are data from the real world [54].

In particular, geo-referenced data of the total harvesting residues load and transport impacts were imported into a project in the GIS software package, together with maps of the main road network, main electricity grid, borders of the Basilicata region and municipalities, and main protected areas, which were freely available through the RSDI Basilicata portal (http://rsdi.regione.basilicata.it/web/guest/mappe-in-linea). The residential areas were taken from the digitalized map (1:25,000) of the Istituto Geografico Militare (IGM). To compute the spatial distribution of the transport impact, we multiplied the harvesting residues transport impacts per distance from the parcel, where buffers were generated using the buffer tool with distances of 1, 5, and 10 km. We highlighted that longer distances from the parcels do not maximize the cost-effectiveness of the residual transport. Finally, layers were then arranged to produce the final maps using ArcMap® 10.4.1 software by Esri (Copyright © Esri). A detailed workflow of the processes is provided in the Supplementary Materials (Figure S1).

3. Results and Discussion

3.1. Harvesting Residue Availability

Table 1 reports the results for each municipality of the analysis of 35 FMPs, referring to the availability of harvesting residues for bioenergy production (expressed in m^3) and environmental impacts (expressed in mPt) relative to harvesting residues loading and harvesting transport per kilometer.

Table 1. Harvesting residues available for bioenergy production and environmental impacts per studied municipality.

AREA	Municipalities	Harvesting Residues Available for Bioenergy (m^3)	Impacts of Harvesting Residues Loading (mPt)	Impacts of Harvesting Residues Transport (mPt km^{-1})
NORTH	Atella	368	128,250	1475
	Balvano	787	274,482	3157
	Baragiano	126	43,795	504
	Castelgrande	233	81,105	933
	Melfi	746	260,138	2992
	Muro Lucano	1132	394,702	4540
	Rapone	2317	807,670	9291
	Rionero	231	80,602	927
	Ruoti	1584	552,146	6351
	Satriano di Lucania	253	88,271	1015
	Savoia di Lucania	89	31,113	358
	Total North	7867	2,742,273	31,545
CENTER	Abriola	4430	1,544,438	17,766
	Brienza	2618	912,635	10,498
	Grumento Nova	623	217,092	2497
	Marsico Nuovo	1948	678,995	7811
	Paterno	738	257,324	2960
	Accettura	1560	543,811	6256
	Brindisi di Montagna	224	78,074	898
	CorletoPerticara	2439	850,363	9782
	Garaguso	234	81,503	938
	Laurenzana	2246	782,865	9005
	Oliveto Lucano	689	240,222	2763
	San Chirico Nuovo	94	32,834	378
	Tolve	508	176,939	2035
	Total Center	18,351	6,397,095	73,587
SOUTH	Castel Saraceno	544	189,744	2183
	Cersosimo	311	108,491	1248
	Chiaromonte	135	47,223	543
	Colobraro	256	89,372	1028
	Lauria	151	52,474	604
	Rotondella	46	15,993	184
	San Giorgio Lucano	873	304,436	3502
	San Paolo Albanese	1270	442,786	5093
	Sant'Arcangelo	49	17,057	196
	Terranova di Pollino	1875	653,603	7518
	Viggianello	4287	1,494,381	17,190
	Total South	9798	3,415,561	39,290
TOTAL		36,015	12,554,929	144,421

Referring to the availability of harvesting residues, the analysis of the 35 FMPs showed that they amounted to about 36,000 m^3, and the Basilicata region could be split into three areas: the largest supply basin was located in the central part (about 18,300 m^3), followed by the south (about 7900 m^3), and then the north (about 9798 m^3). Harvesting residues per forestry parcel ranged from 0.85 to 668 m^3.

In line with the "Smart Basilicata Research and Development" project, investigating the availability and quantity of residual forest woody materials is useful for understanding the feasibility of cogeneration or trigeneration plants powered by biomass, which could be used to produce thermal and electrical energy to create district energy systems. The latter is a growing phenomenon in many cities around the world [55] and, as stated in Perea-Moreno et al. [56], the introduction of such schemes into urban networks has important benefits such as the availability of an open energy supply grid, greater use of renewable energy sources, less reliance on imported resources and fossil fuels, greater leverage over energy supply, and the development of energy supply [57].

At the same time, harvesting residues are widespread in the regional territory, as shown in Figure 2, so there is a need to transport and concentrate them in specific areas for subsequent bioenergetic purposes.

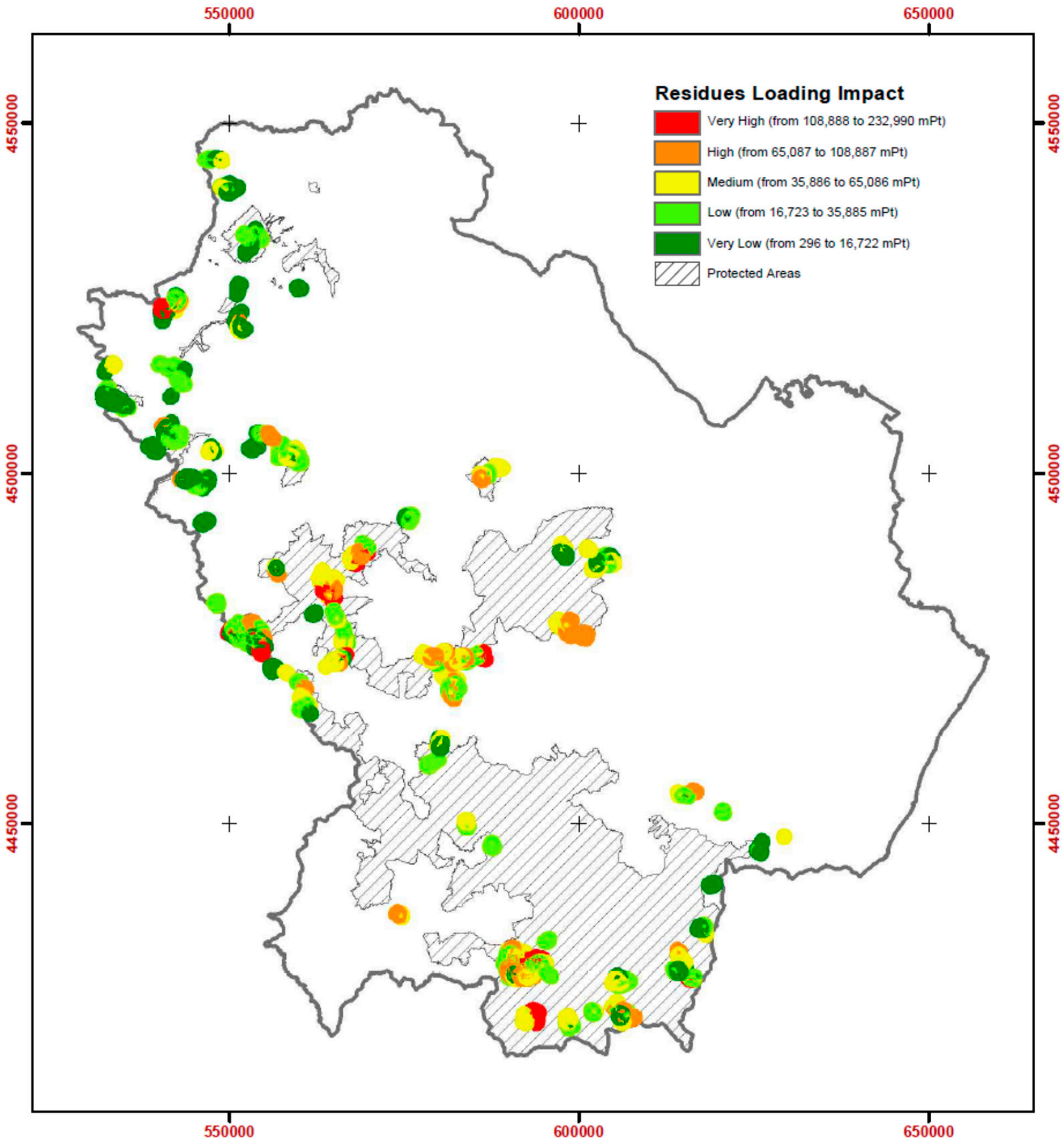

Figure 2. Regional distribution of harvesting residues and relative load impacts per impact class.

3.2. Loading Impacts

Harvesting residues load impacts were, on average, equal to 349 mPt m^{-3} and ranged from about 300 to 233,000 mPt forest $parcel^{-1}$. The main impacts concern human health (284 mPt m^{-3}), followed by resource depletion (59 mPt m^{-3}), and ecosystem quality (6 mPt m^{-3}). Human health damage (in total, equal to 0.173 DALY) was mainly due to the fuel consumed in the various loading operations and the impact categories most responsible for this damage were climate change (75%) and radiation (24%). Resource depletion (in total, equal to 7344 MJ surplus) was essentially affected by the materials and processes necessary for the construction of forest machines. Referring to ecosystem quality (in total, equal to 10,090 $PDFm^{-2}year^{-1}$), the most important impact categories were air acidification and water eutrophication, representing 73% of this damage (Table 2).

Table 2. Characterization of the total harvesting residues load impacts.

Impact Categories	Unit	Total	Diesel	Forest Machinery
Carcinogens	DALY	1.2×10^{-3}	1.8×10^{-4}	1.0×10^{-3}
Respiratory organics	DALY	5.3×10^{-4}	4.3×10^{-4}	1.1×10^{-4}
Respiratory inorganics	DALY	1.3×10^{-1}	1.1×10^{-1}	2.2×10^{-2}
Climate change	DALY	4.2×10^{-2}	3.4×10^{-2}	7.3×10^{-3}
Radiation	DALY	1.8×10^{-5}	1.5×10^{-5}	3.3×10^{-6}
Ozone layer	DALY	1.1×10^{-5}	9.6×10^{-6}	1.6×10^{-6}
Ecotoxicity	$PDFm^{-2}$ $year^{-1}$	4.5×10^{3}	1.2×10^{3}	3.4×10^{3}
Acidification/Eutrophication	$PDFm^{-2}$ $year^{-1}$	1.2×10^{4}	1.2×10^{4}	5.7×10^{2}
Land use	$PDFm^{-2}$ $year^{-1}$	-2.8×10^{3}	-7.0×10^{2}	-2.1×10^{3}
Minerals	MJ surplus	7.3×10^{3}	2.8×10^{2}	7.1×10^{3}

Many of the analyzed forest parcels fell in protected areas and in particular, in two national parks (Appennino Lucano-Val d'Agri-Lagonegrese and Pollino National Parks), in two regional parks (Gallipoli Cognato Piccole Dolomiti Lucane and Vulture), and in several Natura 2000 Network sites (Figure 2), so the load operations should be performed with caution to ensure their conservation for present and future generations [51]. In particular, these areas of relevant naturalistic and ecological value are subjected to a specific rule of protection and management to preserve animal and plant species; safeguard anthropological, historical values, and agro-forestry–pastoral and traditional activities; promote education, training, and scientific research activities; defend and replenish the hydraulic and hydro-geological balance; and promote the enhancement and testing of compatible production activities [58].

3.3. Transport Impacts

LCA analysis showed that the transport of 1 m^3 of harvesting residues caused environmental damage equal to 4.01 mPt km^{-1}, which, in total, for the whole regional territory, corresponded to 144,421 mPt km^{-1} (Table 1). Needless to say, the greatest impacts were recorded in the municipalities with the greatest amount of residues to transport and, therefore, in the middle area (73,587 mPt m^{-3}) (Table 1). Similar to loading, the greatest impacts were on human health (3.81 mPt m^{-3} km^{-1}), but in this case, were followed by ecosystem quality (0.195 mPt m^{-3} km^{-1}).

Human health was mainly affected by climate change (59%) and respiratory inorganics (39%); in particular, the latter refers to "winter" smog caused by inorganic substance emissions. At the same time, eutrophication/acidification was the impact category with the greatest negative effects on the quality of the environment, representing 97% of the total impact of ecosystem quality (Table 3).

Table 3. Total transport damage characterization per impact categories.

Impact Categories	Unit	Values per KM
Carcinogens	DALY	1.8×10^{-5}
Respiratory organics	DALY	2.8×10^{-6}
Respiratory inorganics	DALY	4.5×10^{-4}
Climate change	DALY	6.9×10^{-4}
Radiation	DALY	5.9×10^{-8}
Ozone layer	DALY	5.5×10^{-9}
Ecotoxicity	$PDFm^{-2}year^{-1}$	5.6×10^{-0}
Acidification/Eutrophication	$PDFm^{-2}$ $year^{-1}$	1.6×10^{2}
Land use	$PDFm^{-2}$ $year^{-1}$	0.0×10^{0}
Minerals	MJ surplus	2.5×10^{-1}

Farkavcova et al. [20] stated that transport from the forest to the production site caused significant environmental impacts and, more precisely, mainly caused the consumption of fuel fossil resources, the abiotic depletion of the non-fossil resources, and the potential reduction of the ozone layer. In addition, the environmental impacts of transport are particularly due to the consumption or partial combustion of non-renewable fossil fuels as well as trace elements in fuel and tire abrasion. According to Handler et al. [59] and Sonne [60], the transport of biofuels or raw materials for bioenergy is potentially the major source of environmental impacts in the total supply chain. All of this was confirmed by Murphy et al. [22], and in accordance with these observations, several studies have reported that forest biomass transport accounts for most of the energy consumption and environmental impacts in forest biomass systems [61–63]. The results of these studies have shown that the transport of biomass significantly contributes to both the energy demand and GHG emissions, representing 70%–78% of the overall energy needs and 68%–75% of GHG emissions.

Other comparisons of this research and the results of other LCA studies were not possible since they only focused on the global warming potential (GWP) or energy demand, and therefore did not provide a complete picture; Farkavcova et al. [20] rightly advised that the whole set of indicators should be considered. Moreover, as stated by Murphy et al. [22], comparisons of results are complicated by discrepancies in system boundaries, geographic areas, and the employed characterization methods. According to Heinimann [64], LCA studies neglecting embodied burdens of road infrastructure and forest machines, called "truncated LCAs", always result in an underestimation of environmental impacts or an overestimation of environmental performance, respectively.

3.4. The Territorial Distribution of Impacts

Harvesting residues were widespread in the regional territory and, consequently, their loading and transportation for bioenergy production also had widespread impacts. Figure 3 shows the distribution of the total environmental impact for each forest parcel when transporting residues within 10 km from the source. Since there were many forest parcels (327), for a better representation of the environmental impacts, the calculation was simplified and considered the calculation of the impacts for 1, 5, and 10 km, and not for each kilometer, to best represent the environmental impacts at a territorial level. Red areas represent areas with the greatest environmental impacts, given by the sum of the various "impact rays" calculated for each forest plot. Therefore, the total impact ranged from a minimum of 3.41 mPt to a maximum of about 276,000 mPt (Figure 3).

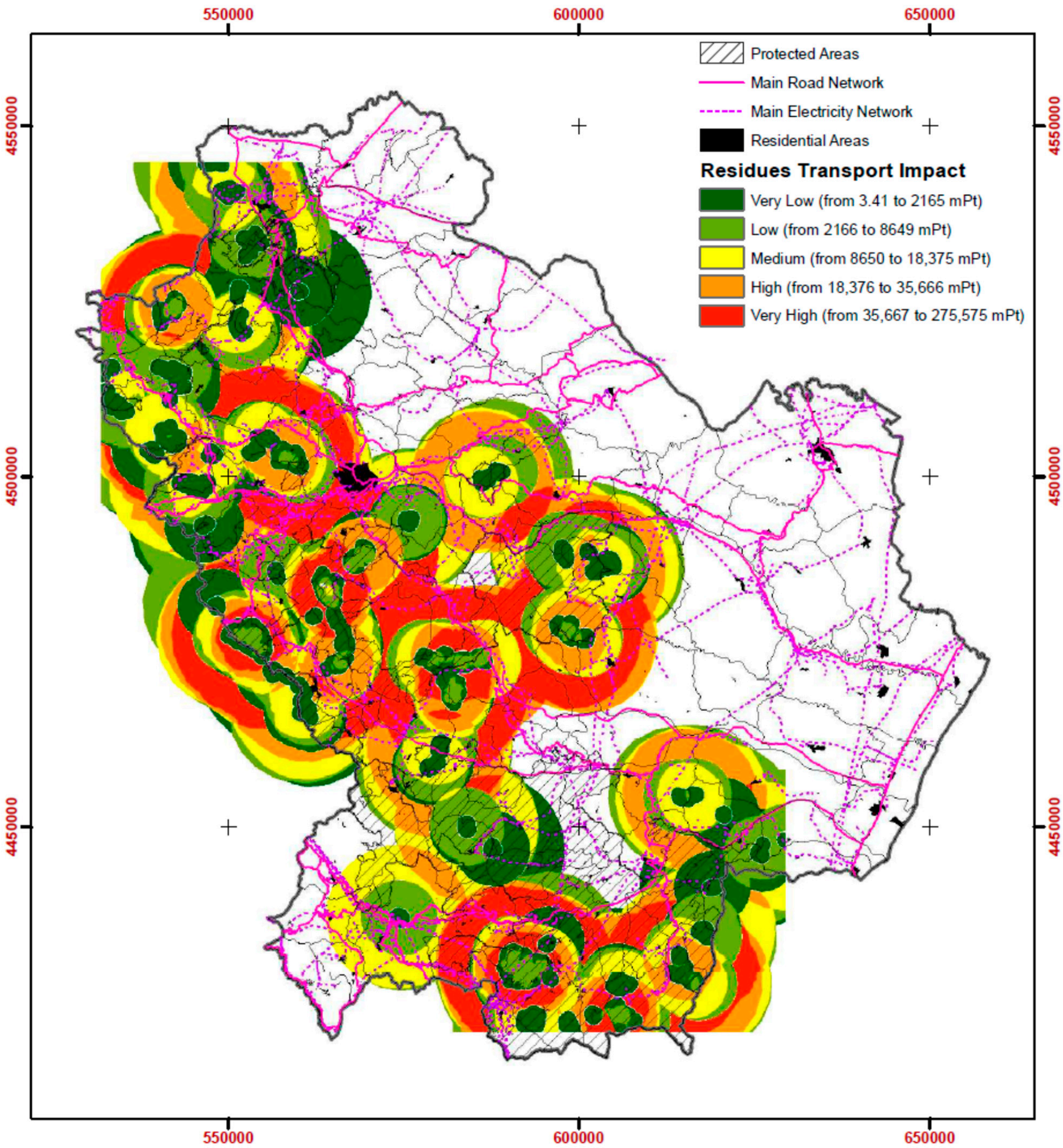

Figure 3. Territorial distribution of harvesting residues transport impacts.

To our best knowledge, this paper is one of the few studies that wish to represent transport environmental impacts territorially, in order to understand how they are distributed when more displacements are involved. In conducting a complete environmental analysis, the present study considered a set of indicators, rather than a single category (e.g., GWP). Other LCA studies of the biomass supply chain [20,22,24] have referred to the movement of lumber from the forest to a bioenergy plant, while the present study, through additionally considering environmental impacts, tried to give indications for the regional administration on which areas may be the most suitable locations for a bioenergy production plant (i.e., without compromising the environment and human health).

Indeed, one of the objectives of the "Smart Basilicata Research and Development" project is the development of cogeneration or trigeneration plants powered by lignocellulosic biomass in the regional territory. As stated by Zubaryeva et al. [65], the site should be readily reachable by transport, close to service points, and achievable for the best planning of energy transport lines. In addition, the plant should be established at an acceptable distance from residential areas, natural reserves, and protected areas to diminish the potential negative impacts of plant operation and waste disposal [35].

According to Hiloidhari et al. [35], the site selection of a biomass power plant based on GIS can be carried out through two methods: (i) suitability analysis and (ii) optimization analysis. The former allows users to recognize the most appropriate site for a power plant among many candidate sites based on user-defined constraints and support criteria. On the other hand, the best analysis accounts for the relationship between biomass and power plants to determine the optimization locations of power facilities with minimal transport and distribution costs [66].

In the present study, we tried to select the most suitable sites considering the map of the impacts; the proximity to the main road and electricity networks as well as residential areas; and the presence/absence of protected areas. Therefore, as reported in Figure 4, three possible sites were identified (one for each area of the Basilicata region):

(1) North Area near Muro Lucano municipality, since it is one of the northern municipalities with the most harvesting residues, has low impacts due to the transport, is not located in a protected area, and is well-served in terms of main roads and the electricity network;

(2) Central Area near Marsico Nuovo municipality, given that it is outside the different protected areas that characterize this area of Basilicata, does not have very high transport-related impact levels, and is well-served in terms of roads and the electricity network; and

(3) South Area near Viggianello, one of the municipalities with the highest amount of forest residues (4300 m^3), obviously outside the Pollino National Park.

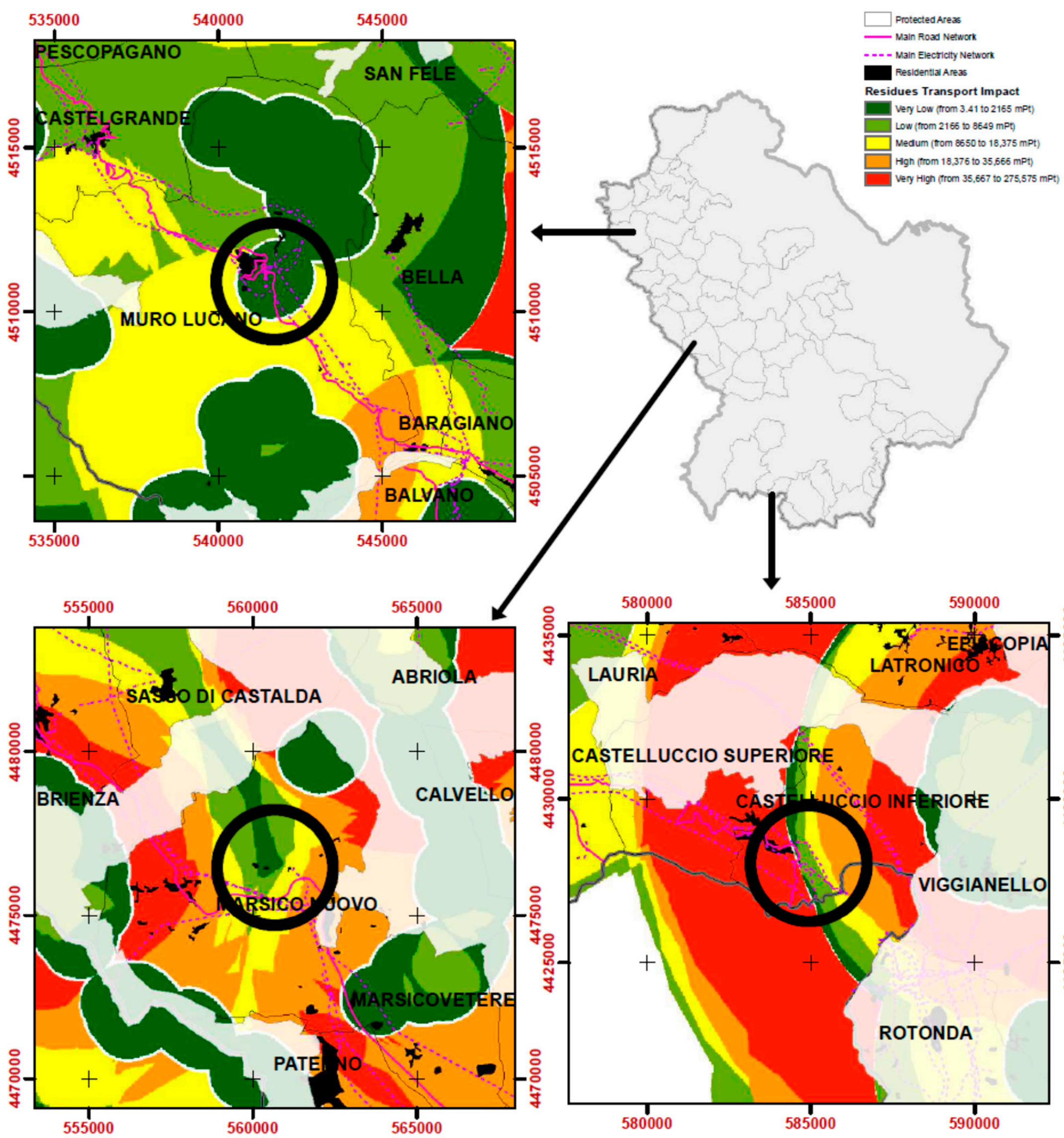

Figure 4. The three sites suitable for biomass power plant construction *.

The optimization of biomass power plant location may be carried out through the modeling of the location–allocation or the modeling of the supply area including or not including the impacts, but, as stated by Cozzi et al. [48], regardless of the applied method, the selection of an appropriate biomass center should take into account several aspects (energy, environmental, and economic) to be in line with the three pillars of sustainability (economic viability, environmental protection, and social equity). From a landscape perspective, it would be effective to place the plant in urbanized areas with similar structures, in order to avoid areas typified by agricultural and forestry aspects, keeping in mind the costs for the transport of biomass, since lower costs are obtained in areas close to the biomass processing plant [48]. Furthermore, it must be considered that the studied forest particles mainly fall in protected areas, which are rural though heavily frequented areas, where the concentration of emissions during traffic congestion could enhance by 100 times [21], further damaging human health and the quality of ecosystems.

4. Conclusions

The present study aimed to identify suitable sites for locating cogeneration/trigeneration plants powered by lignocellulosic biomass in the Basilicata region based on GIS–LCA information, after investigating the quantity of harvesting residues and environmental impacts of their loading and transport. This research allows us to take further steps forward in our knowledge about spatial LCA with regard to bioenergy production. Indeed, traditional LCAs are inadequate to identify the spatial dimensions of environmental impacts, however, this becomes feasible when they are carried out applying a GIS framework. In this study, we first assessed the environmental impacts per kilometer (4.01 mPt m^{-3}), and then built a map of cumulative impacts over a radius of 10 km for the different analyzed forest parcels, in order to identify areas with major and minor impacts. In this way, we were able to identify three areas to locate biomass plants after considering the main road network, electricity network, proximity to residential areas, and excluding protected areas. The present study represents a replicable example of how it is important to consider the environmental impact distribution of feedstock transport and not only those of bioenergy facility construction in the site selection of a biomass power plant.

Finally, we emphasize these essential aspects: only biomass residues from locally performed forest harvesting operations, or wood residues from local saw milling activities should be used for bioenergy production, and each project for bioenergy production should be preceded by a careful assessment of the potential impact of biomass removal on soil fertility and forest ecosystem biodiversity.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/13/11/2699/s1, Figure S1: Workflow of the processes for the GIS analysis.

Author Contributions: Conceptualization, M.P., F.R.; Methodology, M.P., A.R.; Software, M.P., A.R., A.T.; Validation, F.R., M.C., A.R.; Formal Analysis, M.P., M.C., A.R.; Investigation, M.C., G.P.; Resources, M.C.; Data Curation, M.C., M.P.; Writing—Original Draft Preparation, M.P., A.R.; Writing—Review & Editing, A.R., F.R., M.B., D.P., L.T.; Visualization, A.S.D.F., N.M., G.P., D.P., L.T., A.L.; Supervision, F.R.; Project Administration, F.R., D.P., M.B., N.M.; Funding Acquisition, F.R., D.P., M.B., N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the "Smart Basilicata" project (Notice MIUR n. 84/Ric 2012, PON 2007–2013 of 2 March 2012).

Acknowledgments: This research was carried out in the framework of the project "Smart Basilicata", which was approved by the Italian Ministry of Education, University and Research (Notice MIUR n. 84/Ric 2012, PON 2007–2013 of 2 March 2012) and was co-funded by the Cohesion Fund 2007–2013 of the Basilicata Regional authority. "Ufficio Foreste e Tutela del Territorio" of the Basilicata region is duly acknowledged for their kind permission to use data extracted from the "Forest Management Plans". The PhD program in 'Agricultural, Forest and Food Sciences' at the University of Basilicata supported O.P.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Moon, D.; Kitagawa, N.; Genchi, Y. CO_2 emissions and economic impacts of using logging residues and mill residues in Maniwa Japan. *For. Policy Econ.* **2015**, *50*, 163–171. [CrossRef]
2. Kuiper, L.; Oldenburger, J. The Harvest of Forest Residues in EUROPE. Probos. Report on bus ticket no. *D15a*. 2006. Available online: https://www.probos.nl/biomassa-upstream/pdf/reportBUSD15a.pdf (accessed on 20 January 2020).
3. Hoyne, S.; Thomas, A. Forest Residues: Harvesting, Storage and Fuel Value. COFORD (National Council for Forest Research and Development). 2001. Available online: http://www.coford.ie/media/coford/content/publications/projectreports/residues.pdf (accessed on 10 February 2020).
4. Bailey, C.; Dyer, J.F.; Teeter, L. Assessing the rural development potential of lignocellulosic biofuels in Alabama. *Biomass Bioenergy* **2011**, *35*, 1408–1417. [CrossRef]
5. Perez-Verdin, G.; Grebner, D.L.; Munn, I.A.; Sun, C.; Grado, S.C. Economic impacts of woody biomass utilization for bioenergy in Mississippi. *Prod. J.* **2008**, *58*, 75–83.
6. Moon, D.; Isa, A.; Yagishita, T.; Minowa, T. The regional economic impacts on the development of wood chip utilization in Maniwa city. *J. Wood Sci.* **2013**, *59*, 321–330. [CrossRef]
7. Rothe, A.; Moroni, M.; Neyland, M.; Wilnhammer, M. Current and potential use of forest biomass forenergy in Tasmania. *Biomass Bioenergy* **2015**, *80*, 162–172. [CrossRef]
8. Norton, M.; Baldi, A.; Buda, V.; Carli, B.; Cudlin, P.; Jones, M.B.; Korhola, A.; Michalski, R.; Novo, F.; Oszlányi, J.; et al. Serious mismatches continue between science and policy in forest bioenergy. *GCB Bioenergy* **2019**, *11*, 1256–1263. [CrossRef]
9. Shabani, N.; Akhtari, S.; Sowlati, T. Value chain optimization of forest biomass for bioenergy production: A review. *Renew. Sustain. Energy Rev.* **2013**, *23*, 299–311. [CrossRef]
10. Saidur, R.; Abdelaziz, E.A.; Demirbas, A.; Hossain, M.S.; Mekhilef, S. A review on biomass as a fuel for boilers. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2262–2289. [CrossRef]
11. Ahtikoski, A.; Heikkilä, J.; Alenius, V.; Siren, M. Economic viability of utilizing biomass energy from young stands—The case of Finland. *Biomass Bioenergy* **2008**, *32*, 988–996. [CrossRef]
12. FAO. Bioenergy and Food Security Rapid Appraisal (BEFS RA). User Manual. Forest Harvesting and Wood Processing Residues. 2014. Available online: http://www.fao.org/sustainable-forest-management/toolbox/tools/tool-detail/en/c/410267/ (accessed on 25 January 2020).
13. Merchan, A.L.; Léonard, A.; Limbourg, S.; Mostert, M. Life cycle externalities versus external costs: The case of inland freight transport in Belgium. *Transp. Res. Part D Transp. Environ.* **2019**, *67*, 576–595. [CrossRef]
14. Pokharel, R.; Grala, R.K.; Grebner, D.L.; Grado, S.C. Factors affecting utilization of woody residues for bioenergy production in the southern United States. *Biomass Bioenergy* **2017**, *105*, 278–287. [CrossRef]
15. Fletcher, R.J.; Robertson, B.A.; Evans, J.; Doran, P.J.; Alavalapati, J.R.R.; Schemske, D.W. Biodiversity conservation in the era of biofuels: Risks and opportunities. *Front. Ecol. Environ.* **2011**, *9*, 161–168. [CrossRef]
16. Perez-Verdin, G.; Grebner, D.L.; Sun, C.; Munn, I.A.; Schultz, E.B.; Matney, T.G. Woody biomass availability for bioethanol conversion in Mississippi. *Biomass Bioenergy* **2009**, *33*, 492–503. [CrossRef]
17. Panichelli, L.; Gnansounou, E. Estimating greenhouse gas emissions from indirect land-use change in biofuels production: Concepts and exploratory analysis for soybean-based biodiesel production. *J. Sci. Ind. Res. India* **2008**, *67*, 1017–1030.
18. Law, B.E.; Harmon, M.E. Forest sector carbon management, measurement and verification, and discussion of policy related to climate change. *Carbon Manag.* **2011**, *2*, 73–84. Available online: https://content.sierraclub.org/ourwildamerica/sites/content.sierraclub.org.ourwildamerica/files/documents/Law%20and%20Harmon%202011.pdf (accessed on 15 February 2020). [CrossRef]
19. Schulze, E.D.; Körner, C.; Law, B.E.; Haberl, H.; Luyssaert, S. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy* **2012**, *4*, 611–616. [CrossRef]
20. Farkavcova, V.G.; Rieckhof, R.; Guenther, E. Expanding knowledge on environmental impacts of transport processes for more sustainable supply chain decisions: A case study using life cycle assessment. *Transp. Res. D Transp. Environ.* **2018**, *61*, 68–83. [CrossRef]

21. Pashkevich, A.; Beliakova, M.; Ivanov, A.; Purju, A. Development of Interactive Monitoring System for Urban Environmental Impact Assessment of Transport System. 16th Conference on Reliability and Statistics in Transportation and Communication, Riga, Latvia, 19–22 October 2016. *Procedia Eng.* **2017**, *178*, 42–52. [CrossRef]
22. Murphy, F.; Devlin, G.; McDonnell, K. Forest biomass supply chains in Ireland: A life cycle assessment of GHG emissions and primary energy balances. *Appl. Energy* **2014**, *116*, 1–8. [CrossRef]
23. ISO 14040. *Environmental Management, Life Cycle Assessment—Principles and Framework*; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
24. Muench, S.; Guenther, E. A systematic review of bioenergy life cycle assessments. *Appl. Energy* **2013**, *112*, 257–273. [CrossRef]
25. Gold, S.; Seuring, S. Supply chain and logistics issues of bio-energy production. *J. Clean. Prod.* **2011**, *19*, 32–42. [CrossRef]
26. Whittaker, C.; Mortimer, N.; Murphy, R.; Matthews, R. Energy and green house gas balance of the use of forest residues for bioenergy production in the UK. *Biomass Bioenergy* **2011**, *35*, 4581–4594. [CrossRef]
27. Butnar, I.; Rodrigo, J.; Gasol, C.M.; Castells, F. Life-cycle assessment of electricity from biomass: Case studies of two bio crops in Spain. *Biomass Bioenergy* **2010**, *34*, 1780–1788. [CrossRef]
28. Fantozzi, F.; Buratti, C. Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. *Biomass Bioenergy* **2010**, *34*, 1796–1804. [CrossRef]
29. Gasol, C.M.; Gabarrell, X.; Anton, A.; Rigola, M.; Carrasco, J.; Ciria, P.; Rieradevall, J. LCA of poplar bioenergy system compared with Brassica carinata energy crop and natural gas in regional scenario. *Biomass Bioenergy* **2009**, *33*, 119–129. [CrossRef]
30. Wihersaari, M. Greenhouse gas emissions from final harvest fuel chip production in Finland. *Biomass Bioenergy* **2005**, *28*, 435–443. [CrossRef]
31. González-García, S.; Dias, A.C.; Clermidy, S.; Benoist, A.; Maurel, V.B.; Gasol, C.M.; Gabarrell, X.; Arroja, L. Comparative environmental and energy profiles of potential bioenergy production chains in Southern Europe. *J. Clean. Prod.* **2014**, *76*, 42–54. [CrossRef]
32. Chester, M.; Matute, J.; Bunje, P.; Eisenstein, W.; Pincetl, S.; Zoe, E.; Cepeda, C. Life-Cycle Assessment for Transportation Decision-making. UCLA Center for Sustainable Urban Systems. 2010. Available online: https://www.transitwiki.org/TransitWiki/images/7/73/Life-cycle_assessment_fortransportation_decision-making.pdf (accessed on 30 January 2020).
33. Ignea, G.; Ghaffayian, M.R.; Borz, S.A. Impact of operational factors on fossil energy inputs in motor-manual tree felling and processing: Results of two case studies. *Ann. Res.* **2017**, *60*, 161–172. [CrossRef]
34. Picchio, R.; Maesano, M.; Savelli, S.; Marchi, E. Productivity and Energy balance in conversion of a Quercus cerris L. Coppice stand into high forest in Central Italy. *Croat. J. For. Eng.* **2009**, *30*, 15–26.
35. Hiloidhari, M.; Baruah, D.C.; Singh, A.; Kataki, S.; Medhi, K.; Kumari, S.; Ramachandra, T.V.; Jenkins, B.M.; Thakur, I.S. Emerging role of Geographical Information System (GIS), Life Cycle Assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning. *Bioresource Technol.* **2017**, *242*, 218–226. [CrossRef]
36. Sacchelli, S.; Meob, I.D.; Palett, A. Bioenergy production and forest multifunctionality: A trade-off analysis using multi scale GIS model in a case study in Italy. *Appl. Energy.* **2013**, *104*, 10–20. [CrossRef]
37. Angelis-Dimakis, A.; Biberacher, M.; Dominguez, J.; Fiorese, G.; Gadocha, S.; Gnansounou, E.; Guariso, G.; Kartalidis, A.; Panichelli, L.; Pinedo, I.; et al. Methods and tools to evaluate the availability of renewable energy sources. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1182–1200. [CrossRef]
38. Yue, C.; Wang, S. GIS-based evaluation of multifarious local renewable energy sources: A case study of the Chigu area of southwestern Taiwan. *Energy Policy* **2006**, *34*, 730–742. [CrossRef]
39. Ramachandra, T.V.; Krishna, S.V.; Shruthi, B.V. Decision support system to assess regional biomass energy potential. *Int. J. Green Energy* **2005**, *1*, 407–428. [CrossRef]
40. Consiglio Regionale. *Piano di Indirizzo Energetico Ambientale Regionale*; Consiglio Regionale: Potenza, Italy, 2010; Available online: https://www.regione.basilicata.it/giunta/files/docs/DOCUMENT_FILE_543546.pdf (accessed on 20 December 2019).
41. Catullo, G. Sviluppo Agro-Energetico. Benefici Economici e Ambientali Contro la Crisi delle Risorse Fossili. Ufficio Stampa Consiglio regionale della Basilicata. 2012. Available online: https://consiglio.basilicata.it/archivio-news/files/docs/32/36/07/DOCUMENT_FILE_323607.pdf (accessed on 15 January 2020).

42. Consiglio Regionale della Basilicata. Regional Law n.42 of 30 November 1998 "Rules on Forestry". 1998. Available online: https://consiglio.basilicata.it//consiglionew/site/Consiglio/detail.jsp?sec=107173&otype=1150&id=182264&anno=1998 (accessed on 15 December 2019).
43. Rauch, P.; Borz, S.A. Reengineering the Romanian Timber Supply Chain from a Process Management Perspective. *Croat. J. For. Eng.* **2020**, *41*, 85–94. [CrossRef]
44. Rauch, P.; Wolfsmayr, U.J.; Borz, S.A.; Triplat, M.; Krajnc, N.; Kolck, M.; Oberwimmer, R.; Ketikidis, C.; Vasiljevic, A.; Stauder, M.; et al. SWOT analysis and strategy development for forest fuel supply chains in South East Europe. *Forest Policy Econ.* **2015**, *61*, 87–94. [CrossRef]
45. Müllerová, J.; Hédl, R.; Szabó, P. Coppice abandonment and its implications for species diversity in forest vegetation. *For. Ecol. Manag.* **2015**, *343*, 88–100. [CrossRef]
46. ISO 14044. *Environmental Management, Life Cycle Assessment–Requirements and Guidelines*; International Organization for Standardization(ISO): Geneva, Switzerland, 2006.
47. Spielmann, M.; Scholz, R. Life Cycle Inventories of Transport Services: Background Data for Freight Transport (10pp). *Int. J. Life Cycle Ass.* **2005**, *10*, 85–94. [CrossRef]
48. Cozzi, M.; Di Napoli, F.; Viccaro, M.; Romano, S. Use of Forest Residues for Building Forest Biomass Supply Chains: Technical and Economic Analysis of the Production Process. *Forests* **2013**, *4*, 1121–1140. [CrossRef]
49. Pergola, M.; Gialdini, A.; Celano, G.; Basile, M.; Caniani, D.; Cozzi, M.; Gentilesca, T.; Mancini, I.M.; Pastore, V.; Romano, S.; et al. An environmental and economic analysis of the wood-pellet chain: Two case studies in Southern Italy. *Int. J. Life Cycle Ass.* **2018**, *23*, 1675–1684. [CrossRef]
50. Ecoinvent Version 3. 2013. Available online: http://www.ecoinvent.org/database/database.html (accessed on 14 February 2020).
51. HBEFA (Handbook Emission Factors for Road Transport). Umweltbundesamt Wien: Handbuch Emissionsfaktoren des Straßenverkehrs, Version 3.1, Berlin, Bern, Vienna/Germany, Switzerland, Austria. 2010. Available online: http://www.hbefa.net (accessed on 22 January 2020).
52. Fraunhofer. Documentation for Truck Transport Processes. 2012. Available online: http://www.gabi-software.com/fileadmin/gabi/documentation5/Documentation_GaBi_Transport_Processes_Truck.pdf (accessed on 15 November 2019).
53. Ministry of Housing, Spatial Planning and the Environment. *Eco-Indicator 99 Manual for Designers. A damage Oriented Method for Life Cycle Impact Assessment*; Ministry of Housing, Spatial Planning and the Environment: The Hague, The Netherlands, 2000; Available online: https://www.pre-sustainability.com/download/EI99_Manual.pdf (accessed on 15 December 2019).
54. Clarke, K.C. Advances in geographic information systems. *Comput. Environ. Urban Systems* **1986**, *10*, 175–184. [CrossRef]
55. Fuchs, M.; Teichmann, J.; Lauster, M.; Remmen, P.; Streblow, R.; Müller, D. Work flow automation for combined modeling of buildings and district energy systems. *Energy* **2016**, *117*, 478–484. [CrossRef]
56. Perea-Moreno, A.J.; Perea-Moreno, M.A.; Hernandez-Escobedo, Q.; Manzano-Agugliaro, F. Towards forest sustainability in Mediterranean countries using biomass as fuel for heating. *J. Clean. Prod.* **2017**, *156*, 624–634. [CrossRef]
57. Allegrini, J.; Orehounig, K.; Mavromatidis, G.; Ruesch, F.; Dorer, V.; Evins, R. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1391–1404. [CrossRef]
58. Legge 6 Dicembre 1991, n.394. Legge Quadro Sulle Aree Protette. Available online: http://www.parks.it/federparchi/leggi/394.html (accessed on 16 February 2020).
59. Handler, R.M.; Shonnard, D.R.; Lautala, P.; Abbas, D.; Srivastava, A. Environmental impacts of round wood supply chain options in Michigan: Life-cycle assessment of harvest and transport stages. *J. Clean. Prod.* **2014**, *76*, 64–73. [CrossRef]
60. Sonne, E. Greenhouse gas emissions from forestry operations: A life cycle assessment. *J. Environ. Qual.* **2006**, *35*, 1439–1450. [CrossRef]
61. Jäppinen, E.; Korpinen, O.J.; Ranta, T. The Effects of Local Biomass Availability and Possibilities for Truck and Train Transportation on the Greenhouse Gas Emissions of a Small-Diameter Energy Wood Supply Chain. *Bio Energy Res.* **2013**, *6*, 166–177. [CrossRef]
62. Gustavsson, L.; Eriksson, L.; Sathre, R. Costs and CO_2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. *Appl. Energy* **2011**, *88*, 192–197. [CrossRef]

63. Lindholm, E.L.; Berg, S.; Hansson, P.A. Energy efficiency and the environmental impact of harvesting stumps and logging residues. *Eur. J. Forest. Res.* **2010**, *129*, 1223–1235. [CrossRef]
64. Heinimann, H. Life Cycle Assessment (LCA) in Forestry—State and Perspectives. *Croat. J. For. Eng.* **2012**, *33*, 357–372.
65. Zubaryeva, A.; Zaccarelli, N.; Giudice, C.D.; Zurlini, G. Spatially explicit assessment of local biomass availability for distributed biogas production via anaerobic co-digestion—Mediterranean case study. *Renew. Energy* **2012**, *39*, 261–270. [CrossRef]
66. Shi, X.; Elmore, A.; Li, X.; Gorence, N.J.; Jin, H.; Zhang, X.; Wang, F. Using spatial information technologies to select sites for biomass power plants: A case study in Guangdong Province, China. *Biomass Bioenergy* **2008**, *32*, 35–43. [CrossRef]