International Journal of Forestry Research

Forest Biomass Utilization for Biofuels and Bioproducts

Guest Editors: Jingxin Wang, Shirong Liu, Tom Gallagher, David DeVallance, and Levente Denes

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Editorial

Forest Biomass Utilization for Biofuels and Bioproducts

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Demand for biofuels and bioproducts in the world is growing due to shortage of fossil fuels and carbon footprint. Currently, forest biomass, the most abundant naturally occurring resources, is a potentially important feedstock for the production of various forms of biofuels and bioproducts. The benefits of using biomass as feedstock include reduction of the use of nonrenewable fuels, less dependency on fossil fuels, stabilization of income in rural areas, and reduced carbon emissions to the atmosphere. However, there are still some issues for management and harvesting of forest biomass and commercialization of biofuels and bioproducts from it. Knowledge and understanding of these issues have led to the development of technology and policies. In this special issue, we have invited ten papers that will stimulate the continuing efforts to understand the forest biomass management, site and environmental impacts, processing, handling, and logistics, and preprocessing and conversion technologies of biofuels and bioproducts from forest biomass as well as applications of biofuels and bioproducts.

One of the papers of this special issue reviews the recent technologies on co-gasification of coal and biomass using different types of gasifiers under various sets of operating conditions. The influences of cogasification of upstream and downstream processing are also discussed. A paper evaluates the operational performance and cost of a whole-tree biomass operation. The productivity and cost of the integrated system are examined using a standard time motion study method. Of these paper, one provides an overview of the current forest biomass estimation using both Landsat Thematic Mapper and LiDAR data. A case study was conducted to illustrate the applications of these two methods and related uncertainty analyses.

A paper addresses environmental effects of growing feedstocks on rodent community and populations. The results indicate that the planting of switchgrass has species-specific effects on rodents. There is a paper which evaluates biomass production, C and N allocation patterns in *Robinia pseudoacacia* stands between shoot, stump, coarse, and fine roots. Its results show a high potential for C and N storage of *R. pseudoacacia*. The paper that discusses the potency of converting biomass into biomethanol at forest management units through three forest management practices shows that a large amount of net carbon emission can be avoided if biomass can be converted to biofuel.

There is a paper included in this special issue that presents a study on production of 10 woody biomass species. It tries to analyze the structure of 10 woody species in semiarid zones of northeastern Mexico. The paper indicates that high volume of biomass could be yielded by most of the species with great energetic potentials when used as firewood or charcoal. Another one evaluates the impacts of some feedstock and operational factors on cost effectiveness of producing chips and pellets. It indicates that small-scale low-temperature drying and foliage and bark separation are essential to reduce pellet production cost. A paper analyzes the stakeholders' opinions about biomass harvesting guidelines (BHGs) through 60 semistructured interviews with key participants in the forest business sector in North Carolina. The results suggest BHGs need to be better justified for practitioners to protect forest health and reduce

unnecessary costs. Finally, a paper presents the spatial and temporal dynamics of tree fine roots in six common boreal forests in Eastern Sweden. The amount of live and dead fine roots in terms of dry weight was estimated. The results show a high accumulation of carbon from dead tree fine root.

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Research Article

Opinions of Forest Managers, Loggers, and Forest Landowners in North Carolina regarding Biomass Harvesting Guidelines

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Woody biomass has been identified as an important renewable energy source capable of offsetting fossil fuel use. The potential environmental impacts associated with using woody biomass for energy have spurred development of biomass harvesting guidelines (BHGs) in some states and proposals for BHGs in others. We examined stakeholder opinions about BHGs through 60 semistructured interviews with key participants in the North Carolina, USA, forest business sector—forest managers, loggers, and forest landowners. Respondents generally opposed requirements for new BHGs because guidelines added to best management practices (BMPs). Most respondents believed North Carolina's current BMPs have been successful and sufficient in protecting forest health; biomass harvesting is only an additional component to harvesting with little or no modification to conventional harvesting operations; and scientific research does not support claims that biomass harvesting negatively impacts soil, water quality, timber productivity, or wildlife habitat. Some respondents recognized possible benefits from the implementation of BHGs, which included reduced site preparation costs and increases in proactive forest management, soil quality, and wildlife habitat. Some scientific literature suggests that biomass harvests may have adverse site impacts that require amelioration. The results suggest BHGs will need to be better justified for practitioners based on the scientific literature or linked to demand from new profitable uses or subsidies to offset stakeholder perceptions that they create unnecessary costs.

1. Introduction

Woody biomass from southeastern US forests is expected to play an important role in meeting the nation's future energy needs [1, 2]. Woody biomass includes small diameter trees, tops, limbs, or otherwise nonmerchantable forest products which are used for energy production and have not been utilized previously. The expansion of woody biomass-based energy raises concerns of forest sustainability, environmental degradation, and negative impacts on biodiversity [3–5]. North Carolina has mandated forest practice guidelines (FPGs), which are linked to recommended forestry best management practices (BMPs)—voluntary guidelines that were developed to protect water quality. However, these guidelines do not specifically address the harvesting of woody biomass, and removing this material has the potential to affect soil productivity, water quality, and forest biodiversity and could negatively affect forest health [3, 6]. These concerns led to the development of woody biomass harvesting guidelines (BHGs) in five states between 2007 and 2011, and several other states currently have BHGs under consideration [7]. The increasing demand for energy from biomass in proliferation of BHGs makes understanding how stakeholders perceive the suggested guidelines a critical need.

2. Study Objectives

The objective of this study was to assess the perspectives of key players in the forestry sector in North Carolina regarding

BHGs, compare these opinions with the scientific literature on BHGs, and draw conclusions about the implications for biomass markets and policy in North Carolina and the Southeastern US. The forest managers, loggers, and forest landowners interviewed during our study represent groups that will be directly affected by biomass harvesting policies and markets. Their views and willingness to adopt such standards will be crucial in determining the development and success of proposed BHGs.

3. Biomass Harvesting Guidelines

To mitigate the impact of biomass removal, BHGs generally recommend leaving 15 to 30 percent of harvestable coarse woody debris (CWD) [7]—which is dead wood material with a small end diameter of at least three inches and a length of at least three feet [8]—on the site following a harvest.

BHGs typically provide guidance on the form of debris retention, either spreading out or piling the woody debris that remains on a harvesting site. Minnesota established BHGs in 2007 which recommended that fine woody debris should be spread out relatively evenly across the site, rather than left in piles. Minnesota BHGs also recommend retaining and scattering 20 percent of the residual tops and limbs following a harvest. Wisconsin recommends retaining and scattering the tops and limbs from 10 percent of trees harvested on the site (one tree of every 10 trees harvested). Maine biomass retention guidelines recommend leaving as much dead wood on site as possible [9].

4. Literature

Some literature has addressed opinions about woody biomass either directly or indirectly. We summarize it here briefly and then compare our results with that literature more extensively in the discussion.

4.1. Forest Managers. Few studies have analyzed foresters' perspectives of harvesting woody biomass. Schulte et al. [10] conducted interviews with foresters in the US Midwest to learn more about the market for woody biomass. Forester respondents suggested leaving 33 to 55 percent of residues on site following a harvest for the improvement of soil quality and wildlife habitat. Enrich et al. [11] conducted surveys of foresters across the USA to gather perspectives of opportunities and challenges of harvesting wood for energy. According to respondents, the primary method of harvesting biomass was in conjunction with a conventional harvest. Aguilar and Garrett [12] surveyed foresters and discovered that the main opportunities from utilizing woody biomass were considered to be increased business for loggers and harvesters and an increase in commercial thinnings.

4.2. Loggers. Literature addressing loggers' opinions regarding harvesting biomass is uncommon. Abbas et al. [13] conducted semistructured interviews with Minnesota loggers to better understand the logistics of harvesting woody biomass compared with a conventional harvest. Abbas et al. discuss operational and financial challenges that loggers faced when harvesting small diameter trees which include the use of harvesting equipment that is not designed to handle small woody material and the cost burden of harvesting low-value wood products with expensive machinery. A few studies have addressed logger perceptions of BMPs—Milauskas and Wang [14] surveyed loggers in West Virginia and found 89 percent of loggers "always" comply with BMPs. More recently, Bolding et al. [15] surveyed Virginia logging business owners regarding BMPs and discovered that BMPs take significantly more time to be implemented in mountainous regions compared to the coastal plain. Becker et al. [16] reported that forestry stakeholders in the USA including loggers, believed a guaranteed supply of woody biomass was necessary before investments made in harvesting equipment. Communication analyses of the forestry community, particularly the perspectives of loggers regarding environmental policy, have been rare [17].

4.3. Landowners. Many studies have addressed landowner perspectives regarding forest management [17–20], but few have addressed landowner perspectives on BHGs or biomass harvesting. Londo [21] examined Mississippi forest landowners and reported that NIPF landowners had a low level of knowledge regarding BMPs. Many studies have been conducted to determine the effectiveness of forest landowner financial incentive programs [22–24]. Paula et al. [25] surveyed forest landowners in Alabama and found the majority willing to supply timber residues for energy purposes.

Most previous studies regarding woody biomass focused on the costs of harvesting biomass, rather than the experiences and attitudes of the individuals directly involved in the market. A small but growing number of studies explore the perspectives of the forestry community related to the harvesting of woody biomass, but no published research has examined their perceptions of BHGs. This study investigates the opinions of forestry stakeholders who would be directly affected by woody BHGs, if implemented in North Carolina, since they are the ones who would be putting the guidelines into practice.

5. Methods

We interviewed forest owners, foresters, and loggers to assess their opinions about BHGs. In addition, we examined the BHGs that have been developed in other states and reviewed the scientific literature about potential environmental problems with biomass harvests that could prompt the need for BHGs.

We sought to obtain and understand the perspectives of North Carolina forest landowners, professional loggers,

and forest managers about BHGs using a qualitative research approach. We interviewed forest owners, foresters, and loggers to assess their opinions about BHGs. In addition, we examined the BHGs that have been developed in other states and reviewed the scientific literature about potential environmental problems with biomass harvests that could prompt the need for BHGs. We then compared the opinions of respondents in the forest business sector with the literature and approaches taken in other states to assess reasonable policy approaches to BHGs that could be taken in North Carolina or similar southern states.

The individual participants in the study were identified based on key initial contacts and subsequent followups. Five key informants were recommended through sources including the North Carolina Association of Professional Loggers, the State Board of Registration for Foresters, the Association of Consulting Foresters of America, the North Carolina Tree Farm Program, and the North Carolina Forestry Association. The group of key informants included one professional logger, three professional forest managers, and one landowner. The remaining respondents were identified through the snowball sampling method and interviewed to gain insight into the forest industry [26]. Rapport was established with interview subjects while meeting at their homes, places of employment, various logging sites, and public places.

From May 2010 to April 2011, semistructured interviews were conducted with 20 forest managers, 20 loggers, and 20 landowners. We used an interview guide, but the interviews were informant directed, and as a result the respondent was allowed to control the trajectory of the interview and decide which topics of conversation were of importance to them. Consistent with recommended qualitative research practice, the interview guides were allowed to evolve continually throughout the interview process. The questions addressed respondents experience with woody biomass harvesting and their opinions of the operational and financial feasibility of BHGs.

We continued interviewing new informants until saturation, the point where additional interviews did not contribute new information, was reached [26, 27]. Interviews were recorded and audio files were transcribed into QSR Internationals' NVivo 8 qualitative data analysis software. After the transcription of an interview was completed, a pseudonym was assigned to the speaker to ensure confidentiality. For example, a quotation identified as (Peter) was spoken by an interviewee identified with a pseudonym of Peter.

Qualitative data were analyzed using an inductive approach which allowed common themes to emerge from data gathered from interviews. Transcripts were reviewed and analyzed for emerging themes or patterns [27, 28]. Major themes in each interview were identified through finding repetitions of particular subjects. Transcripts of each interview were coded into different categories using the qualitative data analysis software.

Table 1: Highest education of North Carolina forest manager, logger, and forest landowner respondents ($n = 60$).

	n	%
Less than high school	1	1.7%
High school	13	21.7%
Some college/technical college/trade school	6	10.0%
4-year college degree	25	41.7%
Graduate degree	15	25.0%

6. Interview Results

The 60 respondents (Appendix) were predominately male (93%) with an average age of 55. Most respondents had at least a 4-year college degree (Table 1).

The 20 forest managers were consulting foresters (45%), employees of forestry government agencies (15%), and forest managers for private companies (40%). A majority of logger respondents (65%) were currently participating in the woody biomass market, meaning they operated a wood chipper or grinder and sold dirty chips (chipped wood containing bark) to a facility that utilized the material for energy production. The delivered price that logger respondents received for dirty chips was in the range of \$15 to \$30 per ton with an average of \$21 per ton ($n = 9$). According to the loggers interviewed, one to three loads (approximately 25 to 75 tons) of woody biomass are typically harvested per acre, although this amount varies greatly depending on stand condition before it is cut. If loggers were not currently participating in the woody biomass market, they were asked to provide reasons for this decision. Loggers blamed the high costs of entry into the chipping business and the lack of market opportunities to sell the material. However, many of the loggers who were not currently harvesting expressed that they would probably add a chipping component in the future.

Forest landowners interviewed owned an average of 1286 acres of North Carolina forestland ($n = 20$) across 17 different North Carolina counties. Nineteen of the 20 forest landowners interviewed had a management plan, and all 19 were currently implementing that plan. Thus this sample seems representative of the most active forest landowners, not the general population of landowners as a whole, who often lack forest management plans. The primary objective landowners held in forest ownership was earning income from timber harvests. Additional dominant objectives included providing wildlife habitat, recreation, and having a natural resource to pass down to their children.

Our sample was drawn from the more involved and progressive members of each of these professional groups. These respondents represent active participants in the forestry sector of the North Carolina Piedmont and Coastal Plain regions, where forests are typically managed for timber rather than aesthetic purposes. Thus, the results

seem to be a reasonable case in representing the southern timber producers' perspective on additional forest practice regulations.

6.1. Consensus Themes

6.1.1. Current Forest Guidelines Are Sufficient. A majority of respondents (96.6%) believed that North Carolina BMPs had been successful and most commented that the guidelines were "performance based" with "results-driven" standards and high compliance rates and thereby reasonable and had high compliance rates and were reasonable and effective. The majority of the participants believed that harvesting woody biomass could negatively impact water quality; however, they viewed current BMPs as a sufficient protective measure with few exceptions. Lucas, a forest manager, was asked if he believed current BMPs were a success, and he responded, "Yes, I do. Our BMPs are results driven. If you have good results, why change what you are doing? If you look at it, (we are) 97 to 98 percent in compliance of BMPs across the state. To me, that is very successful." Jason, a logger, described why the present positive response of those in the forestry community towards the BMPs can be attributed to the mode of establishment, stating

> I think one of the reasons they have been successful is when it started, it was basically as a volunteer implementation program and they figured out real quick the best way to implement these things and the state and everybody else kind of went along with it, working hand in hand with the forestry associations and various groups to come up with plans that would work. It was not forced on everybody, it was kind of volunteered; therefore, they have come up with a solution that has worked.

6.1.2. Biomass Harvesting: Few Modifications to Operations. Respondents expressed that woody biomass harvesting is only an additional component to harvesting with little or no modification to logging operations. During a typical timber harvesting operation in the Southeastern US, material is felled and brought to the logging deck to be sorted into the different products for processing. Respondents explained that when a biomass harvesting component is introduced to a logging operation, there is limited modification to the flow of operations, only the addition of a product at the logging deck. Henry, a landowner, expressed that biomass harvests were not different from current harvest operations, saying "Biomass harvesting is nothing more than a clearcut. We are doing a good job of that now. There should not be any additional harvesting guidelines for biomass." Connor, a logger, said

> Biomass harvesting is no different than regular clearcut harvesting. You are going to have the same machinery running on the ground, you will have to observe the same buffer zones and forest practice guidelines—there is no difference—same type of equipment doing the same thing.

6.1.3. Lack of Scientific Research Supporting BHGs. Forest manager, logger, and landowner respondents believed the proposed BHGs were being established by policy makers without the support of objective scientific research. Respondents agreed there was a lack of scientific research supporting claims that harvesting biomass leads to adverse effects on soil, water quality, timber productivity, and wildlife habitat. For example, Felix, a forest manager, stated "There is no document in the literature that I've seen that says that nutrients are diminished by biomass harvesting." Adam reiterated this point saying, "There is no research of (biomass harvesting) causing depletion to soil." Shaun, a logger, was asked about the adoption of BHGs, and he responded, "I do not know what benefits would be…whoever sets those guidelines must have documentation saying why this has got to be done. What is it doing for the land? What are the benefits?" The prevailing opinion of forest landowners was that forest policies are created by political forces or emotions rather than science. For example, Elijah, a forest landowner stated, "A lot of our regulations come from people that do not understand." Another landowner, Stephen, agreed saying, "A lot of people make regulations who do not know anything about forests."

6.1.4. Threats of BHGs to Viability of Biomass Harvesting. Forest managers and loggers regarded the woody biomass market as having very low profit margins and worried that BHGs posed a threat to the viability of biomass harvesting. Forest managers and loggers continually declared how they were constrained by small profit margins due to the undeveloped biomass markets in North Carolina. High transportation costs paired with high fuel costs in harvesting operations were the primary reasons given for why it was not feasible to add a chipping component to a harvesting operation. There were also high costs of entry in the logging business. Adding a woody biomass component to a harvesting operation required extra equipment including a fuel chipper and a chip van. The principal difficulty in adding a fuel chipping component to a timber harvesting operation was the increase in amount of fuel used during the time it takes to harvest the woody biomass material.

Forest managers and loggers expressed concern of the introduction of BHGs worsening the already volatile market for biomass. They communicated that if restrictions were placed on a product that had such a low market value in comparison to other forest products, biomass harvesting would become unattractive and not economically possible. A small number of loggers believed that the adoption of BHGs would not impact their logging operations financially, particularly if they were currently working for a large timber company rather than operating independently since these loggers do not purchase their own timber.

6.1.5. Accurate Estimation of Debris Is Not Possible. Most forest managers and loggers believed that estimating a particular percent of woody debris to be left after a harvest would be highly problematic from an operational standpoint. Foresters expressed the view that estimating a percentage would not only be logistically challenging but would also increase enforcement costs. Foresters noted that hardwood stands typically have much more debris left on site compared to pine stands, which, if previously thinned and mature, may have very little debris left. Requiring standardized rules of specific percentages of CWD to be left on a site may be difficult with the high degree of variability among harvests. The debris left on a site may depend on characteristics of the stand rather than whether there has been a biomass harvest or not. In addition, forest manager participants believed that violations of BHGs would be a challenge to remediate, particularly if debris was removed without leaving the recommended amount on site.

6.1.6. BMPs Reflect Public Distrust of Forest Industry. One additional theme that emerged from the interviews with forest managers was that they believed BHGs reflected public distrust of forest industry. This idea of "us versus them" describes the polarization between those who work in the woods and those who influence legislation. Forest managers described how they are skeptical of forest guidelines that are politicized and are a result of polemical lobbying by environmental groups. The reason many foresters gave for the lack of collaboration between environmental policy makers and foresters is because individuals working in the forest industry are seen as the "bad people" who cannot be trusted. Phillip explained this notion stating, "Contrary to what some in the environmental community believe, the mission of a forester is not to cut the last tree."

Forest managers also held the belief that forest guidelines often are established by policy makers without communicating with or considering the perspectives of those working in the forest industry. For example, one consulting forester when speaking about forest guidelines stated, "The new buffer rules were put into place without ever talking to foresters" (Patrick). Brad, a governmental agency forester stated, "It is unfortunate that a lot of folks do not want to believe what the foresters say anymore." Lucas, a forest manager in the industry sector, stated

> I would say a very high percentage of those people, their opinion of biomass harvesting is not based upon their opinion of biomass harvesting, it is based upon their opinion of logging in general. That is just my opinion but it can be verified by a lot of surveys and things that the general public says and does out there.

The public's view of forestry was not so apparent in logger responses although there were mentions of the disconnect between environmentalists and loggers. One logger, Kevin, explained how he hoped successful BMPs would make a difference in the public's perception of logging saying, "(BMPs) have definitely made a difference and I hope it makes a difference in what the public thinks about loggers."

6.1.7. BMPs Reflect Public Fear of a Desolate Site. The polarization between the public and those in the forest industry is illustrated by one particular vivid image of a desolate site, conjured by "outsiders" to the forest industry. Forest managers described the perceptions of the public visualizing timber harvests as "a vacuum cleaner that sucks out everything," a "concrete floor," or a "pool table." The desolate site rhetoric illustrated a perceived disconnect between the perceptions of the two groups. Our informants may have believed biomass harvesting would evoke this bleak image among the general public or environmental groups because of the fear of environmental degradation and loss of biodiversity of forestlands. However, these types of harvests are seen as only a temporary disturbance in the view of forest managers.

6.1.8. Difficulties of Logging Business. The topic of the current state of the economy and the effect on logging businesses permeated throughout most of the logger participants' interviews. One logger who declined to be interviewed only said, "If something does not change, you are going to see loggers go out of business." Walter stated, "The logger needs some help. That's something you need to put in your write up." He continued, discussing the difficulties of the business,

> I am 60 years old and I do not plan to stay in logging. It's too hard; it's nothing I would recommend a young man to do because it's too many rules and regulations right now. The logger do not get paid like he should. . .I have been in logging 14 years and I have not made a cent in the last two years. It's just getting harder and harder, fuel is high and everything you buy is high. . .and the logging rates for what you can get for wood is not going up.

Loggers expressed the need for governmental financial and legislative support. Most loggers interviewed owned or worked for small, family-owned logging businesses, and this often left them with small profit margins and little negotiating power.

6.1.9. Definition of Biomass. Forest landowners voiced concern over conflicting definitions of woody biomass in current political discussions. "I am not hearing anything that the BMPs need to be changed to address biomass concerns. Things I am hearing is that we need a definition of what biomass is," remarked Blaine. Duke stated, "I am all for biomass and developing the appropriate definition of it but I am not so sure there should be a limiting definition of what biomass is." Evelyn described how she was not in favor of the definition of woody biomass including whole trees for chipping. Verl, a landowner, also expressed how the lack of a

clear definition of biomass was a limitation, saying

> Everyone is scared to death about what they are going to do on our definitions here. I talked to a fellow yesterday and he was wondering "Why do not we develop the (biomass) market?" And it's simple, who would make the economic investment, not even knowing if standing trees qualifies in the market. Everything is held hostage right now by definitional issues and debate over standards.

6.1.10. Interest in Woody Biomass as an Additional Forest Product. Only two of the twenty landowner interview respondents indicated they had previously had woody debris removed from their property to be used for energy purposes. Landowners who had not previously participated in the woody biomass market communicated interest in the expansion of the market in hopes that previously unmerchantable material could be used and provide additional income. In addition, landowners discussed the benefit of a cleaner site following a woody biomass harvest, which subsequently reduces fire hazards and improves forest health.

The primary reason given by landowners for not participating in the woody biomass market was the lack of market opportunities. Landowners who were aware of woody biomass market developments and recent legislation were eager to participate and be given the opportunity to use previously unmerchantable woody debris to reduce fire hazards and improve forest health.

6.1.11. Government Support of Woody Biomass Market. The majority of landowners agreed that the government should provide financial support for the biomass market and the positive externalities that landowners are providing to the public. Evelyn stated, "For the successful gathering of woody biomass, you're going to have to have tax incentives for loggers, lumber companies and for some landowners." Landowners were interested in federal woody biomass opportunities; however, there was discussion of the inadequacy of previous financial assistance programs such as the federal Biomass Crop Assistance Program (BCAP).

6.1.12. Private Property Rights. Many forest landowners were reluctant to accept any additional guidelines for a variety of reasons including the belief that forest guidelines are "unconstitutional" or are unnecessary since the private landowner should have the freedom in the responsibility over his or her own forest without an increase in environmental protections. Duke captured the overall attitudes of forest landowners toward forest regulations in his comment; "I do not think I need someone to tell me and my forester how to harvest the trees."

6.1.13. Benefits of Biomass Harvesting and BHGs. Two forest managers, three loggers and two of the forest landowners interviewed were not opposed to the adoption of BHGs and instead welcomed these guidelines, contrary to the beliefs of their counterparts. Although these respondents were in the minority, they did express their belief that removing more material from a site as woody biomass could be problematic and that there would be benefits to implementing BHGs. Spencer, a logger, explained "I would not be against (BHGs) because I think everything brought to the forestry field is for a good reason and a good cause. That is what we need, more guidance, guiding us the right way."

6.1.14. Reduced Site Preparation Costs. Forest manager respondents believed that the utilization of biomass can decrease the costs of site preparation for the landowner, which includes planting and bedding to enhance regeneration. Phillip stated, "(Harvesting of woody biomass) provides a cleaner site that is likely to require minimal site prep activity and less investment from a landowner for reforestation." Andrew stated, "The added benefit we get is by getting our site cleaned up better than it otherwise would" which decreases costs of future planting.

6.1.15. BHGs Provide Increased Business for Consulting Foresters. "The more rules that are in place for any forestry, the more confused the landowner will be, the more likely they will be to hire me," Jackson, a consulting forester, stated. A few consulting foresters noted that if BHGs are adopted in North Carolina, their business is likely to benefit since more people will seek the services of a registered forester to clarify and monitor the new guidelines. However, despite the possible personal advantage of increased guidelines, these foresters still opposed potential BHGs.

6.1.16. Proactive Forest Management. Many forest manager respondents thought that better markets for wood products would encourage landowners to be more proactive in forest management. Forest managers placed a great deal of emphasis on forestry decisions and practices being reliant on "the market." Adam, a forest manager, stated, "What causes good forestry practices? The market. We are not dummies and we know there has to be good markets. The better markets we have, the better we will practice good forestry." Michael stated, "If the logging cost made it uneconomical to harvest that landowner's tract, then that closes a market opportunity for that landowner, so tracts do not get harvested and forest management practices do not get implemented."

6.1.17. Reduced Fire Hazard. Forest managers and forest landowner respondents mentioned the reduction in fire hazard as a benefit to the harvest of woody biomass. In the past, prescribed burning was performed after a harvest. However, with the increase of liability and urbanization,

less burning has been done so there is more debris left on harvesting sites, which can act as a fire hazard, particularly if left in large piles. Removing this debris for energy production can reduce a possible fire and smoke hazard.

6.1.18. Soil Stabilization and Erosion Control. Forest managers, loggers, and landowners expressed concern about biomass harvesting affecting soil quality; however, as mentioned previously, most demanded that sound research document the effects before operations are to be modified. Patricia, a forest manager, stated, "I think (the effect of biomass removal) would happen over time, a consistent removal of biomass in a particular area, over time, sure enough could affect nutrient properties of soil." Max, a logger, was asked about the recommendation of leaving 15 to 30 percent of CWD on site following a harvest, and he responded, "It seems like a fairly reasonable amount to be left, at least there is something being left to stabilize the soil and help the tree growing process. I do not think taking everything off the tract is a good idea." Max continued saying

> A lot of the time we are using all of that debris to stabilize the ground, to stop the run off, so if all that debris was getting chipped up and hauled off, then it could create an issue to where the guidelines may have to be changed, it really would—if we started to grind all that stuff up.

Several landowners expressed concern about soil damage and depletion of nutrients from harvesting woody biomass. "If you continue to take the trees off of there and do not leave some of the mass there to regenerate the soil, you are going to deplete the soil" (Brandon). "We do not pay much attention to the soils that take hundreds of years to develop that we can destroy with a single logging operation. . .I think there needs to be more attention to our soils by BMPs but I would not like to see another set of guidelines imposed on ones that are already there" (Duke). Cory, stated, "You cannot continue taking (woody debris) away and not adding something back to it." He continued saying

> Whenever I have had a harvest, I always encouraged my logger to make sure that (debris) was scattered about. . . I like to see that stuff scattered back on those sites so I do not get an erosion problem. (The debris) will rot and turn back to organic matter. I think that is an excellent guideline.

6.2. Recommendations for BHGs. When asked for suggestions for BHGs, most forest managers took this time to explain why guidelines specifically for biomass harvesting were not necessary. However, there were several recommendations for forestry guidelines to increase focus on soil quality in addition to water quality

> Instead of requiring a percentage left on site, I think it should be more related to soil impacts. In other words, like the FPGs. . .they do not really tell you how to do it, but the end result is to prevent water pollution and sediment and the streams. So I would think it would make sense for the BHGs to move towards preventing soil impacts. So if the logger has tracked equipment, maybe he can harvest all of the woody debris. If he does not, he has to leave 50 percent of the woody debris, if it is in a wet site (Patrick, forest manager).

Jackson, a consulting forester, recommended leaving a percentage of the ground surface covered with woody debris rather than a percentage of debris left on the ground. Brad, a government agency forest manager, suggested, "The BHG itself should be clear enough that it could be easily interpreted and easily measured, easily monitored." Richard, a consulting forester, believed that a five-year look back strategy would be the best way to determine if biomass harvesting was doing any damage on wildlife and soil before placing restrictions on the operations. He stated, "I think (a five year look back) would be much better than making the regulations onerous on the landowners and the buyers and everybody else."

Loggers who thought leaving 15 to 30 percent of CWD was reasonable believed that it should be done on problem areas. For example, Jack was asked about retaining 15 to 30 percent of CWD on site, and he responded, "It would be possible but only necessary in what we call the main skid trails." Clayton stated, "I would think if there was a slope, you would try to leave (debris) there. If it was more of a flat place, it may not take as much."

A small number of loggers suggested that guidelines be tailored to the region. For example, Jason suggested that guidelines should be different for the coast where the productivity of timber growth is higher than areas such as the Piedmont. He stated, "It just depends on what part of North Carolina you're talking about. One law will not fit across the whole state." Kevin was asked if North Carolina's BMPs should be adapted to address biomass harvesting and he responded, "I think in certain counties, maybe not in Neuse River or the Roanoke River area, but when you get in the western part of the state, I think the guidelines do need to change. Because we do not have a problem with erosion in this area like you do in Halifax and Warren County."

Jason, a logger, also offered advice for the formulation of guidelines saying

> (Policy makers) need to visit everybody who is in the biomass business now and get some comments from every single one of them before they come out with a set of rules. And they need to be loggers, they need to have had experience logging, they have to be able to show criteria. As long as you do not just give somebody a briefcase and say, here now you're the expert

> on biomass, and he do not know his damn way from Raleigh to the coast—I'm against that. But if the guy is legitimately trained and knows what he is doing, I am for it.

Landowners were asked if they had any recommendations for BHGs, and a variety of responses and suggestions were given. Some landowners took this opportunity to insist that additional forest guidelines were unnecessary. For example, Duke commented, "I am not sure you can regulate good forestry." A few landowners discussed enforcement and how without it guidelines were futile. Thomas stated

> If you do not have enforcement capabilities of guidelines or rules or regulations with teeth in them that are regularly used, somebody will do whatever they feel is in their best interest to do. So if you are going to have guidelines, have the gumption to have monitoring and enforcement, somewhere or another.

A few landowners suggested that for the woody biomass market to expand, woody material must be gathered for energy at the time of harvest rather than later. For example, Evelyn stated, "There does not need to be a delay, they don't need to come in a year later and gather the woody biomass. . .Come on in right behind, get it done at one time." Elijah stated, "I think it would be much more economical to be there on the spot with the logger doing it or a contractor doing it while the logger is there, as far as going in to the guideline."

6.3. Forestry Organizations. Both the North Carolina Forestry Association (NCFA) and the North Carolina Association of Professional Loggers (NCAPL) are important trade associations in the state, and several respondents were confident that guidelines regarding harvesting woody biomass would not be adopted because of these organizations' influence on the forestry sector and legislature. Jackson, a forest manager, stated

> Legislation will never pass in North Carolina. It is not going to. I think if you go back and look at the teeth we are trying to put in the board of registration laws for registered foresters, the forestry association has fought it all the way. Anything that requires a logger to learn about something, or spend more money, the forestry association fights you all the way.

Max, a logger, explained the NCAPL saying

> We have those guys as watchdogs and they are trying to get wood pellet companies into the state. Another thing too, with having that organization watching out for us, we don't see anything too intense as far as rules and regulations being passed. I do not think they would let it happen; they would do something to put a stop to it. So it's nice to have those guys and organizations in our corner as far as rules and regulations.

7. North Carolina Forestry Sector Opinions versus Biomass Harvesting Impacts Research

Our research interviews did not provide any background of biomass harvesting literature and science before or during the interviews. We were seeking the opinions of North Carolina forest landowners and professionals based on their existing knowledge and awareness of the issue. However, our review of literature on biomass harvesting impacts, the adoption of BHGs in other states, and the perceived fears of adverse environmental impacts by the public and environmental groups suggests discrepancies between the opinions of the forest business sector informants and perceptions of other groups concerned about biomass harvesting and its environmental impacts. These differences and some similarities are examined in this section.

7.1. Current Guidelines Are Sufficient for Woody Biomass Harvests. Our interview findings suggest broad support for BMPs among forestry stakeholder groups, which did not translate into support for BHGs. As in other studies, we found that respondents considered BMPs to have been successful for their effectiveness [29] and had high compliance rates [14, 30, 31]. Respondents believed that current guidelines were not only successful, but also sufficient in the protection of forest resources during harvesting operations. The widespread acceptance of BMPs may explain the perceived benefits of the current forest guidelines [32–34] and opposition to any additional guidelines since they are deemed unnecessary. There will likely be resistance from the North Carolina forestry community if BHGs are implemented. Perspectives of forestry stakeholders in states which have adopted BHGs would be beneficial to understanding the willingness to accept novel forest guidelines.

The perceived similarity between traditional operations and biomass operations also may explain why all groups believed that biomass harvesting should not be treated separately from a conventional harvest in terms of the guidelines applied. During a typical logging operation in the Southeast, after the tree is felled, the whole tree is usually skidded to the log deck where the limbs and tops are removed and the wood is sorted for each market. Adding a woody biomass harvesting component is the addition of a chipper and a chip van which are brought to the logging deck. The material which will be used for woody biomass is put through the chipper at the logging deck, and the operational process of harvesting trees in the woods is not altered.

Therefore, in the southeastern US, harvesting biomass does not significantly change operations in terms of harvesting material; it only supplies an additional product. However, harvesting operations differ across regions. For

example, in the northeastern US, harvesters frequently leave the limbs and tops where the tree is felled, rather than bringing the material to the logging deck. These variations must be considered when adopting guidelines that may have been created for a region with different harvesting methods.

7.2. Lack of Scientific Research Supporting BHGs. Our findings indicate that the North Carolina forestry community does not believe the available science related to woody biomass harvesting is sufficient for the adoption of additional forest guidelines. All three of the groups agreed on the importance of the scientific method to achieve results that supported the creation of BHGs; however, they expressed concern that forest policy may be based on emotions and political expediency and ignore science and the practical constraints of harvesting operations. Similar studies found the same general attitudes towards new forest policy. For example, Holt [35, page 31] discovered that forest stakeholders in Oregon hoped that the biomass industry was "not politicized and driven by politics" and instead based upon funding and informed by science. Eliason et al. [36] found that natural resource professionals were wary of new guidelines and wanted to "understand the reasons" and "understand the end result…the end goal" before new forest guidelines were to be adopted. Dietz et al. [37] documented that forest professionals believed the public had little knowledge of forests. Similarly, Dirkswager et al. [38] interviewed landowners and found them to believe that policy makers who formulated biomass harvesting policies did not understand the economics of harvesting timber.

There is a large body of research that has explored the science behind the dynamics of woody biomass and the detrimental effects that harvesting the material could have on forest ecosystems. Harmon et al. [39] documented snags and downed coarse woody debris to be important to forest ecosystems and critical to wildlife habitat. Downed CWD has been shown to benefit a variety of organisms, including invertebrates, vertebrates, fungi, and plants [40, 41]. Downed CWD may also be important for nutrient retention [39]. It has been shown to limit erosion by reducing overland flow [42].

Despite the ample evidence for the importance of specific habitat elements (e.g., CWD, snags, cavity trees, etc.) to forest biodiversity, there is still reluctance among the forestry community to accept additional regulations to protect forest ecosystems in the event of increased biomass harvests. Conflict between practitioners, policy makers, and researchers likely emerges from efforts to set a specific number or amount of each habitat elements that should remain on an acre of forest land. This is comparable to the results of both Botkin [43] and Peterson [44] who found that the scientific method often exacerbates, rather than lessens, environmental conflict.

The growth in woody biomass markets may significantly increase the amount of CWD that is harvested [45], and Moorman et al. [46] suggest that the extraction of woody biomass may alter the dynamics of CWD and lead to lower amounts of the material due to shorter harvest rotations. This reduction in downed CWD could have detrimental effects on many species of wildlife including mice, small snakes, lizards, and salamanders [39, 47]. The Pennsylvania BHGs state that "good biomass practices can enhance and improve forestland; poor practices can damage and devalue it" [48, page 30]. Similarly, Hess and Zimmerman [45, page 6] discovered there to be a consensus among experts that the "absence of downed woody debris would be detrimental to biodiversity and ecological processes."

Some ambiguity in the science addressing the effects of woody biomass harvesting and the high level of conflict between interest groups suggests that it will be difficult to implement BHGs, since there is neither a top-down nor bottom-up pressure and little support from the interest groups interviewed here [49]. Per Matland [49], the coalition of local level actors will determine the policy implementation depending on their influence and strength. The resistance of loggers, landowners, and foresters to more BHGs will impede their adoption. Environmental interest groups and agencies may support the rules, but it appears they will face fairly pervasive opposition. The new conservative legislature in North Carolina, and much of the South, will also make development of new laws or even new BHG guidelines difficult.

On the other hand, a recent court ruling in North Carolina that all woody materials, even whole trees, qualify as biomass, along with the rapid expansion of more wood pellet plants, may cause enough pressure that BHGs will be developed. Also, all large energy and forestry companies already have corporate environmental policies, staff, and programs. Large companies also are ranked on their sustainability efforts by many sources, such as the Dow Jones Sustainability Index, which evaluates the sustainability performance of the companies listed on the Dow Jones and will surely require them to have proactive policies to prevent adverse impacts during biomass harvests.

7.3. Threats of BHGs to Viability of Biomass Harvesting. Woody biomass is currently a low-value product, and we found that respondents believed the market was too volatile to introduce further guidelines on the harvesting process. Forest managers and loggers identified the transportation costs of woody biomass as one of the most challenging factors of adding a chipping component to an operation. These findings are in line with those of Aguilar and Garrett [12], who reported that the costs of harvesting and transporting were identified by professional forest managers as the biggest challenge to harvesting woody biomass as a renewable energy feedstock.

Similarly, Dirkswager et al. [38] conducted a phone survey with logging business owners in Minnesota and found low product prices, high equipment and fuel costs, the lack of material, and environmental regulations were primary barriers in the harvesting of biomass. They also found that landowners believed increased forest regulations would threaten sustainability in timber harvesting. It is not clear which group will bear costs of BHGs. Loggers will

spend more time implementing BHGs which will result in increased fuel costs and equipment usage. This suggests that the price landowners receive for woody biomass material may be reduced with BHG implementation.

7.4. BMPs Reflect Public Distrust of Forest Industry. Respondents believed that forest guidelines often were formulated by policy makers based on the public's distrust of logging rather than sound science. A review of the literature suggests the polarization between those in the forest industry and the public is not a new concept. Foresters have had decreasing public esteem for years. For example, the association of British Columbia Professional Foresters sponsors opinion polls of the public's perception of foresters each year and found that in 1997, 66 percent of the public believed it was "very important" to have forestry reserved for professional foresters. This percentage decreased each year, and in 2002, this number dropped to 40 percent [50].

Thomas [51] as cited in Luckert [52] wrote of American foresters and stated, "Twenty or so years ago, foresters were among the most respected and trusted professionals in the United States. Sadly that is no longer so." Keefer et al. surveyed loggers in Pennsylvania, and 70 percent felt the "negative public image of the logging industry" was the most significant pressure faced in the logging business [53, page 91]. These sentiments of forest managers and loggers illuminate the isolation and lack of effective communication between those working in the forestry industry and the public.

Forest managers frequently mentioned the public's fear of having a timber harvest site left as a denuded landscape of stumps. This perception was a reason forest managers cited as why policy makers believed that biomass harvesting needed to be regulated although, according to respondents, this bleak observation was only a temporary scene which is quickly replaced by new growth of the forest. The public's fear of a desolate site is explored throughout the literature and can be explained by the public's negative perception of clearcutting. Egan et al. [54] investigated tree farmer opinions in West Virginia and discovered that 55 percent believed clearcutting should be banned. Bliss [55] investigated the public's perceptions of clearcutting and found that several opinion polls have continually reported the widespread disapproval. Bliss also describes that Americans find clearcutting to be "aesthetically offensive" and the practice leads to conjured images of vast deforestation and degradation. Understanding the relationship between the public's negative view of forestry and forest regulations is necessary in the development of forest guidelines.

7.5. Logging Economic Hardships. The economic challenges of operating a logging business during a poor economy were discussed frequently by loggers throughout the interview process. Recent literature discusses the difficulties of the logging business. For example, Bolding and others [15] documented the challenges of logging in Virginia which include an aging workforce, recent mill closures, and volatility of the market. Egan and Taggart [56] found 69 percent of loggers surveyed in New England did not encourage their children to enter the logging business, and only 51 percent of respondents stated that they would still be logging in five years. Loggers are constrained by low prices, lack of markets, and high operation and fuel costs and expressed the desire to capitalize on available business opportunities. This suggests that the poor economic climate for loggers paired with the volatile woody biomass market will make it difficult for the forestry community to accept any regulations that further constrain profit margins for loggers. Additional research is needed to better understand the economics of harvesting operations using BHGs.

7.6. Definition of Biomass. Our results show that forest landowners are concerned with the conflicting definitions of woody biomass in political discussions. A number of landowners believed that definitions of woody biomass should not be restrictive based on the type of material or if the material is located on public or private land. A small number of landowners mentioned that they did not want the woody biomass definitions to include whole-tree chipping. There have been ongoing political debates regarding the formulation of a clear definition of woody biomass, particularly as it relates to renewable energy standards. Benjamin et al. [3] noted that the terms "forest biomass" and "biomass harvests" often create confusion among forest professionals and those in academia. Aguilar and Garrett [12] surveyed state foresters, state energy biomass contacts, and members of the National Council of Forestry Association Executives to understand perspectives of the definition of biomass and found that respondents believed the definition of biomass "should not differentiate between naturally regenerated forest stands and plantations or private and public forestlands." The current ambiguity in woody biomass definitions, particularly in North Carolina legislation, will likely impede the implementation of additional forest guidelines.

7.7. Private Property Rights. Forest landowners were adamant about their private property rights and believed they deserved the freedom to manage their forest as they wished, without an increase in environmental protections. These perceived landowner rights were the main reasons given for landowner respondents' opposition to BHGs. These results are comparable to Williams and others [57] who found a majority of Arkansas NIPF landowners believed they should have the ability to use their land as they chose without regulations although the landowners supported environmental protection.

In contrast, Bliss et al. [58] surveyed southeastern landowners and reported 76 percent felt their property rights should be limited if it was essential for the protection of the environment. In a similar study, Bliss et al. [18] reported rural residents, urban residents, and forest landowners believed that private property rights were necessary but secondary to environmental protection, and there was no significant difference between the groups. These two studies

suggest landowners may support BHGs despite the opposition to additional forest protections, if guidelines ensure the protection of the forest.

8. Conclusions

Forest managers, forest landowners, and loggers in North Carolina were reluctant to accept any additional forestry guidelines, particularly related to the harvesting of woody biomass, due to the perceived economic and social impact of increased regulation. Reconciling these perspectives on woody biomass harvests with public concern over environmental impacts is necessary for effective expansion of biomass markets, and public policies that will facilitate the use of this potentially important natural resource.

Most forest manager, logger, and landowner respondents in this study believed that there was not sufficient scientific literature or evidence to support claims that biomass harvesting threatens wildlife habitat or ecosystem function. Available science related to the negative effects of woody biomass harvesting is either not well known by the forestry community or not believed. This suggests that the introduction of science has had little practical influence on the perceptions, or at least that literature has not been extended well to the forestry sector respondents in the field.

The opposition to BHGs among forest managers, loggers, and landowners parallels the resistance that the public typically has for additional environmental policies and regulations. However, this study provided unique results in that respondents expressed positive opinions and acceptance of BMPs yet antipathy towards additional forest guidelines. The differences among sectors were not always as anticipated. For example, consulting foresters could potentially profit from additional forest guidelines yet still opposed BHGs. Loggers would likely incur more costs from the implementation of BHGs, at least in the short run, than landowners, yet were more positive regarding adoption of BHGs.

Our interviews in North Carolina, and indeed the general literature, have not examined the role of market factors such as corporate social responsibility, environmental management systems (EMS) such as ISO 14000, external corporate sustainability rankings for investors and consumers, and forest certification in driving the demand for BHGs. Large electric and wood chip companies have extensive environmental management programs and must submit and demonstrate environmental compliance in all their activities. Woody biomass production will be required to meet these same strictures, and BHGs, forest certification, chain of custody, or other approaches surely will be necessary to obtain investor approval and bank financing for these projects. Thus the market drivers may lead the traditional forestry sector toward BHGs despite stakeholder concerns.

The findings from this qualitative study point to several recommendations in developing appropriate forest policies and incentives for practicing sustainable forestry on privately owned land. Recommendations for policy makers include the following.

(i) Bridge the divide between public and the forestry community's discourse regarding biomass policy to lessen conflict between environmental groups, forest managers, forest landowners, and loggers.

(ii) Consider the forestry community's reluctance to adopt additional guidelines.

(iii) Use market drivers of environmental management systems, corporate sustainability rankings, and certification to convey the need for BHGs.

(iv) Develop guidelines based on research and focus on harvesting impacts that are not already covered by BMPs, such as biodiversity, wildlife, and site productivity.

(v) Provide enhanced outreach and extension about the science regarding potential adverse impacts of biomass harvesting and the role of BHGs in ameliorating problems.

(vi) Develop standard protocols for measuring the amount of biomass initially and the amount to be left on site.

(vii) Specify local relevance of woody BHGs.

(viii) Define the term *woody biomass* clearly in appropriate policy.

(ix) Engage all stakeholders in discussions and development of BHGs, including environmental nongovernment organizations and bioenergy companies.

(x) Develop new, low-cost, innovative outreach methods for young and "tech-savvy" landowners, foresters, and loggers to participate in biomass markets and BHGs.

Future research needs to include assessing the perceptions of environmental groups and energy companies and users regarding BHGs. Other future studies could include a cost analysis to assess the financial impact of BHGs on logging operations. In conclusion, this study can aid in making informed policy decisions around BHGs that are not only sustainable, but also integrate the suggestions of the forestry community and scientific literature into guideline formulation. This information can also contribute to management decisions regarding sustainable BHGs and certification standards. The qualitative data and recommendations provided can be used for further education and outreach for the southeastern forest community and for the evaluation of specific solutions for the barriers of harvesting woody biomass.

Appendix

See Tables 2, 3, and 4.

Table 2: Forest manager respondents.

	Pseudonym	Age	Gender	Education	Job type
1	Ronald	49	M	Graduate school	Consultant
2	Jonathan	53	M	College	Consultant
3	Patrick	53	M	College	Consultant
4	Peter	51	M	Graduate school	Government agency
5	Beverly	44	F	College	Private industry
6	Joseph	39	M	College	Private industry
7	Andrew	53	M	College	Private industry
8	Wayne	58	M	Graduate school	Consultant
9	Patricia	39	F	College	Private industry
10	Jackson	54	M	College	Consultant
11	Wesley	38	M	College	Consultant
12	Michael	49	M	Graduate school	Government agency
13	Brad	38	M	College	Government agency
14	Matthew	55	M	College	Consultant
15	Adam	62	M	College	Consultant
16	Robert	56	M	College	Consultant
17	Lucas	56	M	Graduate school	Private industry
18	James	48	M	Graduate school	Private industry
19	Phillip	60	M	College	Private industry
20	Felix	56	M	Graduate school	Private industry
	Average	50.5			
	Standard deviation	7.4			

Table 3: Logger respondents.

	Pseudonym	Age	Gender	Education	Owns chipper
1	Spencer	50	M	College	No
2	Walter	60	M	8th grade	No
3	Clayton	45	M	High school	No
4	Blake	56	M	Some college	Yes
5	Hugh	52	M	College	Yes
6	Drew	50	M	Some college	No
7	Harrell	59	M	Some college	Yes
8	Anthony	52	M	High school	Yes
9	Austin	32	M	High school	Yes
10	Max	55	M	Some college	No
11	Shaun	75	M	High school	Yes
12	Connor	67	M	College	No
13	Owen	51	M	High school	Yes
14	Alex	31	M	Some college	Yes
15	Kevin	54	M	High school	No
16	Charles	47	M	High school	Yes
17	Jason	63	M	Graduate school	Yes
18	Gary	40	M	High school	Yes
19	Jack	51	M	College	Yes
20	Edward	48	M	High school	Yes
	Average	51.9			
	Standard deviation	10.5			

Table 4: Landowner respondents.

	Pseudonym	Age	Gender	Education	Acreage of woodlands	Management plan
1	Duke	76	M	Graduate school	164	Yes
2	Cory	59	M	College	107	Yes
3	Mark	44	M	Graduate school	180	Yes
4	Stephen	71	M	College	3000	Yes
5	Ronald	67	M	College	355	Yes
6	Thomas	68	M	College	250	Yes
7	Ken	55	M	Graduate school	70	Yes
8	Brandon	67	M	College	5000	Yes
9	Elijah	72	M	High school	750	Yes
10	Evelyn	59	F	Graduate school	650	Yes
11	Blaine	59	M	Graduate school	2500	Yes
12	Verl	60	M	Graduate school	125	Yes
13	Henry	48	M	Graduate school	2900	Yes
14	William	73	M	Some college	250	Yes
15	Simon	52	M	High school	25	Yes
16	Margaret	69	F	High school	110	Yes
17	Todd	80	M	Graduate school	94	Yes
18	Chuck	65	M	High school	400	No
19	Roger	58	M	College	7500	Yes
	Average	63.2			1285.7	
	Standard deviation	9.6			2041.3	

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Research Article

Nontraditional Use of Biomass at Certified Forest Management Units: Forest Biomass for Energy Production and Carbon Emissions Reduction in Indonesia

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Biomass conversion technologies that produce energy and reduce carbon emissions have become more feasible to develop. This paper analyzes the potential of converting biomass into biomethanol at forest management units experiencing three forest management practices (community-based forest management (CBFM), plantation forest (PF), and natural production forest (NPF)). Dry aboveground biomass collected varied considerably: 0.26–2.16 Mg/ha/year (CBFM), 8.08–8.35 Mg/ha/year (NPF), and 36.48–63.55 Mg/ha/year (PF). If 5% of the biomass was shifted to produce biomethanol for electricity production, the NPF and PF could provide continuous power to 138 and 2,762 households, respectively. Dedicating 5% of the biomass was not a viable option from one CBFM unit. However, if all biomasses were converted, the CBFM could provide electricity to 19–27 households. If 100% biomass from two selected PF was dedicated to biomethanol production: (1) 52,200–72,600 households could be provided electricity for one year; (2) 142–285% of the electricity demand in Jambi province could be satisfied; (3) all gasoline consumed in Jambi, in 2009, would be replaced. The net carbon emissions avoided could vary from 323 to 8,503 Mg when biomethanol was substituted for the natural gas methanol in fuel cells and from 294 to 7,730 Mg when it was used as a gasoline substitute.

1. Introduction

Indonesia's demand for energy is high and the in-country supplies are not currently sufficient to satisfy these requirements. According to the Oil and Gas Journal, as cited by the U S A Energy Information Administration [1], Indonesia has the equivalent of about 620 billion cubic meters (3.9 billion barrels) of proven oil reserves and 3 trillion cubic meters (97.8 trillion cubic feet) of natural gas. Since 1996, however, Indonesia's total oil production has dropped by 35 percent [1]. Yet 63% of Indonesian energy consumption and economic growth continues to be based on consuming oil [2].

Furthermore, Indonesia is mostly dependent on its own fossil energy supplies in global markets to generate income; 27.2% of the Indonesian government's 2008 budget was generated from taxable and nontaxable revenues derived from in-country supplies of oil, gas, and minerals [3]. At the same time, Indonesia must continually extract or import more oil to satisfy its current oil demand as well as to power new development projects. The rising prices of international

fossil fuel supplies has forced the government of Indonesia to raise fossil fuel prices by 29 percent in March of 2005 and by another 114 percent in October of the same year [4]. This situation means that Indonesia has to explore the production of alternative energy resources to satisfy local in-country demand for energy. Energy consumption in Indonesia is projected to increase by 2.9 percent per year during the next 20 years due to the growth of both its economy and its population [2]. Approximately 40 percent of this increased energy demand is projected to occur in the industrial sector, followed by the residential (29 percent), transportation (28 percent), and commercial (3 percent) sectors [5].

It is challenging for Indonesia to acquire these new supplies of energy because increasing the extraction levels of any energy supply will have to address concerns regarding environmental and social issues. For example, expansion of coal, oil, and gas exploitation is a less viable option because it could seriously threaten the territories and livelihoods of indigenous peoples in Indonesia [6]. Furthermore, there is a strong reluctance to develop and use nuclear energy. Indonesia therefore has few alternative options that would satisfy the energy demand of its growing economy. At the same time, any energy option selected by Indonesia has to simultaneously address: (1) how much greenhouse gases are emitted during the combustion of any selected energy source since Indonesia is ranked as the third highest emitter of GHG due to land use and land use change in forestry; (2) the potential of production of the energy to contribute to local/regional economic revitalization of communities.

Agricultural- and/or forestry-based bioenergy programs are now being considered as viable alternative approaches to produce energy. These resources are abundant in the regions of Indonesia that lack energy security and they can be designed to significantly reduce GHG emissions when they substitute for fossil energy sources. Bioenergy also has the potential to be environmentally sustainable, economically viable, and socially and politically acceptable. Furthermore, most of forest management units are located in remote areas of Indonesia where the electrical grid and fossil fuel supplies are not always available and where it is too expensive to build the infrastructure to deliver the needed energy. This situation has also stifled regional economic development since managers of forest operations and small wood industries (e.g., sawmill and wood working) are finding it difficult to meet their production targets because of fossil fuel shortages. Even local communities and indigenous peoples that collect nonwood products (e.g., rattan, honey, and *Tengkawang*' fruits (*Shorea* spp)) are facing difficulties in transporting their products to markets due to energy shortages.

There are four major strategies available to mitigate carbon emission through forest-based activities: (1) increase forested land area through reforestation; (2) increase the carbon density of existing forests at both the stand and landscape scales; (3) expand the use of forest products that sustainably replace fossil-fuel CO_2 (or carbon) emissions, (4) reduce emissions derived from deforestation and forest degradation [7]. These strategies are in line with most countries' policies regarding their biomass energy programs, that is, energy production and mitigating greenhouse gas (GHG) emissions [8–13]. This being the case, there is a need to determine whether sufficient biomass exists to economically replace fossil fuel use and whether this use will avoid carbon emissions so that it qualifies for carbon or renewable energy credits. With the use of today's technology to efficiently convert forest biomass into biomethanol, the annual amount of forest wastes generated throughout Indonesia has the potential to produce over 40 billion liters of methanol each year [14]. If this higher conversion efficiency potential is possible based on the chemical quality of trees found in Indonesia, this amount of methanol fed into fuel cells would be able to produce sufficient electricity on a continuous basis to power 10,063 million households while significantly reducing Indonesian net carbon emissions (~29.48 Tg of avoided carbon emission [14]).

These country-level estimates suggest that using forest wastes is a viable option for the Indonesia's landscape, nevertheless, these country-level potentials need to be verified at the level of a forest management unit. It is at this level where bioenergy production can be evaluated to determine which parts of forest landscape matrix can be sustainable used to collect forest materials suitable for new energy products. Since forests are not managed at the same intensity across the Indonesia's landscape, forest being intensively managed should be able to generate additional biomass wastes and therefore more alternative energy products. Unmanaged forests may be less suitable for these purposes. Currently, several forest management operations and small forest industries have expressed interest in increasing their energy production potential from their forests. If the development of new energy products from forest wastes is going to become a viable option, however, local forest managers will have to demonstrate that they can collect a sufficient amount of waste materials and still maintain their forest certification status.

Clean energy produced from locally harvested biomass could alleviate these energy shortages and provide alternative economic activity for rural community members living in or adjacent to forests. Converting biomass to methanol and substituting it for fossil-fuel-based energy production is one viable option in locations that generate high biomass waste supplies [8, 15, 16]. Building biofuel production capacity is ideal products to generate in Indonesia because it can be produced in a distributed manner by local community members and can satisfy several different energy needs. For example, it can be readily blended with gasoline and can be distributed to customers without the need to develop additional distribution infrastructures. Hydrogen fuels, on the other hand, would require new engine designs and additional infrastructure that would create the immediate need for large financial investments [17]. As an added incentive, green fuels from cellulosic or lignin-based biomass produce lower emissions of greenhouse gases and atmospheric pollutants when compared to gasoline produced from fossil fuels [17–19].

Recent technological developments in the energy sector (e.g., gasifiers more efficient in converting wet biomass to bio-oils or fuel oils, and hydrogen fuel cells [16, 20–25]) are creating alternative opportunities to produce energy locally to alleviate fuel shortages. Using wood wastes to

produce biofuels rather than using agricultural wastes is ideal because wood has a chemistry that results in higher efficiencies of conversion to biofuels [8]. Although the chemical composition of wood varies among tree species [26], wood is a more efficient and reliable starting material to produce methanol compared to other nonwood biomass sources [27]. Furthermore, extensive areas of forests that exist that need to be managed to remove woody debris wastes and to remove invasive species to restore forest health (e.g., reduce fire risk). Much of this biomass has little economic value today so promoting its conversion to biofuels adds value to forest waste materials and can reduce local "environmental and energy insecurity" [28].

Past technologies to convert biomass into gases or liquid coproducts were not considered economical except when these facilities were large scale and centralized [15, 29]. Large scale facilities are expensive to build. They also face significant distribution challenges due to the need to transport wood from beyond an economically viable transportation network. This is a less viable option for rural communities. Today, development of decentralized facilities that consume local or regional resources [8] is becoming a more viable option due to environmental and human health concerns related to consuming traditional energy supplies, energy security issues, and the higher costs of buying fossil fuels. In fact, local energy production can simultaneously contribute to developing sustainable livelihoods for rural communities, consume abundant local biomass resources to build decentralized energy production systems, stimulate sustainable development, and help to mitigate climate change.

It is important to determine how much additional regional energy can be generated from forests wastes and how this varies across forest management types. The objective of the study is to explore how (1) the amount of forest biomass wastes generated varies between less intensively managed forests (e.g., community-based forest management units) and moderately to intensively managed forests, that is, plantations or managed natural forests, and (2) how much biomethanol can be produced from the available biomass wastes and how much electricity it can generate or contribute to alleviate local transportation fuel demand. This study was not designed to contribute to an Indonesian market and policy-level analysis of forest bioenergy production but to determine the potential for expanding regional energy production and determine how different forest management types influence which forest management units should have their energy capacity developed further.

2. Research and Calculation Methods

2.1. Forest Management Units Types. Most of the woody biomasses harvested in Indonesia are collected from three different forest management types: community-based forest management (CBFM) units with the lowest management inputs, natural production forests (NPF) with intermediate levels of management input, and plantation forests (PF) which receive the highest intensity of management input. Management units selected for this study were all certified as being sustainably managed forests under the aegis of the Indonesian Ecolabelling Institute (LEI) forest certification system. LEI system includes three different forest management certification schemes, namely, NPF, PF, and CBFM certification. Since sustainability of forest management requires that biomass is harvested from a sustainably managed forest (as stated in certificates of their forest performances), this study only includes those forests designated primarily for the production of wood fiber, bioenergy, and/or nonwood forest products, that is, production forests [30].

Although the International Tropical Timber Organization/ITTO [30] divides permanent forest estates into two categories, natural production forest (NPF) and planted forests (PF), this study assessed three forest management types. This study included a category of timber production from forest that is managed by rural and indigenous community members, that is, community-based forest management (CBFM).

Large forest concession holders that manage both NPF and PF control 35.5 million hectares or 71% of the total production forest in Indonesia [31]. Of the total production forests that are managed under the concessionaires system, 26.6 million ha are managed under the natural production forest (NPF) system approach (harvesting is done using a selective cutting system) and the timber harvested is mostly consumed by the plywood industry [31]. Plantation forests (PF) or timber plantation are developed either independently of, or in association with, existing natural forest production concessionaires [32]. Plantation forest management protocols are based on clear cutting practices. These timber supplies are consumed by either the pulp and paper or wood construction industries. Among various definitions, community-based forest management (CBFM) can be defined as a variety of forest resources management practices developed by local community members living in or in the surrounding forest areas [33]. Most CBFM do not apply intensive forest management system practices and typically do not have a written forest management and harvesting plan. The timber harvested is mostly consumed by the sawmill and woodworking industries in the region where the CBFM areas are located.

2.2. Forest Management Units Included in This Study. Forest biomass data were derived from several sources: the forest certification assessment reports conducted under the auspices of Lembaga Ekolabel Indonesia (LEI) and various other reliable sources (e.g., data directly submitted by the certified forest management units). Data were collated and summarized for the six certified forest management units included in this study and are nested in three different forest management types: NPF, PF, and NPF (Figure 1).

For this study, the community managed forests are abbreviated as CBFM-1 and CBFM-2; CBFM-1 manages 1,179 ha of forest land in the Sukoharjo district and CBFM-2 manages 2,434 ha of forest land in the Wonogiri district. Both forests are located in Central Java province. The certified NPF unit number 1 (NPF-1) is located in Rokan Hilir district in Riau province and consists of 90,956 ha of managed forest, and NPF-2 manages 269,660 ha of forest in the Kutai Barat district in East Kalimantan province. The certified PF units

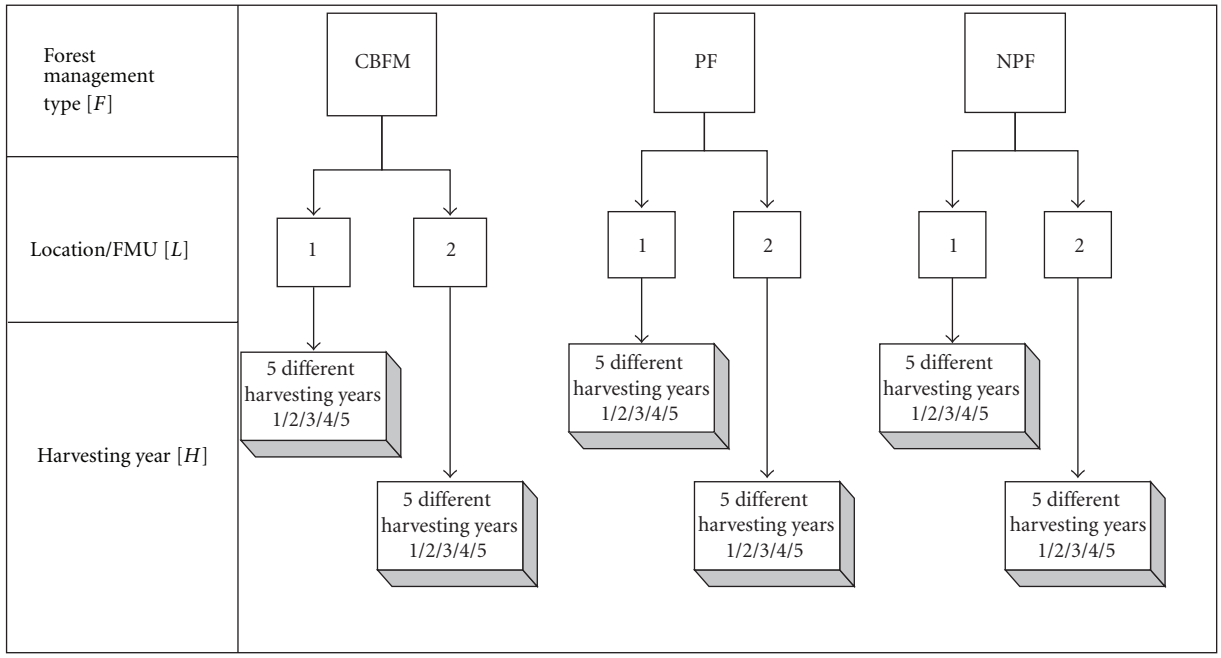

Figure 1: Research design for the forest biomass data collected from the certified forest management units nested in different forest management types and based on five separate years of data collection. Note: CBFM: Community-Based Forest Management; NPF: Natural Production Forest, and; PF: Plantation Forest.

are located in the Kampar district in the Riau province (PF-1) and Tanjung Jabung Timur in the Jambi province (PF-2); PF-1 manages 235,140 ha of forest land and PF-2 manages 293,812 ha of forest lands.

Except for the plantation forests that can be dedicated entirely for energy production (energy farm), not all of the available forest biomass can be used to produce energy because of alternative or competitive uses. Certain forest industries may have a higher rate of return from alternative uses and therefore provide limited opportunities for biomethanol production, for example, teak (*Tectona grandis*) plantations that are managed by CBFM practitioners (forest farmers group) and state-owned companies. For the calculations conducted here, a conservative five percent of aboveground forest biomass was assumed to be available each year from each forest management type; this collection level is based on ecological criteria and represents the annual growth or productivity of a natural forest. Natural production forests management units could generate 22% wastes from their forest operations [34] so the five percent used in this study is a very realistic and conservative figure.

Calculations are based on the output of the energy produced and do not include the inputs since this information is confidential company data and was unavailable for this study. Since waste wood methanol has a default greenhouse gas emissions savings of 94% [35], focusing on the output can be used for comparative purposes to determine how the intensity of management affects the potential amount of energy coproducts that can be produced by each forest management unit.

2.3. Management Unit Level Calculations: Biomass Conversion to Methanol and Coproducts. All calculations were conducted at the forest management unit (FMU) level using information collected at each site. The five-year average aboveground biomass collected at the FMU level was used in the calculations for the quantity of methanol that could be produced from each management unit.

Calculations were scaled up to the FMU level with assumptions of the efficiency of converting a dry metric ton of biomass into methanol [10]. This conversion efficiency was developed for a small-scale mobile facility where methanol (high energy density) is being transported from the forest instead of wood (a high mass density material but of a low energy density). For the purposes of this study, an extraction efficiency of 50% was assumed when converting wood wastes to methanol. The efficiency of methanol production from wood has been reported to vary between 45 to 57% based on the technology and the chemistry of the wood [8, 27, 36]. For this study, all results were based on the same units of measurement, either 1 MWh of electrical energy produced or 1 Mg of dry biomass was used.

The amount of carbon emissions avoided were estimated by determining the amount of energy produced from 1 Mg of dry biomass and then using the estimate of carbon emitted when producing the equivalent amount of energy using a nonrenewable resource. One dry Mg of biomass produces 630 L of biomethanol when the conversion efficiency is 50% based on Perry's Chemical Engineers Handbook [37]. Substituting the biomethanol derived from 1 Mg dry biomass (with extraction efficiencies of 50%) for natural

gas-derived methanol used for electricity production would avoid carbon emissions equivalent to 462 kg carbon. Substituting biomethanol derived from 1 Mg dry biomass (with extraction efficiencies of 50%) for gasoline is substituted would avoid carbon emissions equivalent to 420 kg carbon. In our study, the estimates of carbon emissions avoided are conservative since: (1) waste-wood methanol has a lower CO_2 emissions during cultivation, processing, transport, and distribution compared to other biomass derived fuels [35], and (2) CO_2 emissions from the procurement, shipping, and processing of gasoline and natural gas were not considered.

The carbon emissions avoided were then calculated when using biomethanol as a substitute for gasoline or replacing an energy-equivalent amount of natural gas methanol in fuel cells to produce electricity. In estimating carbon emissions, fuel cells powered by biomethanol were compared to fuel cells using natural gas-methanol since most of the methanol today is derived from natural gas [38]. For scenarios using biomethanol as a gasoline substitute, 100% substitution of gasoline in regular motor vehicles was assumed even though there is a range of methanol/gasoline mixtures in use. Currently, M85, a fuel mixture consisting of 85% methanol mixed with 15% unleaded gasoline, or lower blends are commonly discussed and are already being used in fleet vehicles. Hasegawa et al. [39] mentioned that several hundred methanol vehicles that use neat methanol (M100) were manufactured as low-emission vehicles in Japan.

It was assumed that gasoline (representing fossil fuels) would be substituted by an equal volume of biomethanol even though it is well known that gasoline by volume has more energy produced per equivalent volume of methanol. Many factors will determine the efficiency at which machineries and/or vehicles burn fuels [39, 40]. The total amount of fossil fuels and electricity consumed in: (a) Asia Pulp and Paper (APP) industry and (b) Jambi province were used to calculate possible carbon emissions reduction in this paper. Since many of the district and provincial governments do not publish data on gasoline consumptions and carbon emissions, site specific data at the forest management unit level could not be calculated.

2.4. Statistical Model and Assumptions. The statistical model used in this study was designed to consider that data shown in Table 1 from each FMU as a random factor. The following considerations explain the model: (1) the research does not have any intention to control the experimental population, so randomization happens during the experiment, (2) the list of certified FMUs is published by the Indonesian Ecolabeling Institute (LEI), and (3) although there is a narrow certified FMU population, the research experimental design is still random as they represent an uncontrolled selection from total management units that were available for this research.

In this study, the statistical model was:

$$y_{ijk} = \mu + F_i + (L)_{j(i)} + (e)_{k(ij)}, \quad i = 1,\ldots,3; \quad j = 1,2,\ldots,6; \quad k = 1,2,\ldots,5,\ldots, \tag{1}$$

where y_{ijk} is the amount of aboveground commercial biomass of timber by kth harvesting year in the jth location/FMU in the ith forest management type, μ is the overall mean of aboveground commercial biomass of timber, F_i is the fixed effect of the ith forest management type, $(L)_{j(i)}$ is the random effect of the jth randomly selected location/FMU nested within ith forest management type, $(e)_{k(ij)}$ is the random error, and $(L)_{j(i)}$ are i.i.d. as $N(0, \sigma^2_{L(F)})$, $(e)_{k(ij)}$ is i.i.d. as $N(0, \sigma^2)$, and $(L)_{j(i)}$, $(e)_{k(ij)}$ are mutually independent.

3. Result and Discussion

3.1. Biomass Harvested from CBFM, PF, and NPF. All the data were collected from certified FMUs that are nested in the certified CBFM, PF, and NPF. For each management unit, the average aboveground biomass value for the total commercial harvest of forest biomass was used when calculating the amount of biomethanol that could be produced. The quantity of commercial forest biomass (timber) that was harvested each year within a five-year period (2001–2005) from six certified forest management units (FMUs) can be found in Table 1.

Analysis of variance (ANOVA) indicates that significant differences occurred between the average production of commercial biomass per hectare per year by forest management type (CBFM, PF, and NPF). These data suggest that the highest amount of biomass could be harvested from the PF and the least amount from CBFM.

Based on the statistical calculations, data fulfills the normality assumption of the research. The tail of the normal curve is quite heavy (Figure 2); however, this does not alter the mean of the data but does increase its variances. Since field-collected data are typically not normally distributed, these data need to be transformed (such as log transformation) to correct for data distributional problems or data outliers [41, 42]. For this study, this transformation did provide a reasonable inference when the data varied from the assumptions especially since the data sets were not too large [42]. Data from this study resulted in a linear relationship (Figure 3), but this transformation reduced the variance considerably despite the fact that outliers still existed. Since the transformation applied for the whole data, the distributions are the same as the distributions before the transformation [42].

3.2. Biomethanol to Substitute Fossil Fuels in Electricity Production and Gasoline Consumption. Our calculations suggest that it is worthwhile to convert forest biomass harvested from certified forest management units into biomethanol for use in electricity production and also as a gasoline substitute. However, this potential varied considerably depending on the forest management type being evaluated. Since there are 48 types of community-based forest managements systems in Indonesia [43], this study's data may not represent all the possible types of community-based forest managements units.

Some of the differences in forest management unit results from what are the main products harvested from the forest and the land tenure status of the forested lands (whether the land belongs to the national government or forest farmers).

Table 1: Commercial forest biomass harvested from each certified forest management unit between 2001–2005.

Forest management unit	Harvesting year	Harvested aboveground biomass (Dry)		
		m^3	Mg	Mg/ha
CBFM-1	2001	573	287	1.64
	2002	692	346	1.99
	2003	691	345	1.98
	2004	894	447	2.56
	2005	919	460	2.64
	2001–2005 average	**754**	**377**	**2.16**
CBFM-2	2001	235	118	0.16
	2002	120	60	0.08
	2003	447	224	0.30
	2004	469	234	0.31
	2005	666	333	0.44
	2001–2005 average	**387**	**194**	**0.26**
NPF-1	2001	74,477	37,238	10.74
	2002	41,635	20,818	7.49
	2003	46,664	23,332	6.54
	2004	54,474	27,237	7.80
	2005	62,373	31,186	9.17
	2001–2005 average	**55,925**	**27,962**	**8.35**
NPF-2	2001	123,642	61,821	10.52
	2002	49,332	24,666	3.99
	2003	104,461	52,230	9.99
	2004	75,193	37,597	5.82
	2005	104,010	52,005	10.10
	2001–2005 average	**91,328**	**45,664**	**8.08**
PF-1	2001	1,142,794	571,397	87.69
	2002	943,421	471,711	54.26
	2003	125,599	627,995	56.98
	2004	1,947,206	973,603	45.40
	2005	2,072,905	1,036,453	73.44
	2001–2005 average	**1,246,385**	**736,232**	**63.55**
PF-2	2001	851,104	203,791	37.71
	2002	1,100,960	550,480	40.48
	2003	905,416	422,117	44.01
	2004	1,054,606	532,391	22.87
	2005	1,684,171	842,086	37.33
	2001–2005 average	**1,119,251**	**510,173**	**36.48**

For example, CBFM that grows teak (*Tectona grandis*) on private lands may have different economical consideration than when the forest is managed for subsistence purposes. For this study, data were collected from both CBFM-1 and CBFM-2 which are managed by forest farmers as part of agroforestry systems. Forest farmers manage not only commercial trees, such as teak, mahogany (*Swietenia mahagoni*), acacia (*Acacia auriculiformis*), and rain tree (*Samanea saman*) but also lesser known tree species as well as agricultural plants. Most of forest farmers manage their forests for their long-term benefits, but they also view the forests as instantly cashable bank accounts, such as in *tebang butuh* or "harvesting for needs" approach [44, 45], where forest farmers harvest timber due to immediate family needs for cash. In some areas this approach is changing as commercial interests have now become the main driver for farmers. For example, forest farmers continue to plant trees but now recognize and are even more aware of the true value of their forests [45]. Forest farmers expect to acquire greater economic benefits by becoming certified and combining bioenergy production with traditional forest management practices.

In the community forest management type, harvesting and converting 100% of the annually available timber into liquid fuels using the *tebang butuh* management approach have the potential to produce biomethanol quantities capable of generating sufficient electricity to satisfy the demand of

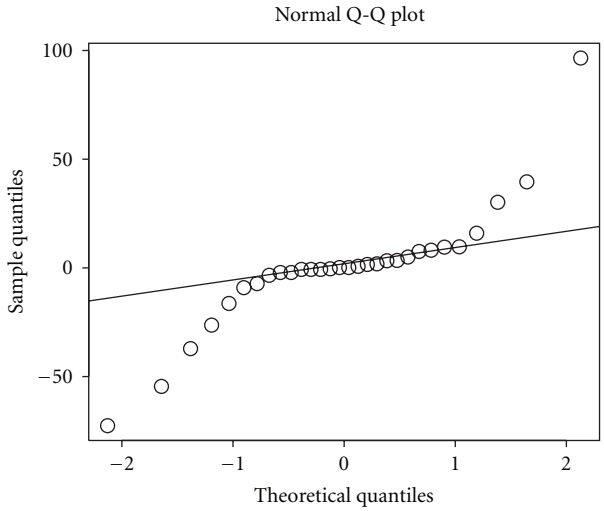

Figure 2: Normal Q-Q Plot: comparing research data to a standard normal population.

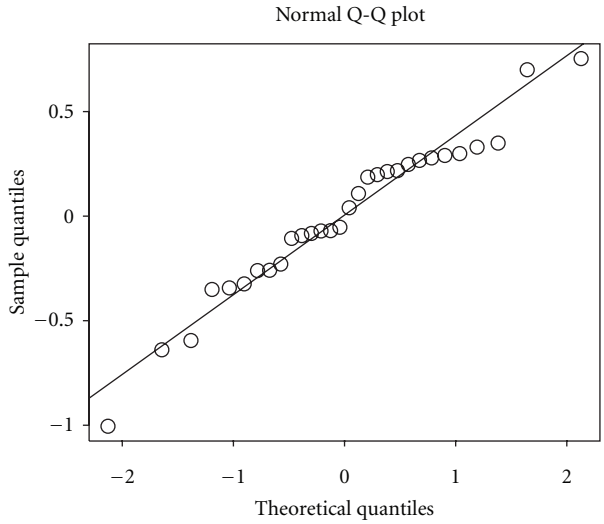

Figure 3: Normal Q-Q plot at logarithmic data.

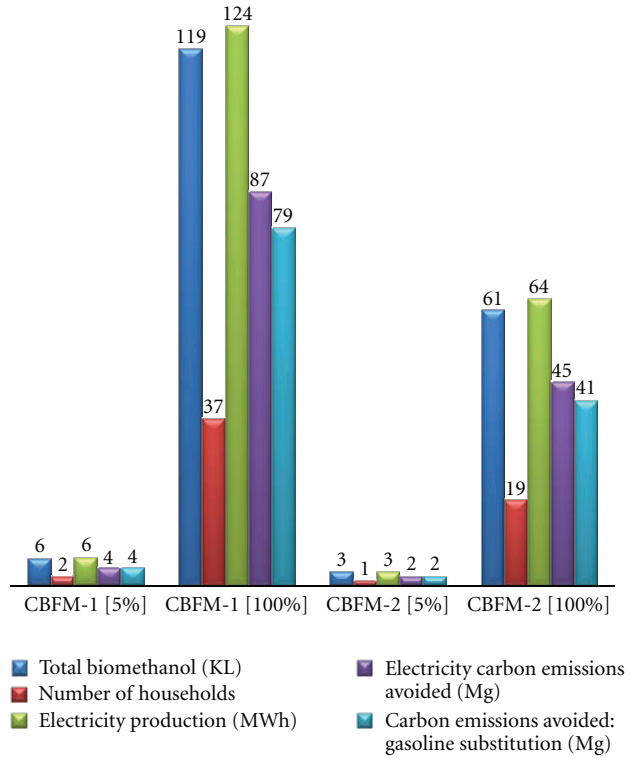

Figure 4: The amount of biomethanol produced and the amount of fossil-resource-derived electricity and gasoline, this amount can potentially replace and avoid carbon emissions when converting 5% or 100% of the annually available biomass collected from certified community managed production forests (CBFM).

19 (CBFM-1) to 27 (CBFM-2) households (Figure 4). The differences in the volume of biomass harvested between both of these management units depended solely on the forest farmers' decision on how much to cut. There is no existing regulation that controls the total quantity of timber harvested from these forested lands. Depending on whether 5% or 100% of the biomass was collected and converted to biomethanol, the biomethanol production potential varied from 3,050–5,938 or 61,009–118,768 liters, respectively (Figure 4). The potential carbon emissions reduction from using biomethanol to produce electricity varied from 2–4 Mg (5% of the biomass harvested) and from 45 to 87 Mg (at 100%). By replacing gasoline as a transportation fuel, the potential reduction in carbon emission varied from 2–4 Mg and from 41–79 at a 5% or a 100% level of biomass harvesting, respectively.

Where biomass availability is scarce because of high fuel-wood demand or where large areas are degraded as a result of past land uses [15, 46], planting fast growing tree species using agroforestry techniques as part of managed reforestation programs may be an effective option to restore these lands while providing socioeconomic benefits and electricity to communities dependent on resource extraction to survive. The villages in Gunung Kidul district, Jogjakarta province as well as in Wonogiri district, Central Java province practice community-based forestry that consists of planting and managing various species of trees. These trees are suitable for use in energy production [26].

Using a decentralized energy planning strategy for the Tumkur district in India, that included a sustainable development scenario, the study has concluded that biomass feedstock harvested from plantations could meet all the electricity needs of the village [47]. The study also stated that the plantation, however, needed a production capacity of 6–8 Mg of biomass per hectare per year, a moderate biomass productivity [47]. This range of biomass production is considerably higher than the production capacity of both the CBFM-1 and CBFM-2 since their average production was 2.16 Mg per hectare per year.

In contrast, this study had much higher forest biomass supplies available from the certified PF-1, PF-2, NPF-1, and NPF-2 forests. In this situation, biomethanol production

Table 2: Total electricity and gasoline consumption at district and provincial levels in Jambi and East Kalimantan (2009).

Name of district/province	Total electricity consumption by households (MWh)		Total electricity consumption at 2009 (MWh)		Gasoline consumption (kiloliters)	
	District level	Provincial level	District level	Provincial level	District level	Province level
Tanjung Jabung Timur, Jambi[a]	13,737	394,759	18,222	643,800	4,876	282,120
Kutai Barat, East Kalimantan[b]	29,832	408,307	32,695	451,330	NA[c]	482,840

[(a)]Total inhabitants at Tanjung Jabung Timur district and Jambi province are 213,781, and 2,834,164, respectively. *Badan Pusat Statistik Jambi 2010 [48].*
[(b)]Total inhabitants at Kutai Barat district and East Kalimantan province are 161,778, and 3,164,800, respectively. *Badan Pusat Statistik Kalimantan Timur 2010 [49].*
[(c)]Not all district level governments published their data annually. The surveys and publications are based on district government consideration and their annual budget plan. Tanjung Jabung Timur and Kuta Barat districts (where two of PF and NPF forest management units located) published more comprehensive data than others.

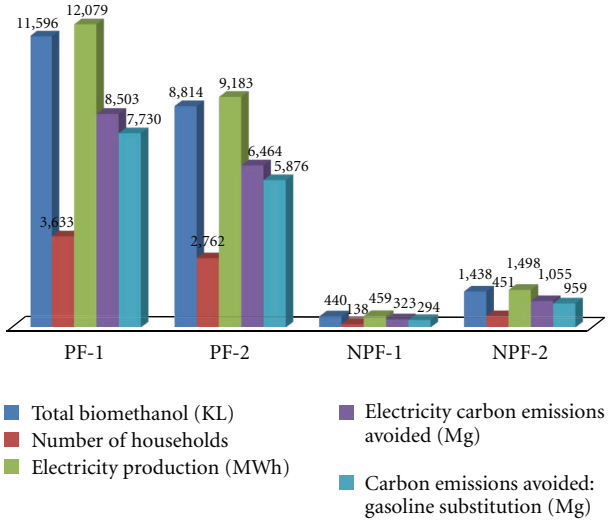

Figure 5: The amount of biomethanol produced and the amount of fossil-resource-derived electricity and gasoline, this amount can potentially replace and avoid carbon emissions when converting 5% of the annually available biomass collected from certified production forests (NPF and PF).

varied from 8,818–11,596 kiloliters in the certified PFs and 440–1,438 KL in the NPFs (Figure 5).

These quantities of biomethanol production would satisfy the electricity demand annually for 2,762–3,633 households using a 1 KW fuel cell powered by biomethanol. The maximum generation of electricity possible would be 12,079 MWh (at PF-1) or, in 2009, that amounted to around 88% and 41% of the total electricity which consumed by households in Tanjung Jabung Timur district and in the Kutai Barat district, respectively (Table 2). This 12,079 MWh electricity production will also satisfy around 66% and 37% of total electricity consumption at the two districts respectively.

If the comparison were made for the total electricity delivered at the provincial level (Table 2), the following summaries would be possible: (1) around 3% of total household demand for electricity could be satisfied at the district level in both of the two provinces (2) around 2-3% total households consumption of electricity could be met at Jambi and East Kalimantan provinces, respectively. In this scenario, the net carbon emissions avoided will vary from 323 to 8,503 Mg when substituting biomethanol for natural gas-methanol in a fuel cell and from 294 to 7,730 Mg when biomethanol is used to supplement gasoline consumption.

If all forest biomasses from both PF-1 and PF-2 were harvested and converted to biomethanol, the following results are possible (from Figure 6): (1) each year 127,867 households could receive electricity continuously using a 1 kW fuel cell. If the average household size in Indonesia is 4.15 persons [50], this efficiency of converting biomass to biomethanol would allow 19% of the households in Jambi province and 248% of Tanjung Jabung Timur district to be supplied with electricity using fuel cells; (2) If biomethanol is substituted for fossil fuels to produce electricity with fuel cells, from 187–375% of the electricity demand in Jambi province could be satisfied from biomass harvested from PF-1. In comparison, PF-2 would satisfy 142–285% of the electricity demand; (3) Collecting all the biomass from either PF-1 or PF-2 and converting it to biomethanol for use as a gasoline substitute would be sufficient to meet all the gasoline consumed in Jambi in 2009; (4) in addition, surplus biomethanol would be available for other uses.

According to *Dewan Nasional Perubahan Iklim*/DNPI or the National Council for Climate Change (NCCC) of Indonesia, Jambi province emitted 57 million Mg of carbon in 2005 and is projected to emit 74 million tons by 2030 [51]. In its published report, Asian Pulp and Paper (APP), a holding company mentioned that their GHG emissions were 6,416,058 Mg CO_2e in 2006 [52]. The same report stated that the company: (1) imported about 2,666 Terra Joule (TJ) of electricity; (2) consumed about 76,204 TJ of fossil fuels at both their stationary and mobile combustion units. Although the overall findings of this report have been criticized as not representing the total carbon footprint of the company [53], they can still be used to compare the magnitude of biomethanol that would be needed by this company for it to significantly decrease its carbon emissions.

In APP case, the amounts of carbon emissions avoided when using biomethanol to produce electricity and as a gasoline substitute are summarized in Figure 7. The highest reductions in carbon emissions occurred when an equivalent amount of biomethanol was used as biofuels to replace fossil fuels (gasoline) by the company. The highest reduction in

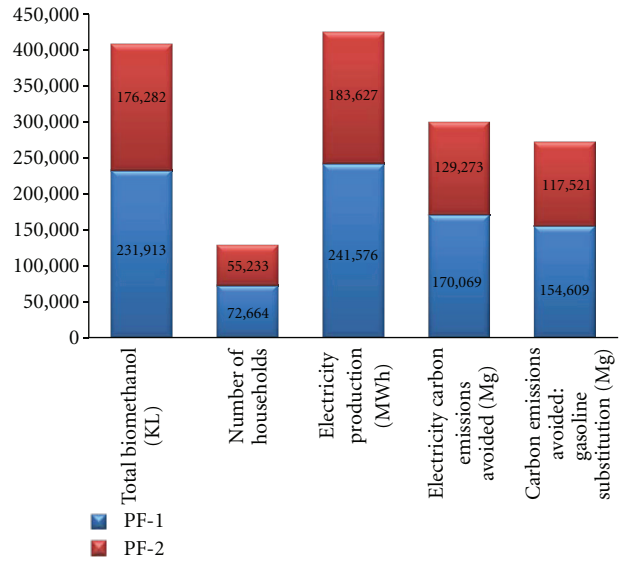

Figure 6: The amount of biomethanol produced and the amount of fossil-resource-derived electricity and gasoline, this amount can potentially replace and avoid carbon emissions when converting 100% of the annually available biomass collected from certified plantation production forests (PF).

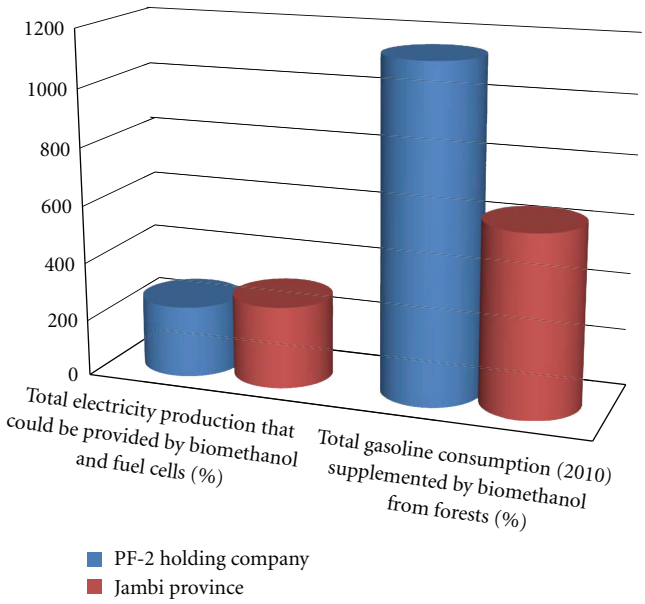

Figure 7: The Proportion APP and Jambi Province Consumption of Gasoline and Electricity Production that can be substituted by biomethanol.

carbon emissions was possible when biomethanol was used to produce electricity from fuel cells in both the company and in Jambi province.

In another scenario where all the biomasses harvested were converted to biomethanol from forests managed by APP the biomethanol would be sufficient to produce enough energy over an 11-year time period (this assumes that the annual consumption is equivalent to 2006 levels). In this situation, the carbon emissions reductions possible from using biomethanol as a substitute for fossil fuels would be: (1) 5 million Mg of carbon emissions avoided being emitted in 2006 either from producing electricity or from replacing gasoline with biomethanol using data from APP, and (2) around 6 million Mg of carbon not emitted in Jambi using 2009 data (Table 3).

Beside the above calculation (as stated in Table 3), Hasegawa et al. [39] suggested to analyze carbon dioxide emissions (instead of carbon emissions) reduction. In their study, Hasegawa et al. [39] calculated the emissions reductions from a fuel cell vehicle (FCV) that consumed M100 (neat biomethanol). For this scenario, driving a FCV reduced carbon dioxide emissions by 1,001 kg for every ton of forest biomass that was used to substitute for fossil fuel use [39]. If the provincial governments of East Kalimantan and Jambi required that all new vehicles use the products from this technology, available biomass from NPF-2 (East Kalimantan) and PF-2 (Jambi) would be able to reduce their carbon dioxide emissions from 45,618 to 559,626 Mg every year, respectively.

Using wood to produce biofuels has not received as much attention as the use of agricultural crops or grasses. This is a result of economic analyses conducted during the early 1990's that indicated that the conversion of wood biomass to methanol was more expensive than using natural gas as a feedstock [22, 54]. However, several new factors are suggesting that the past economic analyses are less relevant in today's landscape. Biomethanol production is now competitive with methanol production from natural gas because of the economic externalities of environmental problems that include [55–57], for example: (1) the costs of forest fires due to an abundance of over-stocked forests that create high fire risks; (2) greenhouse gas emissions from using fossil fuels; (3) the societal costs of rural communities with high unemployment and insecure resource extraction environments; (4) the development of gasifiers that efficiently convert wood with up to 40% moisture contents; (5) the commercial availability of "turn-key" fuel cells running on methanol; (6) subsidies/incentives for generating energy from renewable resources; (7) the decline of oil and gas reserves in several countries; (8) the need to improve the social, economic, and ecological values derived from forest, particularly production forests.

Those factors together now make wood a competitive alternative to use in producing energy and will provide a greater diversity of economic values to forests (e.g., clean energy, "green credits," "green electricity") [58, 59]. Emissions trading and green certificates (i.e., market-based mechanisms enforced to curb greenhouse gas emissions and increase electricity production from renewable energy resources) will also increase the competitiveness and markets for biofuels compared to fossil fuels [60]. Although technologies to produce bioethanol and biomethanol from lignocellulosic biomass are still under development, according to Hasegawa et al. [39], the biomethanol production process was revealed as being preferable to the bioethanol process in terms of energy yield, carbon conversion, and the environmental burden.

Table 3: Proportion of C emissions avoided by substituting electricity generated from fuel cells using biomethanol in place of electricity generated from fossil fuels and by substituting biomethanol for gasoline consumed in transportation fuels. Assumptions: timber is converted into biomethanol at a 50% conversion efficiency.

	C emissions avoided by substituting biomethanol and fuel cells to produce electricity relative to total produced (per-mil)	Carbon emissions avoided by substituting biomethanol for gasoline relatively to total produced (per-mil)
APP	0.55	0.50
Jambi province	0.61	0.59

Forest concessionaires and CBFM practitioners are willing to consider planting-specific trees or simply use forest residues for bioenergy. Since the market for woody biomass for bioenergy is not yet available, particularly for CBFM and small wood industry practitioners, managing forests to produce biomass for bioenergy programs has not been considered economically viable. Additionally, there is no evidence to suggest that the economics of biofuels industry are likely to change in the foreseeable future unless the government of Indonesia reevaluates its biofuel plan and increases transparency in the development of biofuels for energy security [61].

Two principles are apparently crucial for successfully developing bioenergy, namely, flexibility (the right level of devolution depends on the resource stake and negotiation with local stakeholders) and lessons learned from projects being implemented at the local level [62]. Several pilot projects at various forest management types and locations may provide a clearer picture about how bioenergy may affect energy security at the local level, and how it will restore forest health as well as its potential to create new businesses and jobs for local people.

4. Concluding Remark

Adopting forest bioenergy systems is a logical solution to address the problems of reducing carbon emissions while satisfying local energy demands and developing local economies. New technology provides better options to transform forest biomass into biomethanol and subsequently using it to generate electricity or as a supplement or substitute for fossil-based transportation fuels. This study demonstrates that a significant amount of biomethanol can be produced from a certified (sustainably managed) plantation forest, particularly if all harvested biomass is dedicated for bioenergy production (energy farms). In addition, bioenergy has the potential to supply other energy requiring demands, for example, forest base camp, small industries (not necessarily related to forestry), and the needs of local communities. This form of energy production should be developed to satisfy the existing demand in most of the remote areas in Indonesia, particularly when the distribution of on-grid electricity and fossil fuels (for both producing electricity and transportation fuels) are not always available. In Indonesia, energy distribution is challenging for several reasons, for example, fuel prices, quota systems, weather, broken bridges, and land erosion. This means that many locations do not receive sufficient energy to satisfy the local demand or needs of the industries located in these areas.

Developing mobile biomethanol production systems, which could be more easily moved to forest harvesting areas or to other areas where biomass is available, would keep biomethanol production sustainable, particularly in CBFM areas. Managing forests under the sustainable rubric and/or being certified under a sustainable forest management protocol may be a necessary condition to make sure that any biomass harvested from the production forest areas does fulfill the minimum requirements capable of sustaining the function of the social, economical, and environmental aspects of the forest.

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Research Article

Wood Volume Production and Use of 10 Woody Species in Semiarid Zones of Northeastern Mexico

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A research strategy was established to analyze the structure of timber trees in terms of forest productivity (volume and wood density) of 10 species. The native species *Acacia farnesiana, Acacia schaffneri*, *Bumelia celastrina*, *Cercidium macrun*, *Condalia hookeri*, *Ebenopsis ebano*, *Helietta parvifolia*, and *Prosopis laevigata* and the exotic species *Eucalyptus camaldulensis* and *Leucaena leucocephala* were chosen due to their ecological and economic importance to the rural villages of northeastern Mexico. Measurements of different growth parameters and volume of trees were evaluated. The introduced species *E. camaldulensis* and *L. leucocephala* showed the best performance in wood volume production per tree and per hectare when compared to the native species. Likewise, among the native species, *E. ebano*, *P. laevigata*, *C. hookeri*, and *A. farnesiana* tended to show better characteristics in terms of wood volume production in comparison to *H. parvifolia*, *A. schaffneri*, *C. macrum*, and *B. celastrina*. Results showed a high diversity on the properties studied. The high biomass produced by most of the species considered in this study revealed their great energetic potential when used as wood and firewood or vegetal charcoal.

1. Introduction

Forest resources of Mexico rank third in importance in Latin America, covering more than 0.6 million km^2, 32.75% of the country area [1]. Eight different vegetation types have been described from northeastern Mexico. Among them, thornscrubs (low forest) are widely distributed under arid and semiarid conditions and also occurring in the high-altitude plateau. Seventy percent of this type of vegetation is located in areas suitable for rain-fed cropping and the rest in tropical and subtropical lowlands. Today all forest areas in Mexico cover less than a fifth of the national territory over an estimated area of less than 34 million ha with temperate and tropical lowland forests [2, 3]. In northeastern Mexico the semiarid thornscrub vegetation extends over an area of about 20 million ha where 60 to 80 shrubs and tree species are found, some used by people living in the rural areas for either agriculture, livestock, or forest harvesting [4]. The obtained wood is mainly used for furniture, wagons, tool handles, and different kitchen utensils for rural households, as well as for firewood or charcoal [5–7]. A great number of studies regarding thornscrubs have been reported with frequent topics such as description of flowering patterns, germination rates, and fruit production as well as ecological interactions between microclimatic conditions, water relations, soil modification, and nitrogen fixation [8, 9]. Concerning forestry management, the topics included are seed collecting and scarification, germination, pests and diseases, pruning, and species selection. A great number of studies on thornscrub have been reported, but a complete analysis of wood properties has been carried out for only a few species [10, 11]. Thus, the main objective of the present research is to determine the forest potential of thornscrubs in terms of the physical properties of the wood of 10 timber species of major importance in the ecology and the economy of the arid and semiarid regions of northeastern Mexico and to establish a basis for

better utilization of these species. Most of these species have a high atmospheric nitrogen fixation capacity, fast growth, shooting capacity, wood and firewood production capacity of high caloric value, and the capacity to grow successfully under a wide range of conditions [12, 13].

2. Material and Methods

2.1. Description of the Study Area. The experimental area is situated on a plain region at 400–600 m altitude in the piedmont of the Sierra Madre Oriental in Mexico (24° 47″ north latitude and 99° 32″ west longitude). All the area is covered by the typical semiarid thornscrub dominated by woody plants which support cattle production and crops. The regional climate in the scheme of Köppen modified by García [14] is defined as semiarid and subhumid [(A) C (Wo)] with two rainy seasons (summer and autumn) and a dry spell between November and April. Mean annual precipitation is 780 mm [15]. The month with the largest mean rainfall is September (180–200 mm), and the lowest monthly registration occurs in December and January (15–20 mm). Average number of days with rain precipitation per year is 85 ± 15. About half of these days show precipitation amounts of <5 mm, mainly related to thunderstorms resulting from deep convection by midlatitude disturbances [16]. Cold-front systems generate most of the winter rainfall, accounting for <10% of the long-term annual average. Potential evapotranspiration estimated by the Thornthwaite method is −1150 mm [17]. The mean annual temperature is 22.3°C with a large difference between winter and summer (abs. min. 12°C, abs. max. 45°C) and even within the same month. Hail and frosts usually occur each year even after the beginning of the growing season in March. The water budget is unbalanced. The ratio of precipitation to free evaporation is 0.48 and precipitation to potential evaporation is 0.62.

Most soils of the region are of rocky type of Upper Cretaceous rich in calcite and dolomite. The dominant soils are deep, dark grey, lime-clay vertisols which are the result of alluvial and colluvial processes [18]. They are characterized by high clay and calcium carbonate content (pH 7.0–8.0) and low organic matter content. Analysis of major nutrients reveals phosphorus and nitrogen deficiencies. Nitrogen is very volatile in the prevailing climate, and it is apparently lost when the vegetation is cleared from sites with diverse species of woody legumes, leaving the soil exposed to alternating conditions of heavy rain and extreme isolation. Such soils can be 3 m deep or more and are preferred for agricultural seepage. Underground water is hard but nonsaline.

Most plant species overlap vertically from 0.5 to 6.0 m [19, 20], and horizontally average distance between shrubby stems is 30 cm while mean crown radius is 47 cm, resulting in a mean overlapping radius of 17 cm. Average open space between shrub canopies is 10 cm.

2.2. Species and Sample Trees. The 10 timber species used for this research were selected from those most preferred and used by the rural population because of their availability, high wood volume as timber for construction natural durability, and good construction quality [10, 21].

Those harvested trees for high-quality craftsmanship were selected after their combination of beauty, working properties, and stability. Thus, 10 native and introduced species were considered.

Table 1 shows information about the name, family, and the wood characteristics of each of these species. Eight of the species used in the experiment are native to arid and semiarid zones in Mexico and adjacent USA territories. *Eucalyptus camaldulensis* and *Leucaena leucocephala* were also included in this investigation due to their importance as a naturalized species in the region.

The area of study covered 2,000 ha rich in wood arboreal and shrub vegetation with a density of 1,800 to 2,500 plants ha^{-1} according to the forest inventory carried out by Heiseke and Foroughbakhch [22]. Twenty plants from each of the eight native species considered as arboreal representatives of the local vegetation were selected through a stratified and random sampling. A previous growth ring count study [22] revealed that trees are currently 35 to 40 years old in average. For the naturalized wood species in this area (*L. leucocephala* and *E. camaldulensis*), plantations with representative trees around 35 years old were located next to the adjacent natural vegetation, and 20 individuals for each of the two species were selected at random. Results on the growth and yield parameters of native plants growing in nature were compared to the same parameters obtained in plantations of the same species in a monoculture system of about 30 years old. Thus, the experiment was evaluated on the basis of measurements of the following variables taken on 20 individuals per species: height increment (using a height pole), basal diameter BD (at 10 cm above the ground, using a diameter tape), diameter at breast height DBH (at 1.38 m above the ground, using a tree caliper), crown surface area (C) which was determined by projecting the edges of the crown to the ground and measuring the length from edge to edge through the crown center along the North-South axis ($D1$) and East-West axis ($D2$) to enter the obtained values in the formula $C = [(D1 + D2)/4]2 * \pi$ [23], and firewood volume. All these parameters were estimated based in the age of the trees. Firewood volume (V) was estimated by using the Smalian equation [24] based on each yield $plant^{-1}$ $species^{-1}$ (standing without cutting the tree) taking into account all of those trunks with a length of 1.8 m or higher and 0.1 m in diameter in both upper and lower extremes or those individuals with diameter values at breast height equal to or greater than 0.1 m, as it is considered a suitable commercial size for constructions in the rural areas in Mexico:

$$V = \frac{\pi}{4[(D_1^2 + D_2^2)/2]} L, \tag{1}$$

where D_1 (m) and D_2 (m) are the diameters in both upper and lower extremes of the pole and L is the pole length (m).

2.3. Physical Properties (Wood Density). The material for physical and mechanical assays was obtained from heartwood in the bole zone, 0.3 m to 1.3 m above the tree base, according to Panshin and Zeeuw [31]. The basic densities of the ten species were measured by testing 30 wood specimens

Table 1: Outstanding characteristics of the 10 woody plant species selected for study.

Family	Species	Characteristics and life form	Uses
Leguminosae (Mimosoideae)	*Acacia farnesiana* (L.) Willd	Shrubs/trees 3–6 (10) m, 10–20 cm diameter, early invader of pastures, good natural resistance of wood, distributed throughout semiarid zones of Mexico, southern USA, and Central and South America	Firewood, wood, charcoal, posts, construction, and honey (Flowers)
Leguminosae (Fabaceae)	*Acacia schaffneri* var. *schaffneri* (S. Watson) F. J. Herm.	Tree 4–6 m height, 20–25 cm diameter, covered with velvety or stiff hair. Distribution: northern Mexico and south Texas, USA	Firewood, wood hard and heavy, charcoal, construction, forage (pods)
Sapotaceae	*Bumelia celastrina* Kunth	Small, thorny tree 8–10 (12 m) height, 30–40 cm diameter, tall shrub of the Rio Grande Plains, hardwood with a very good natural resistance	Wood, firewood, post, and shade for animal
Rhamnaceae	*Condalia hookeri* M. C. Johnst.	Small spiny tree 6–9 m height, 30–40 cm diameter that forms thickets and chaparral. Distribution: northeastern, northwestern and Baja California, Mexico	Wood, firewood, forage, and food
Leguminosae (Caesalpiniaceae)	*Cercidium macrum* Johnst.	Small tree 3–6 m tall, 15–20 cm diameters, bark smooth, green, branches slightly zigzagging and armed with solitary spines	Firewood, post, forage (goat)
Leguminosae	*Ebenopsis ebano* (Berl.) Barneby and Grimes	Tree 3–10 (15) m, 50 (120) cm diameter, hardwood, dark with a very good natural resistance. Distributed in northern Mexico, southwestern Texas, in the lowland	Firewood, charcoal, wood (furniture), shade for animal protection, and food (fruit and pods)
Myrtaceae	*Eucalyptus camaldulensis* Dehnh. (river red gum)	Tall fast growing tree 15 to 45 m; basal diameter over 2 m with flaky or smooth bark ranging in color from white and grey to red-brown which is shed in long ribbons. The tree has a large, dense crown. The base of the trunk can be covered with rough, reddish-brown bark. The tree grows straight under favorable conditions but can develop twisted branches in drier conditions	Stumps, fence posts and wood sleepers, craft furniture, timber for wood, firewood, charcoal, paper pulp, ornamental, and medicinal
Rutaceae	*Helietta parvifolia* (Gray) Benth.	Large shrub or small tree 2–10 (12) m, early invader in calcareous soils, deep root system with very high natural resistance of wood, is distributed in northeastern Mexico and Texas, USA	Poles, shelves, wood, charcoal, medicinal
Leguminosae	*Leucaena leucocephala* (Lam.) de Wit. Naturalized species to the region	Native from Yucatan Peninsula, 5–8 (20) m thick, half dense wood, average natural resistance. It is distributed in southern Mexico and Central America	Firewood, charcoal, shelves, rural construction, green manure, windbreak, nitrogen-fixing
Leguminosae	*Prosopis laevigata* (Humb. et Bonpl.) M. C. Johnst.	Tree 5–10 (15) m, 50 (80) cm diameter, dense wood with a high natural resistance. It is distributed in northeastern Mexico, especially in the mountain scrub, and southern Texas	Poles, shelves, wood, charcoal, construction, and shade for edible pastures

Sources: [25–30].

per species with dimensions $10 \times 20 \times 20$ mm, corresponding to longitudinal $\times$ radial $\times$ tangential directions, respectively. Volume was measured on green condition of the specimens (specimens obtained immediately after felling the trees). Dry weight was obtained after drying the specimens at $103 \pm 3^{\circ}$C until constant weight was reached. The basic density was calculated by the following formula:

$$\rho^{B} = \frac{m_{\text{dry}}}{v_{g}}, \tag{2}$$

where ρ^{B} = Basic density (g cm^{-3}), m_{dry} = mass (g) on oven dry condition (103°C) and v_{g} = green volume (cm^{3}).

2.4. Statistical Analysis. Growth parameters and volume measurements were converted to amounts per each woody tree. The mean values and standard errors were calculated for each species. Regression models were applied to determine the R^{2} (coefficient of determination) between crown area and the increment parameters (height and basal diameter) [32]. Contrast tests (Duncan's multiple-range test—DMRT) were applied to compare the obtained mean values [33] with

Table 2: Duncan's multiple-range test (DMRT) for height, basal diameter (BD), and diameter at breast height (DBH) parameters. Coefficient of determination (R^2) was calculated between crown area and height and between crown area and basal diameter.

Species	Average dimension (m)			R^2 between crown and	
	Height	BD	DBH	Height	BD
Acacia farnesiana	4.8^{G*}	0.41^{CD}	0.36^{C}	0.61	0.75
Acacia schaffneri	4.1^{H}	0.30^{G}	0.27^{F}	0.58	0.54
Bumelia celastrina	5.2^{F}	0.33^{EF}	0.31^{E}	0.72	0.64
Cercidium macrum	6.8^{D}	0.36^{E}	0.30^{E}	0.81	0.85
Condalia hookeri	6.1^{E}	0.42^{CD}	0.37^{CD}	0.52	0.57
Ebenopsis ebano	7.4^{C}	0.44^{C}	0.39^{C}	0.73	0.78
Eucalyptus camaldulensis	15.6^{A}	0.58^{A}	0.52^{A}	0.70	0.64
Helietta parvifolia	5.0^{F}	0.26^{GH}	0.23^{G}	0.64	0.57
Leucaena leucocephala	6.5^{D}	0.32^{EF}	0.25^{F}	0.62	0.51
Prosopis laevigata	8.7^{B}	0.51^{AB}	0.48^{B}	0.71	0.63

* Values in columns with different superscripts differ ($P < 0.05$).

the statistical package SPSS (v. 15.0). Least significant differences were calculated at 5% probability level (LSD 0.05) according to Zar [32].

3. Results and Discussion

3.1. Height, Diameter, and Crown Development. The height and diameter parameters are proper indicators of the site conditions (soil and climate) although they are also dependent on factors such as interspecific competition, standard density, and climatic conditions. The latter factor seems to determine the growth and development of the evaluated species in northeastern Mexico. In the present investigation the introduced woody species (in monoculture systems) showed an adequate height, diameter at breast height, and basal diameter increments in comparison to the native species in northeastern Mexico (Table 2).

Eucalyptus camaldulensis and *Leucaena leucocephala*, naturalized species with an average height of 15.6 and 6.5 m, respectively, and 0.52 m and 0.25 m of BD increment, showed both a remarkable and fastest growth rate in addition to a particularly high drought resistance even though their individuals were more sensitive to low temperatures during winter and at the beginning of the growing season. However, their sensitivity to low temperatures does not limit their use as a forest tree while their rapid growth makes them ideal for forestry and agroforestry purposes.

Prosopis laevigata (8.7 m in height and 0.51 m in BD), *Ebenopsis ebano* (7.4 m in height, 0.44 m in BD), *Cercidium macrum* (6.8 m in height and 0.36 m in BD), and *Condalia hookeri* (6.1 m in height and 0.42 m in BD) showed high growth potential, although to a lesser extent than *Eucalyptus* camaldulensis and *Leucaena leucocephala* and in general terms did not suffer significant reductions in height due to environmental causes. *Acacia farnesiana* (4.8 m), *Acacia schaffneri* (4.1 m), *Bumelia celastrina* (5.2 m), and *Helietta parvifolia* (5.0 m) constitute a special group of species and showed an intermediate growth rate between these two groups.

Since most of the species employed in this study developed a broad disperse canopy, the stand density varied among species as the trees matured. The high plant density corresponding to the thornscrub of northeastern Mexico (over 2,500 plants ha^{-1}) and the surface available (between trees) in the natural vegetation notably influenced the growth in height and diameter of all species.

Under normal conditions, wood and firewood volume production is a function of height and crown size in arborescent dicotyledonous species in which the lateral branches grow more quickly than the central apex. This growth habit gives rise to a broad disperse canopy, especially in poor or dry sites [34].

Cercidium macrum ($R^2 = 0.85$), *Ebenopsis ebano* ($R^2 = 0.78$), *Acacia farnesiana* ($R^2 = 0.75$), and *Prosopis laevigata* ($R^2 = 0.71$) produced a broad crown which promote their ability to develop a large basal diameter. Data suggest that these species are more capable to develop properly in cleared sites along their natural distribution areas than other native and introduced woody plants. This is an important consideration for forestry and silvicultural management in the Tamaulipan thornscrub. Aggressive crown expansion of native species may inhibit the growth of slow-growing valuable wood-producing trees in mixed stands if species have heterogeneous growth rates.

The analysis of the development and environmental responses of each tree species using commonly accepted criteria, such as survivorship and growth in height, diameter, and projected foliage cover, suggest that each species has unique aspects of growth potential. The relationship between variables helps to highlight these characteristics. It has been observed that the growth rate of the ten species is very different in semiarid zones of northeastern Mexico. Heiseke and Foroughbakhch [22] obtained a mean annual diameter increment (at breast height) of 0.2–0.4 cm $year^{-1}$ and a height increment of 13–24 cm $year^{-1}$ for 296 woody native species. The data are the means for approximately 30 species, including most of native species grown in natural vegetation.

3.2. Wood Volume Determination. The high biomass production of most species is important not only to the production of the shoots as pasture for the animals but also as an energetic source in production of posts, firewood, and other

Table 3: Comparison between wood volume production (m^3 $tree^{-1}$) of ten wood species in the natural vegetation and monoculture systems in a semiarid region of Mexico.

Species	Firewood volume per tree in		Monoculture systems	
	Natural vegetation	Monoculture systems	Firewood volume ha^{-1}	Density ha^{-1}
Acacia farnesiana	0.011585^{D*}	0.014715^{F}	29.43^{EF}	2300
Acacia schaffneri	0.010342^{E}	0.012155^{G}	21.88^{H}	2000
Bumelia celastrina	0.011103^{D}	0.010640^{H}	21.28^{H}	1850
Cercidium macrum	0.012231^{D}	0.011527^{G}	25.36^{G}	2000
Condalia hookeri	0.015245^{B}	0.018091^{DE}	31.66^{E}	1850
Ebenopsis ebano	0.020349^{A}	0.026618^{B}	43.92^{C}	1850
Eucalyptus camaldulensis	—	0.083642^{A}	58.54^{A}	700
Helietta parvifolia	0.014635^{BC}	0.019160^{D}	28.74^{EF}	1850
Leucaena leucocephala	—	0.024367^{C}	48.73^{B}	2000
Prosopis laevigata	0.020788^{A}	0.027553^{B}	41.33^{CD}	1750

* Values in columns with different superscripts differ ($P < 0.05$).

products. The results of the harvested firewood yield volume of 10 native and naturalized species (Table 3) in natural and monoculture vegetation of northeastern Mexico indicated a higher production in forest biomass. Data on volume indicated that *Eucalyptus camaldulensis* ($0.083642\ m^3$ $plant^{-1}$ and $58.54\ m^3\ ha^{-1}$), *Leucaena leucocephala* ($0.024367\ m^3$ $plant^{-1}$ and $48.73\ m^3$ ha^{-1}), *Prosopis laevigata* ($0.020788\ m^3$), and *Ebenopsis ebano* ($0.020349\ m^3$) demonstrated a high production per tree in natural vegetation, with an average population density of woody tree species between 700 (introduced species in plantation) and 1800 plant ha^{-1} (native species). Results indicate that the biomass production is high for most of the evaluated species compared to the native species as *Acacia schaffneri* ($0.010342\ m^3$), *Bumelia celastrina* ($0.011103\ m^3$), *Acacia farnesiana* ($0.011585\ m^3$), and *Cercidium macrum* ($0.012231\ m^3$ $plant^{-1}$) thereby indicating a quick growth of these species both in height and diameter.

In general terms, the production of firewood and timber by native plant species growing in nature is well below the values obtained for the same species under plantation in monoculture systems. This difference is attributed to the high density of plants (more than 2,500 plants ha^{-1}), the interspecific competition, and the presence of species such as *Helietta parvifolia* with allelopathic characteristics. The fuelwood situation in developing countries can be improved by planting more trees and improving the management practices of the existing forest resources [35]. In the arid and semiarid zones of northeastern Mexico, firewood planting can use species with short boles, crooked trunk, or wood that warps or splits as it dries. These features are not as detrimental to fuelwood use as to timber production nor is stem size. In simple cook stoves, for example, branches as small as 4 or 5 cm in diameter may be ideal. Thus a shrub may prove satisfactory for village fuelwood silviculture if it grows fast and produces a dense wood that burns with intense heat [36].

Indiscriminate wood and firewood collection is currently one of the main causes of reduction of native vegetation in northeastern Mexico. Intensive plantations with native woody species on accessible sites can help to relieve this pressure on natural forests by supplying a large share of the needed firewood more conveniently.

3.3. Physical Properties of Woody Plants. Density defined as the mass per unit volume is an accurate indicator regarding wood resistance of wood and the amount of cell wall substance. Thus, there should be a strong correlation between the basic density and the mechanical properties [31, 37, 38]. The basic density of the ten species from thornscrub is presented in Table 4.

Basic density from the tree species was classified according to the 10-type classification system developed by Panshin and Zeeuw [31]. Table 4 shows the five classes obtained. *Leucaena leucocephala* and *Eucalyptus camaldulensis* (6th class) with 0.42–0.50 $g\ cm^{-3}$ (average basic density = $0.47 \pm 0.05\ g\ cm^{-3}$). *Cercidium macrum* (7th class) with $0.55 \pm 0.01\ g\ cm^{-3}$, the only species in this group. A density value of 0.54 from plantations for *L. leucocephala* was reported [39]. Two species on class 8th (0.60–0.72 $g\ cm^{-3}$) were found: *Bumelia celastrina* ($0.64 \pm 0.03\ g\ cm^{-3}$) and *Acacia farnesiana* ($0.65 \pm 0.02\ g\ cm^{-3}$). On class 9th were *Prosopis laevigata* ($0.75 \pm 0.04\ g\ cm^{-3}$), *Acacia schaffneri* ($0.79 \pm 0.05\ g\ cm^{-3}$), and *Helietta parvifolia* ($0.82 \pm 0.03\ g\ cm^{-3}$). Class 10th stands for species with a density higher than $0.86\ g\ cm^{-3}$; the only two species on this class were *Ebenopsis ebano* ($0.86 \pm 0.08\ g\ cm^{-3}$) and *Condalia hookeri* ($0.93\ g\ cm^{-3}$). According to the basic densities detected on this research, the management of thornscrub species should be focused in promoting their industrial use, especially those from classes from 7 to 9. However, the least dense species as *Leucaena leucocephala* and *E. camaldulensis* could be integrated on multipurpose plantations for biomass production.

Mechanical properties are used to describe the wood strength and the ability of the wood to resist applied or external forces [40]. Elasticity is defined as the property which enables a loaded material to recover its original form after the load is removed; if the load is greater than a certain value,

Table 4: Physical properties (density g cm^{-3}) of ten timber species of northeastern Mexico.

Species	Min.	Average	Max.	STD	CV
Acacia farnesiana	0.61	0.65	0.69	0.02	3.13
Acacia schaffneri	0.65	0.79	0.88	0.06	7.50
Bumelia celastrina	0.50	0.64	0.70	0.04	5.98
Cercidium macrum	0.53	0.55	0.58	0.02	2.82
Condalia hookeri	0.76	0.93	1.06	0.07	8.01
Ebenopsis ebano	0.70	0.87	1.00	0.08	9.60
Eucalyptus camaldulensis	0.49	0.55	0.61	0.09	10.45
Helietta parvifolia	0.77	0.83	0.89	0.04	4.44
Leucaena leucocephala	0.41	0.48	0.57	0.06	11.51
Prosopis laevigata	0.60	0.76	0.82	0.04	5.48

the material will display a plastic deformity or even failure. The elasticity and density properties are fundamental in determining the quality of wood [41].

4. Conclusions

A major need for the semiarid forest of northeastern Mexico is the rehabilitation of those marginal lands which have been highly degraded, compacted, and presently eroded by inadequate forestry and agroforestry activities. On less productive soils, forestry with a pastoral component should be established, especially in places with native vegetation, which is under severe pressure due to wood exploitation and overgrazing. In this sense, a structural analysis on woody trees in terms of growth and forest productivity (volume and density of wood) of ten species of ecological importance to the rural population and regional industry in northeastern Mexico was made.

Growth rates and wood volume of *Eucalyptus camaldulensis* and *Leucaena leucocephala* as exotics species were clearly superior to all other species and showed the highest yield under the soil and climate of thornscrubs of northeastern Mexico; thus, these species have the potentiality to become important for fuelwood and forestry activity for the region. *Prosopis laevigata*, *Ebenopsis ebano*, and *Condalia hookeri* showed characteristics of woody species and a strong capacity for precocious canopy expansion. *Helietta parvifolia* and in a lesser extend *Bumelia celastrina* share similar characteristics.

Acacia farnesiana and *Acacia schaffneri* are exploited for multiple purposes and should be considered for future planting in forestry and silvicultural systems. *Helietta parvifolia* and *Condalia hookeri* are considered important fuelwood sources, but detailed studies are required because these species are an important timber resource in the Tamaulipan thornscrub providing the rural community with hard and durable posts for fences and construction. The rest of the species showed good growth and a high forest potential playing an important role in the diversification of silvicultural activities and management programs in native areas.

Results on the physical and mechanical properties of these ten species from thornscrub show noteworthy values on several woody species, for example, basic density for *Condalia hookeri*, *Ebenopsis ebano*, and *Helietta parvifolia*, high modulus elasticity, and rupture for *Acacia schaffneri*, *Ebenopsis ebano*, and *Helietta parvifolia*. Grouping species on density classes allow us to find species with similar characteristics that could be used together. This grouping may apply for several tree species growing in the thornscrub with similar density values, for example, between species on classes II and III, to be used for similar purposes.

There is obviously a great interest for a larger use of leguminous trees for wood volume, firewood, and shade. Among the main reasons is the need for reforestation with trees that restore soil fertility (leguminous species) while binding the soil with their roots and allowing better water infiltration. The general methodology applied in this research gave positive results that could be used to develop strategy actions in forest programs (reforestation and rehabilitation of degraded ecosystems) with proper management plans for timber species in order to preserve plant communities of semiarid areas of Mexico.

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Research Article

Biomass, Carbon and Nitrogen Distribution in Living Woody Plant Parts of *Robinia pseudoacacia* L. Growing on Reclamation Sites in the Mining Region of Lower Lusatia (Northeast Germany)

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In the lignite mining region of Lower Lusatia (NE-Germany), *Robinia pseudoacacia* L. is an increasingly popular tree for the biomass production with short rotation coppices (SRCs) on reclamation sites. In order to evaluate biomass production, C and N allocation patterns in *R. pseudoacacia* stands between shoot, stump, coarse, and fine roots samples were collected from seedlings and three adjacent plantations and plants that were one, two and twelve years old. Results indicated that the summarized average dry matter production (DM) of the woody plant parts increased with plant age up to 7.45 t DM ha^{-1} yr^{-1} with a corresponding shoot increment of up to 4.77 t DM ha^{-1} yr^{-1} in the twelve-year-old stands. The shoot to root ratio changed from 0.2 for the one-year-old trees to 2.0 in the twelve-year-old plantation, whereby an average amount of 3.4 t C ha^{-1} yr^{-1} and 0.1 t N ha^{-1} yr^{-1} was annually bound in the living woody plant parts over the period of twelve years. Summing up, the results suggest a high potential for C and N storage of *R. pseudoacacia* what is also beneficial for land reclamation due to positive implications on soil humus and general site fertility.

1. Introduction

Short rotation coppice (SRC) is an alternative land use system, usually established on agricultural sites, that aims for the fast production of woody biomass for energetical or material use. Within these systems, cuttings or saplings of fast growing trees such as poplar (*Populus* spp.), black locust (*Robinia pseudoacacia* L.), or willow (*Salix* spp.) are planted in high densities of typically up to 15,000 (and more) plants per hectare for willow and up to 12,000 plants per hectare for poplar or *R. pseudoacacia*. The planting pattern facilitates quick growth and easy harvesting at intervals of between two and six years. The cut trees are able to resprout following harvest, which allows such systems to be run for 20 to 30 years without replanting.

Dependent on the tree species, the growth conditions (climate, soil quality), and the management system (planting density, rotation interval, fertilization, pest control), the biomass productivity of SRC differs widely [1–4]. On agricultural sites of average fertility, dry matter (DM) yields between 8 and 14 t DM ha^{-1} yr^{-1} for poplar and willow can be achieved under temperate conditions [5, 6], but, on marginal sites with nutrient-poor soils and a low water availability, the usual tree species poplar and willow show comparatively weak growth. A large area of marginal sites can be found in the open mining district of Lower Lusatia (State of Brandenburg, northeast Germany), which extends to a total area of about 31,000 ha in 2009 [7]. Growth experiments on reclamation sites within this region have resulted in aboveground growth rates of 2 to 6 t DM ha^{-1} yr^{-1} for poplar

and about 1 t DM ha^{-1} yr^{-1} for willow [8, 9]. On the same sites, high yields of woody biomass and average growth increments for *R. pseudoacacia* of about 5.8 t DM ha^{-1} yr^{-1} dry matter were reported [9].

R. pseudoacacia is a pioneer species that grows remarkably fast in youth and produces wood with an oven-dry density of 0.7 to 0.8 g cm^{-3} [10, 11], whereas hybrid poplars exhibit densities of 0.3 to 0.4 g cm^{-3} [12, 13]. The high wood density of *R. pseudoacacia* results in volume-related calorific values for *R. pseudoacacia*, which are significantly higher than the values for the other potential SRC species. Accordingly, Gruenewald et al. [9] reported calorific values of 4,818 MJ m^{-3} for *R. pseudoacacia,* 2,854 to 2,886 MJ m^{-3} for poplar, and 3,619 MJ m^{-3} for willow. This difference is economically relevant if the wood is used for bioenergy generation and storage or transport capacity is a limiting factor. In addition to the high biomass productivity on marginal sites, several studies also highlight the potential of *R. pseudoacacia* to enhance soil properties in terms of cation exchange capacity, biomass and organic carbon (C) accumulation [14, 15], nitrogen (N) accumulation and nitrification [16–19], soil phosphate [20], as well as the potential to improve soil structure, soil stability, and to support revitalization of degraded land [21, 22]. The ability to fix atmospheric N reduces the plants requirement for N fertilization compared to other energy species and, in combination with the general high biomass productivity, supports the restoration of a high and sustainable soil productivity on reclamation sites [23]. Furthermore, *R. pseudoacacia* is used in windbreaks and shelterbelts, as a nurse crop for honey production and as an ornamental tree [24, 25]. Besides bioenergy production, the high quality wood is also utilized for the production of furniture and for many specialized purposes such as fence posts, mine timbers, poles, railroad ties, ship timber, and boxes [24, 26].

For the prospected life-time of SRC, these wood plantations do not only produce woody biomass for bioenergy but also accumulate large amounts of C within the aboveground and belowground woody plant parts. While the shoots are frequently cut and removed, the stump and the roots remain at the site after a harvest [27]. These plant parts form a mid-term storage pool for C and also for N, especially, if legume trees such as *R. pseudoacacia* are cultivated. Accordingly, SRC provides three different C sequestration mechanisms: (1) production of woody biomass for bioenergy production (what helps reducing usage of fossil fuels and for this reason might be referred to as "indirect C sequestration"), (2) mid-term C storage in living (woody) plant parts, and (3) long-term C storage due to buildup of soil organic matter (humus) as a consequence of biomass decomposition and incorporation of organic compounds within the soil organic C pool. However, little is known regarding the actual productive capacity, biomass accumulation in different plant parts, or effects on nutrient cycles of *R. pseudoacacia* on marginal reclamation sites. This paper examines the biomass production by *R. pseudoacacia*, grown in tree plantations in the Lower Lusatian mining district. The objective of this study was to highlight the variations of biomass distribution as well as C and N allocation in the shoot, stump, fine roots and coarse roots of one-, two-, and twelve-year-old *R. pseudoacacia* stands and to derive accumulation rates on an annually basis.

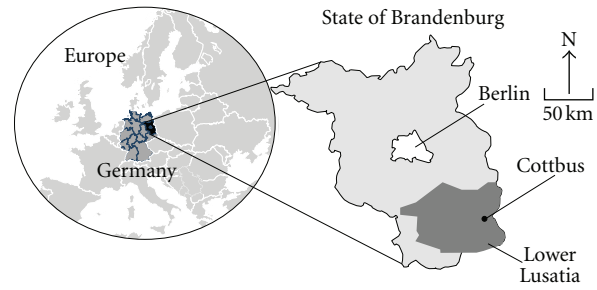

Figure 1: Location map of the lignite mining region of Lower Lusatia in NE Germany.

2. Material and Methods

2.1. Experimental Sites. Field experiments were performed in three plantations of *R. pseudoacacia*. The study sites are located in the Lower Lusatian region in the State of Brandenburg in northeast Germany (Figure 1) approximately 20 km south of the city of Cottbus (51.6°N, 14.3°E) in the area of the lignite strip mining site "Welzow-Süd." The tree plantations were established in 1995 (*WI*), 2005 (*WII*), and 2006 (*WIII*), respectively, on reclamation sites within the former open-mining cast, now refilled, meliorated, and brought back into cultivation. For establishment of the SRC, one-year-old rooted seedlings were used. The survival rate in the first growth year was high for all plantations, and interspecies competition was minimal as the sites were nearly weed free. All sites are situated within a small area: *WII and WIII* adjoin each other, the *WI* site is located nearby (about 4 km distance).

Growth conditions in the area are characterized by an annual mean temperature of 9.3°C and an average annual precipitation sum of 556 mm. During the main vegetation period (April to October), the average temperature is 14.2°C and the total precipitation sum is 375 mm. The plantations are situated in a flat terrain at an average altitude between 120 and 130 m a.s.l. Substrates at the sites are derived from overburden material dumped during the course of lignite mining. Initial site mapping resulted in substrate types dominated by loamy sand at the *WII and WIII* sites (LMBV International GmbH, pers. communication) and clayey sand at *WI* [8]. The nutrient status of the soils is generally low with typically less than 0.05% N in a soil depth of 0–30 cm [28]. Apart from the melioration, as described by Katzur and Haubold-Rosar [29], no additional fertilization was applied and no other cultivation activities were executed at any of the sites. The main characteristics of the experimental sites are given in Table 1.

2.2. Sampling. Samples were collected during the winters of 2006/2007 and 2007/2008. The plants were one (*WIII*), two (*WII*), and twelve (*WI*) years old (counted as vegetation

Table 1: Site descriptions of the three experimental sites with one-, two-, and twelve-year-old stands of *Robinia pseudoacacia*.

	WIII	WII	WI
Area (ha)	8.6	13.2	<2.5
Site installation	2006	2005	1995
Origin of *R. pseudoacacia*	Müncheberg/Calvörde, Germany	Bihor, Romania	Unknown
Plant age at sampling (years)	1	2	12
Plant spacing	Double row: (1.80 m + 0.75 m) × 0.85 m		Single row: 1.9 m × 0.8 m
Unit soil area per plant (m^2)	1.08	1.08	1.52
Density (plants per ha)	9200	9200	6500

periods from the year of plantation establishment on). All trees were not cut before, and almost all of them had only one shoot. In each plantation, five sampling plots were established, representative of the overall plantation structure. At each plot, the shoot diameter of 30 randomly selected trees was measured and the average value calculated. For sampling, one tree with the average shoot diameter was selected. It was visually verified that the growth conditions of the sampling site were equal to the average conditions in the plantation and that the selected tree appeared vigorous and exhibited the average height as well as the average "general form" of the surrounding plants. The biomass of each selected tree was completely harvested. The aboveground shoots were sawn off and subdivided into stump (0–10 cm from ground) and shoot (>10 cm).

Belowground root biomass was sampled in 15 cm depth intervals using an 8 cm diameter auger. At each selected tree, five auger holes were drilled, that is, at the base of the sampled tree, at 1/4 and at 1/2 the distance to the next tree within the same tree row, as well as 1/4 and 1/2 the distance to the next parallel tree row. *R. pseudoacacia* is known to develop a shallow but far reaching root system [24, 30]. To determine rooting depths of the trees, three to four soil profiles were dug at the WIII and at the WII site. In accordance with the findings from these soil profiles, the overall sampling depth at the WIII site was set to 45 cm and at the WII site to 60 cm. Sampling depth at the WI site was set to 90 cm due to practical considerations. Sampling with the root auger was limited to a root thickness of a maximum diameter of about 2.5 cm. Roots with larger diameters could not be sampled with the utilized auger and at appropriate reliability. All roots exceeding 2.5 cm in diameter were followed until their diameter reached 2.5 cm and completely unearthed. Their biomass was added to the coarse root biomass and calculated with the remaining auger samples at a later date. Additionally, to get initial values for the biomass allocation patterns in new established plantations, black locust seedlings were sampled (sample "Initial"). This could be done easily without the use of an auger.

2.3. Sample Analysis. As eluded to previously, the sampled aboveground biomass was subdivided into stump (0 to 10 cm from the ground surface) and shoot (anything above 10 cm) to comply with the common SRC management practices. In such plantations, the trees are frequently harvested and usually cut to an average height of 10 cm above the ground. The stump then remains in the plantation, while the shoot biomass is removed.

Root core samples were washed with water and sieved with a mesh size of 1 mm to separate soil from the root biomass. The retained roots were divided into coarse (diameter > 2 mm) and fine roots (diameter ≤ 2 mm). Root nodules were treated separately. The corresponding measurement results were later added to the results of the fine root pool for data evaluation. Root fragments shorter than 1 cm as well as dead roots were discarded.

Biomass samples were dried at a maximum temperature of 65°C until weight was constant. Average aboveground biomass stock per compartment and hectare was determined by multiplying the average dry weight per plant with the average plant densities of the plantations (Table 1).

Carbon and nitrogen contents of the biomass samples were measured using a CNS analyzer (*elmentar varioEL*, Hanau/Germany). All plant parts (shoots, stump, coarse, and fine roots) were measured independently.

For calculation of the belowground biomass, a unit soil area per plant according to Bengough et al. [31] was defined (Table 1). The dimensions of this rectangular-shaped area were defined as half of the distance to the next tree in the tree row and to the next tree in the neighboring tree row. Based on the regular planting pattern within the plantations, it was assumed that the soil below each unit soil area contained a total root length equal to the mean root length per plant. Many of the roots within the minimum area may belong to neighboring plants, but, similarly, an equal number of roots from the plant may have extended outside the area. For each sampled tree, the root biomass in the unit soil area was calculated and then multiplied with the plant density to achieve the root biomass for the entire plantation.

Average annual shoot growth increments were calculated by dividing the shoot biomass by the corresponding plant age. The summarized average dry matter production of all woody plant parts was calculated by summarizing the shoot, stump, coarse root, and fine root biomass and dividing the result by the corresponding plant age. For the calculation of hectare related values for the seedling samples, a planting density of 9200 plants ha^{-1} such as in WIII and WII was assumed (see Table 1).

2.4. Statistical Analysis. The data sets were joined to form a pseudo-chronosequence from a tree age of one year up to an age of twelve years. GNU R [32] was used for the statistical

Table 2: Average biomass per plant compartment and shoot : root ratio calculated as (shoot + stump)/(fine roots + coarse roots) for different plant ages of *Robinia pseudoacacia* (standard deviation is given as error).

	Biomass (kg dry matter per plant)			
	Initial	1 years	2 years	12 years
Coarse roots	0.0010 ± 0.0008	0.1203 ± 0.0624	0.6663 ± 0.6427	4.0701 ± 1.9718
Fine roots	0.0004 ± 0.0003	0.0622 ± 0.0144	0.1818 ± 0.0394	0.5546 ± 0.0722
Stump	0.0010 ± 0.0004	0.0080 ± 0.0013	0.0601 ± 0.0329	0.3167 ± 0.0739
Shoot	0.0041 ± 0.0024	0.0319 ± 0.0081	0.5556 ± 0.2238	8.8089 ± 2.0447
Shoot : root	3.5	0.2	0.7	2.0

Table 3: Average contents (all samples combined) and stocks of carbon and nitrogen in the woody biomass compartments (coarse roots, fine roots, stump and shoot) of seedlings ("Initial") and three differently aged stands of *Robinia pseudoacacia* (standard deviation is given as error).

	Organic Carbon	Organic Carbon ($kg \cdot ha^{-1}$)			
	(%)	Initial	1 years	2 years	12 years
Coarse roots	43.4 ± 1.4	4.3 ± 3.0	477.9 ± 260.7	2650.0 ± 2563.2	11512.5 ± 5560.7
Fine roots	41.9 ± 1.0	1.7 ± 1.3	251.4 ± 41.9	712.2 ± 167.6	1508.2 ± 209.5
Stump	46.8 ± 1.4	4.2 ± 1.9	46.8 ± 0.0	281.0 ± 140.5	983.4 ± 234.2
Shoot	46.4 ± 1.0	17.6 ± 10.2	139.2 ± 46.4	2365.8 ± 974.1	26579.9 ± 6169.5
	Nitrogen	Nitrogen ($kg \cdot ha^{-1}$)			
	(%)	Initial	1 years	2 years	12 years
Coarse roots	1.8 ± 0.6	0.2 ± 0.1	20.0 ± 10.9	110.8 ± 107.2	481.4 ± 232.5
Fine roots	3.0 ± 0.4	0.1 ± 0.1	18.0 ± 3.0	51.0 ± 12.0	108.1 ± 15.0
Stump	1.1 ± 0.5	0.1 ± 0.0	1.1 ± 0.0	6.6 ± 3.3	23.0 ± 5.5
Shoot	1.2 ± 0.5	0.5 ± 0.3	3.7 ± 1.2	63.6 ± 26.2	714.7 ± 165.9

exploration and plotting of the data sets. The data were tested for significant differences between the different plantations with the nonparametric Mann-Whitney U-test [33].

3. Results

Biomass accumulation in the first two years of growth was seen to be rapid in the *R. pseudoacacia* plantations. The results showed a distinct increase in the biomass of each plant compartment with plant age (Tables 2 and 3). Average stocks per hectare ranged for shoot biomass from 0.04 t DM ha^{-1} for the seedlings and 0.29 t DM ha^{-1} for one-year-old plants to 57.26 t DM ha^{-1} for the twelve-year-old plants (Figure 2). While the biomass stocks for stump were 0.01 to 2.1 t DM ha^{-1}, the stocks for coarse roots were 0.01 to 26.5 t DM ha^{-1} and for fine roots 0.004 to 3.6 t DM ha^{-1}, respectively (Figure 2). The corresponding total C stocks in the biomass were 27.8 kg C ha^{-1} for the seedlings, 915.3 kg C ha^{-1} for the one-year-old, 6,009.0 kg C ha^{-1} for the two-year-old and 40,584.0 kg C ha^{-1} for the twelve-year-old plants. The measured average C contents in the biomass pools were 43.4% for coarse roots, 41.9% for fine roots, 46.8% for stump, and 46.4% for shoot (Table 3). Differences in absolute biomass for each compartment and stand age were found to be significant for shoot, stump, coarse, and fine roots ($P < 0.05$) with higher values in older stands. Only for the coarse root biomass between the two-and the twelve-year-old plants, a slightly lower significance level of $P = 0.07$ was calculated.

The overall annual shoot growth increment was seen to be increasing in the first years starting at 0.29 t DM ha^{-1} yr^{-1} for the one-year-old plants, continuing with 2.56 t DM ha^{-1} yr^{-1} for the two-year-old and 4.77 t DM ha^{-1} yr^{-1} for the twelve-year-old plants (Figure 3). The increase was significant comparing the one-, two- and twelve-year-old stand ($P < 0.05$; Figure 3), indicating a general higher biomass productivity in older stands. Coarse root growth increments did not show significant differences between stand ages. The fine root growth increments decreased comparing the one- and two-year-old stands with the twelve years old stand ($P < 0.05$) with no significant difference between the one- and the two-year-old plantation. The annual stump growth increments were significantly lower in the one-year-old stand compared to the two-year-old stand as well as compared to the twelve-year-old stand ($P > 0.05$), but no significant difference was observed between two and twelve years.

Comparing the different aged plants, the relative allocation of the biomass compartments is seen to change (Figure 4, Table 2). The ratio of shoot (aboveground biomass) to root (belowground biomass) for the seedlings is 3.5 (78% : 22%) and changes to 0.2 (18% : 82%) for the one-year-old plants, respectively; to 0.7 (42% : 58%) for the two-year-old plants

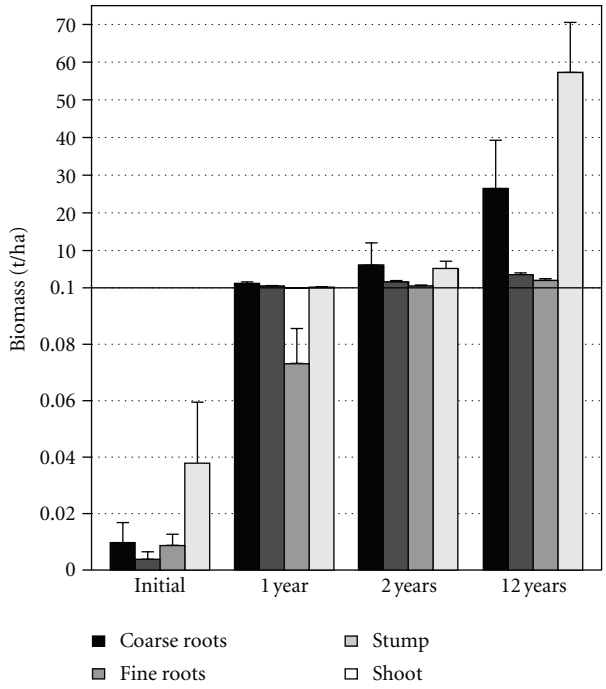

Figure 2: Absolute dry matter distribution of the woody biomass compartments *shoot*, *stump*, *fine roots* and *coarse roots*, for seedlings (Initial), a one-, two- and a twelve-year-old stand of *Robinia pseudoacacia* (standard deviation is plotted as error bar).

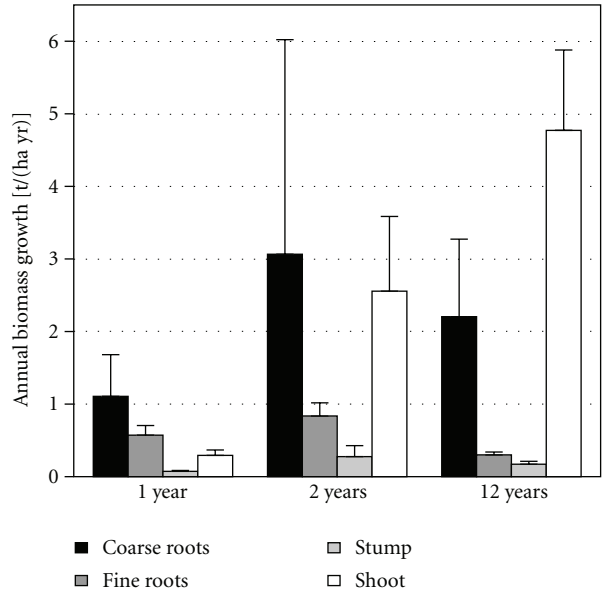

Figure 3: Plot of the average annual growth of the woody biomass compartments *shoot*, *stump*, *fine roots,* and *coarse roots* of a one-, two-, and a twelve-year-old stand of black locust (*Robinia pseudoacacia*).

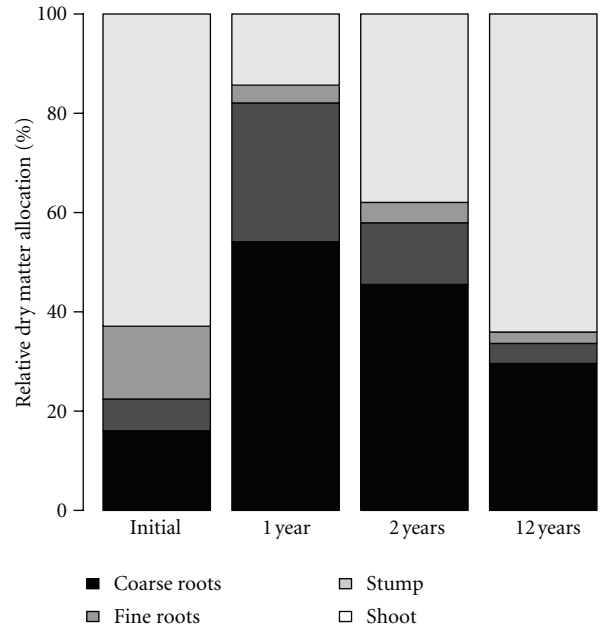

Figure 4: Relative dry matter distribution of the woody biomass compartments *shoot*, *stump*, *fine roots,* and *coarse roots* of seedlings (Initial), a one-, two-, and a 12-year-old stand of black locust (*Robinia pseudoacacia*).

and reaches a value of 2.0 (66% : 34%) for the twelve-year-old plants (Table 2). In Figure 5, the logarithmized belowground biomass (coarse roots + fine roots) versus aboveground biomass (stump + shoot) is presented. The plot reveals a strong increase of root biomass during the first vegetation period (initial value compared to the one-year-old plants) with a slope >1. This allocation pattern changes between the one-year and the two-year-old plants, and then more biomass is allocated to the aboveground biomass than to the belowground biomass (slope < 1).

C/N ratios for the one-, two- and twelve-year-old stands were 29.9, 31.6, and 81.0 for the shoots, 30.7, 48.2, and 84.2 for the stump, 13.2, 13.6, and 15.7 for the fine roots and 19.0, 25.0, and 37.9 for the coarse roots. Total N stocks in the woody biomass amounted to 0.9 kg N ha^{-1} for the seedlings (assuming 9200 plants ha^{-1}), 42.8 kg N ha^{-1} for one-year, 232.0 kg N ha^{-1} for two-year, and 1327.2 kg N ha^{-1} for the twelve-year-old plants. For the calculation the measured average N contents of 1.8% in the coarse roots, 3.0% in the fine roots (including root nodules), 1.1% in the stump, and 1.2% in the shoot were used (Table 3).

4. Discussion

4.1. Biomass Productivity of R. pseudoacacia. The shoot compartment represents yield biomass and therefore the direct economical value of an energy plantation. The obtained results for the biomass productivity of *R. pseudoacacia* on the study sites resemble those reported in literature. Gruenewald et al. [9] investigated biomass accumulation of *R. pseudoacacia* in an alley cropping system on a reclamation site in the Lusatian lignite-mining district (Brandenburg, Germany) and reported values of 29.8 t DM ha^{-1} after six years and a peak biomass productivity of 5.8 t DM ha^{-1} yr^{-1}. Furthermore, they reported average biomass accumulations ranging from 3.2 to 4.6 t DM ha^{-1} yr^{-1} after two years in an

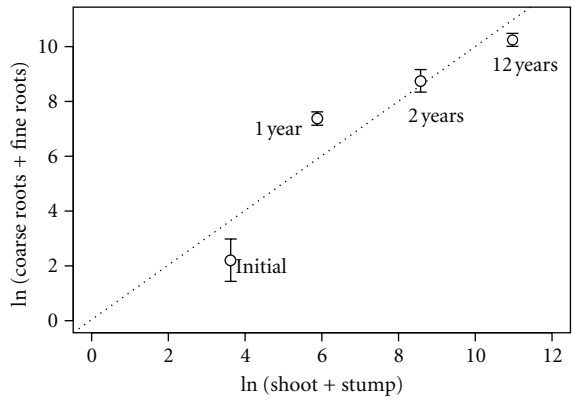

Figure 5: Plot of the aboveground (stump + shoot) versus the belowground biomass (coarse + fine roots) of seedlings (Initial), a one-, two-, and a 12-year-old stand of black locust (*Robinia pseudoacacia*).

alley cropping system in the Helmstedt lignite-mining district (Lower Saxony, Germany). Even higher annual growth increments of up to 9.5 t DM ha^{-1} yr^{-1} were reported by Grünewald et al. [34] for a fourteen-year-old *R. pseudoacacia* plantation on reclamation sites in the Lusatian mining area of "Welzow-Süd" (Brandenburg, Germany). Also, in "Welzow-Süd," Böhm et al. [35] investigated a *R. pseudoacacia* SRC and reported an average biomass productivity of about 3 t DM ha^{-1} yr^{-1} for the first three years of growth. Peters et al. [36] measured average annual growth rates of 5.5 t DM ha^{-1} yr^{-1} for *R. pseudoacacia* on study sites in Brandenburg with plant densities of between 4100 and 5700 trees ha^{-1} following six years. Growth data on *R. pseudoacacia* reported from other temperate regions present similar findings. Rédei et al. [26] investigated the growth of different *R. pseudoacacia* clones growing on marginal sites in Hungary and measured mean annual increments of 2.9 to 9.7 t DM ha^{-1} yr^{-1} at ages between 3 and 7 years using a stocking density of 6667 trees ha^{-1}. Bongarten et al. [23] reported 3 to 8 t DM ha^{-1} yr^{-1} after three years of growth in an intensive short-rotation system in the Piedmont region of Georgia (USA). Dickmann et al. [37] measured *R. pseudoacacia* growth in the same region and found average values after four years of growth of 4.2 t DM ha^{-1} yr^{-1} and in Eastern Kansas (USA) Geyer [1] found comparatively high average growth rates of 14.2 t DM ha^{-1} yr^{-1} with planting densities of around 1400 to 7000 trees ha^{-1} after five years.

Remarkably, the measured growth increments of *R. pseudoacacia* were at least equal to those of poplar or willow under comparable growth conditions. Accordingly, Gruenewald et al. [9] measured average growth increments for two poplar clones (*Hybrid 275* and *Androscoggin*) of 1.1 to 2.0 t DM ha^{-1} yr^{-1} and for willow of 1.0 t DM ha^{-1} yr^{-1} after a rotation of six years at the Lusatian alley cropping system. For the Helmstedt study site biomass accumulations between 2.2 t DM ha^{-1} yr^{-1} and 3.9 t DM ha^{-1} yr^{-1} were reported for *Androscoggin* and *Hybrid 275*, respectively. Bungart and Hüttl [8] investigated the growth of different hybrid poplar clones in a short-rotation plantation on another neighboring reclamation site in the mining-area of "Welzow-Süd" and found aboveground biomass accumulations ranging from 24 to 49 t DM ha^{-1} at age 8, corresponding to a growth rate of 2.7 to 5.4 t DM ha^{-1} yr^{-1}.

The study results suggest that at least in the Lusatian region *R. pseudoacacia* is very productive compared to willow and poplar, and therefore a promising tree for biomass production. This is especially true for the harsh growth conditions on marginal reclamation sites.

4.2. Biomass Allocation. The proportion of biomass allocated belowground increased considerably within the early growth years (Figure 4). The data suggest that in the state of planting (label "Initial") the aboveground biomass (shoot and stump) dominates clearly with a share of 78% of the total biomass. This allocation pattern reflects the growth conditions in the seed bed and might be influenced by a general loss of root biomass caused by replanting the seedlings from the seed bed into the plantation. Therefore, the results of the seedlings may not reflect an undisturbed growth of *R. pseudoacacia*. In the subsequent early growing seasons, the plants seem to invest a lot in the expansion of their root systems; the aboveground plant parts become more and more dominant and at the age of twelve, the distribution of the biomass has changed. Aboveground growth has overhauled root growth and as a result the aboveground biomass represents 66% of total biomass which corresponds with a shoot : root ratio of 2. Figure 5 indicates that equilibrium appears to have been reached between ages 2 and 12 (slight gradient between two and twelve years) meaning allometry has become constant. Such a distribution of biomass allocated aboveground to that belowground is frequently found in mature forests, whereas the reported ratios vary considerably [38, 39].

The observed change in the shoot : root ratio reflects a typical change during the plant life cycle, because usually, the relative mass of belowground organs increases from the juvenile to the generative stage and decreases during the senile stage [40]. Comparable shoot : root ratios were reported by Boring and Swank [41] who found for a 4, a 17, and a 38 years old *R. pseudoacacia* stand root fractions of 33%, 18%, and 18% compared to total biomass, corresponding to shoot : root ratios of 2.0, 4.6 and 4.6, respectively. The authors found higher values for older stands, but took root samples from 0–30 cm only. In contrast, in the presented study measurements were performed down to a soil depths of 90 cm in the oldest stand. Furthermore, Boring and Swank [41] used allometric functions to estimate large lateral root biomass. These differences in approach might have contributed to lower reported shares of total root biomass by Boring and Swank [41], especially for the older stands.

However, studies on the C allocation patterns of *R. pseudoacacia* in biomass plantations are very limited. For poplar and willow more comprehensive studies have been conducted. Accordingly, Coleman et al. [42] investigated C allocation in young poplar plantations (*Populus deltoides* Bartr.) in the USA and found a shoot : root ratio of 2.3 for an unfertilized one year old plantation. Liberloo et al. [43] investigated different poplar clones at planting densities

of 5000 and 10000 trees ha^{-1} in a field trial in Central-Italy and measured comparably high shoot : root ratios of between 8 and 10 at the end of the second three-year rotation. The results, however, may not be directly comparable with those reported in this study. Apart from the likely growth response to harvesting following three years of growth (first rotation), the authors did not include the fine root biomass (<2 mm) in their calculation and, additionally, regarded the stump biomass as part of the root biomass. For lysimeter-grown basket willows (*Salix viminalis* L.), Rytter [44] reported shoot : root ratios, excluding leaves and cuttings, that declined from 2.5 to 1.8 in the first year and then increased to between 6.7 and 9.1 in subsequent years in clayey and sandy soils, respectively. Dušek and Květ [40] investigated different aged plantings of *Salix caprea* L. in a field trial in the Czech Republic. The authors reported a shoot : root ratio ranging from 3 to 4 for three-year-old plants. However, if the plantations are harvested frequently, the shoot : root ratio might be influenced.

In non-N_2-fixing woody plants, biomass allocation to roots typically increases as soil N becomes increasingly limited [45]. Johnsen and Bongarten [46] investigated seedlings of *R. pseudoacacia* and found no impact of soil N availability on biomass allocation to roots. They observed no change in shoot : root ratio with increasing plant age while investigating impacts of N-fertilization on the plants. Nevertheless, the accumulated root biomass accounts for a remarkable share of total biomass in the *R. pseudoacacia* plantations. Therefore, the belowground biomass may play an important role in the formation of soil humus via root and root nodule turnover and following decomposition with resultant positive influences on both soil moisture and soil fertility.

The amount of woody biomass accumulated under the imposed coppice regimes (stumps) reflects the tree management conditions within the plantation. For the seedlings and one-year-old trees, the stump (defined as the first 10 cm of the shoot) was within 20–25%, compared to the shoot, a considerable compartment of the aboveground biomass. It was found that the stump compartment contributes a relative share of between 3.6% in the one-year-old plantation and 2.3% in the twelve-year-old plantation. The biomass of the stump compartment in relation to the shoot compartment decreased with plant age and thus with plant size. In the twelve-years-old plantation, the stump was seen to decrease to a share of only about 3.6% of that of the shoot. Nevertheless, the total mass of 2 t DM ha^{-1} is a considerable biomass stock as it remains after harvest at the site and together with root biomass increases the permanent baseline C stock in the living plant compartments.

4.3. Effects on the Carbon and Nitrogen Cycle. Gross primary production (GPP) represents the main photosynthesis-derived C input into ecosystems but does not represent the C balance of a system as autotrophic and heterotrophic respiration reduces the C input. In a spruce forest according to Schulze [47], around 75% of the assimilatory C gain is used for respiration of the plants and roughly 25% of the C is respired by microbes within the soil. Subtracting the C loss due to additional disturbances (such as harvest, grazing, and fire) of the remaining biomass, only approximately 1% of the photosynthetic C input is stored at the biome level, or the C balance of the ecosystem may indeed become negative.

In the present study, the totalized above- and belowground woody biomass production, which complies with the GPP minus autotrophic respiration minus foliage biomass, in the investigated *R. pseudoacacia* plantations is 2.0 t DM ha^{-1} yr^{-1} for one-year, 6.7 t DM ha^{-1} yr^{-1} for two-year, and 7.4 t DM ha^{-1} yr^{-1} for the twelve-year-old stand (Figure 3). These values represent the annual C accumulation in the woody plant parts following one, two, and twelve years. For twelve years, these values correspond with an additional C storage of around 3.38 t C ha^{-1} yr^{-1} and even if the potential yield biomass (shoot growth) is subtracted from that value an average C storage of 1.17 t C ha^{-1} yr^{-1} in stump, fine and coarse roots can be concluded (Table 3).

One advantage of *R. pseudoacacia* on marginal sites is that the tree is a legume and as such has the ability to fix atmospheric N, a nutrient that is usually limited on the Lower Lusatian reclamation sites if no additional fertilizer is applied. In the plantations under study, the trees seem to intensively fixate air N as the major part of the N is bound in the root system (the root nodules), at least up to an age of two years. Even at age twelve, the N stock in the root compartments is nearly as high as the N stock in the shoot (Table 3), although the shoot to root ratio has increased to about 2.0 in the twelfth year. Because nutrients (such as N) in woody plant parts are usually concentrated in the bark, older plants with thicker branches have lower total nutrient concentrations in lignified plant parts due to a lower bark fraction in relation to a higher fraction of nutrient-poor wood [48, 49]. Accordingly, the shoots, stumps, and coarse roots of the older plants had wider C/N ratios than the younger plants, whereas the C/N ratio of the less intensively lignifying fine roots does not change substantially with increasing plant age. Furthermore, the measured N concentrations and N stocks in the shoots of *R. pseudoacacia* are higher than values reported for willow and poplar on comparable sites. Bungart and Hüttl [50] measured the nutrient contents in aboveground plant parts of different four-year-old clones of poplar, willow, and aspen on reclamation sites in the mining area of "Welzow-Süd" (average biomass productivity of the plantation was 2.3 t DM ha^{-1} yr^{-1}) and reported average contents of 4.9 mg N g^{-1} DM and a total N accumulation of 51 kg ha^{-1}.

Dependent upon stand age, stand density, nutrient demand, and climate, typical annual fixation rates of *R. pseudoacacia* range between 30 and 120 kg N ha^{-1} [41, 51, 52]. Some authors report a general increase in the soil N under *R. pseudoacacia* cover [53], whereas the increase is not only a result of release from decaying N-rich leaves and roots, but also from root exudates that may contain 1–2% of the recently fixed N [54]. Berthold et al. [55] also reported of higher N amounts under *R. pseudoacacia* forest stands in Hungary (ages ranged between 28 and 56 years) but also presented results indicating that an excess of nitrate under *R. pseudoacacia* leached together with base cations (K^+, Ca^{2+}, Mg^{2+}) causing soil acidification and a decrease of soil

fertility compared to adjacent oak stands. Similar findings were reported for stands in eastern Germany [56].

The measured N stocks in the biomass compartments of *R. pseudoacacia* quantify the amount of N that is stored in the living woody plant compartments. In the shoot compartment alone, about 0.71 t N ha^{-1} are stored in the twelve-year-old stand compared to a total N storage of 1.3 t N ha^{-1} in the whole plants. This would result in an average accumulation rate of 0.11 t N ha^{-1} yr^{-1}. Parts of this N are continually injected into the processes of decomposition, ammonification, nitrification, and denitrification [57] via aboveground and belowground litter fall. However, a significant N enrichment in the vegetation and the soil under *R. pseudoacacia* might result in high nitrification rates in the mineral soil [16]. As a result, nitrate and base cations can be leached, and, depending on the buffer capacity of the soil pH may decrease [55, 56]. However, an enrichment of soil N in response to the presence of *R. pseudoacacia* may also have a considerable positive impact, for example, on the growth of other adjacent tree species especially on nutrient poor mining substrates [58].

The performed growth experiments in the presented study do not reveal any adverse impacts of *R. pseudoacacia* on the C or the N household. On the contrary, the self-fertilization in combination with a comparatively good resistance against drought enabled *R. pseudoacacia* to be competitive compared to other fast growing tree species such as willow or poplar on the reclamation sites [9]. Furthermore, according to other studies performed on Lusatian mine sites, *R. pseudoacacia* contributes substantially to an C sequestration in the soil and a buildup of soil humus pools [28, 59].

5. Conclusions

It was found that the biomass accumulation in the woody plant parts and the annual shoot increments in the *R. pseudoacacia* plantations were higher or at least similar high as growth performances reported for willow and poplar on comparable sites. The results suggest that *R. pseudoacacia* is comparatively well adapted to the harsh growth conditions that can be found on the Lower Lusatian reclamation sites. A remaining average C accumulation rate in stump and roots (excluding harvest removals) of at least 1.17 t C ha^{-1} yr^{-1} after twelve years of growth was estimated. At a maximum biomass accumulation rate in the woody plant parts of 7.45 t DM ha^{-1} yr^{-1}, a remarkable share of the woody biomass growth in the twelve-year-old plantation was allocated into the root system accounting for 34% of the total biomass. It was found that the stump compartment contributes a relative share of between 3.6% and 2.3% of the total biomass and therefore builds together with the root biomass a notable baseline C stock in SRC. This mid-term C pool is SRC-specific, as it does not exist in conventional land use systems with annual energy crops.

Nitrogen stocks in the living woody biomass compartments ranged between 42.8 kg N ha^{-1} for the one-year and 1327.2 kg N ha^{-1} for the twelve-year-old plants (corresponding N stocks without shoots were 39.1 kg N ha^{-1} and 612.5 kg N ha^{-1}), confirming that the living biomass compartments in the *R. pseudoacacia* plantations may represent a considerable source of N input into the N-poor reclamation systems via the processes of decomposition.

In regards to the produced shoot biomass as a possible replacement for fossil energy resources and the accumulated stump and root biomass as advantageous for C sequestration, soil humus status, and general site fertility, the results suggest that *R. pseudoacacia* would be a good candidate for biomass production in SRC systems on reclamation sites and other marginal lands. Assuming a life time of 20–30 years for a SRC with a following conversion of the plantation back into agricultural land, as was demonstrated for a study site in Lusatia [60], the C sequestration capacity of a landscape could be enhanced by establishing a rotation system with alternating cultivation of conventional crops and SRC. If the areas for SRC are shifted, the permanent existence of a root and a stump pool for C storage would be ensured. Furthermore, conventional crops would benefit from higher soil humus and soil N contents if they were cultivated on former SRC areas after removal of the plantation. However, knowledge of the C and N household in *R. pseudoacacia* plantations on reclamation sites and possible implications for soil quality are still somewhat incomplete. Further investigations (e.g., additional sampling of plants at complementary ages with a focus on element flows and turnover processes) would help to receive a more solid data base and to obtain a more detailed picture of the C and N translocation processes within the plantations.

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Research Article

Production Costs and Markets for Pellet Chips: Case Studies in Northern Sweden

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Increasing use of woody fuels requires that nontraditional types of raw materials are exploited, including logging residues and small-diameter trees. Although medium-scale combustors often use pellets, they could conceivably use dried chips of sufficiently narrow size distribution (henceforth pellet chips). The influence of the following factors on the relative cost-effectiveness of producing pellets and pellet chips was investigated for three plant sites in northern Sweden: (1) harvesting and transporting of forest residues; (2) the potential of existing energy plants to supply drying heat in periods of capacity surplus; (3) the distance to potential end-users. Data from the national forest inventory were used to estimate raw material costs. The resulting production costs were 144–176 \$ per oven-dry tonnes (OD t) for pellets (27.4–33.5 \$ MWh^{-1}) and 143–173 \$ OD t^{-1} (27.2–33.0 \$ MWh^{-1}) for pellet chips, with harvesting, forwarding, chipping, and transporting of logging residues to the sites amounting to 114–122 \$ OD t^{-1} (21.7–23.2 \$ MWh^{-1}) for both fuels. Even though the differences in production costs were minor, the production of pellet chips requires significantly less electricity input per OD t of produced fuel. For cost reductions improved methods for wood fuel procurement, compacting and transporting of chips, small-scale low-temperature drying and foliage and bark separation are needed.

1. Introduction

Interest in renewable energy has been spurred by public awareness of climate change, international obligations to decrease greenhouse gas emissions, and the scarcity of fossil fuels. Consequently, woody fuels are becoming increasingly popular sources of heat and power worldwide. They are used in new biofuel-based heat and power plants, converted-coal- and oil-based boilers, and in systems based on cogeneration with coal [1].

In Europe and North America, woody fuels have to some extent replaced oil and electricity for small-scale residential heating and for medium-scale combustors supplying users such as small district heating networks, schools, and industrial facilities. Most of this is pellets from dried woody biomass (which are also used in large-scale power plants because densification facilitates handling and long-range transport), but chips are also used. The pellet consumption in the small- and medium-scale markets in these regions was in 2005 12.5 to 15 TWh [2]. In Sweden, 3.9 TWh of the pellets was used for small-scale residential heating in 2010 and about 0.4 TWh was used in medium-scale district heating (annual heat deliveries below 10 GWh) [3, 4]. Further, about 0.5 TWh of chips was used in small-scale residential heating [5] and about 0.3 TWh (possibly including crushed and hogged woody fuel) in the smallest district heating plant [4].

The availability of woody biomass depends on local and regional conditions. However, energy plants in different regions face similar challenges regarding forest biomass procurement, refining, and combustion technology. In order for fuel pellet production to keep pace with the expected increases in demand, it will be necessary to exploit nontraditional raw materials. While there is still a surplus of saw mill residues in some markets, for example, Canada, Latin

America, and parts of India [6–8], there is definitely a shortage in Sweden. One such source of nontraditional raw biomass is the Canadian stands affected by the mountain pine beetle, which have little use except as fuel [9]. In the southern and western USA, thinning operations have been suggested as a wildfire prevention measure, and it has been proposed that material from the extracted trees could be used for power production [10, 11].

Ash-forming elements in the fuel, which are mostly from branches, bark, and foliage or from contamination [12, 13], determine the formation of potentially health-threatening particles [14] and the risk of ash-related operational problems [15]. While high-quality biomass generate relatively low particle emissions even when burned in small-scale combustors, more ash-rich fuels require combustors fitted with flue gas cleaning systems such as multicyclones, which are rare in combustors for single-family houses. The strictest standard for fuel pellets, SS 187120, requires ash contents below 0.7% wt.d.s. [16]; fuels meeting this requirement are typically made from stemwood-derived raw materials such as saw dust and planer shavings.

In Fennoscandia, high-quality round wood is highly utilized by sawmills and the pulp industry, so the energy sector is increasingly reliant on stumps, logging residues, small-diameter trees, and low-quality round wood. Despite their bark content, energy wood (which is of lower quality than pulpwood or derived from stands that are further from sawmills) and small wood from early thinnings both represent fuel assortments that could potentially result in fuels with ash contents below 0.7%. Conversely, fuels derived from logging residues (whose ash concentrations range from 1 to 8% wt.d.s., depending on how they are handled), are best used in medium-scale combustors with particle filtering systems [17–20]. Annually, 3.2–4.2 million oven-dry tonnes (OD t) of potentially harvestable logging residues and stumps are generated during regeneration fellings in Sweden [21]. For comparative purposes, the current annual consumption of logging residues in Sweden is approximately 2 million OD t [22].

Common types of small-to-medium-scale combustors (below 10 MWth) for chips are (1) precombustors/preovens with separate secondary combustors, (2) grates, or (3) stoker burners [23, 24]. They are adapted to a certain range of moisture content (MC) [25]. To cope with moist chips, insulated precombustors/primary combustors and air preheating can be used [23, 26]. Grate areas must be 120% larger when the MC increases from 30 to 60% and combustor volume must be larger. Stoker burners are more sensitive to high MC, compared to precombustors and grate combustors. Smaller-scale combustors are more sensitive, as the combustion is concentrated to a smaller area with less fuel [24]. The cost of adaptation to moist fuels is a serious disadvantage, and dried fuels are therefore often preferred at small-to-medium scale [27]. Variations in fuel chip particle size (causing fluctuations in fuel feeding rate and in MC) cause serious control problems in small-to-medium-scale chip combustion [27, 28]. Particle sizes above 50 mm may require more complex fuel feeding systems than augers like vibroconveyors or troughed chain conveyors [24].

Small-scale combustion thus requires fuel of a higher quality than that used on larger scales. Pellets are made from dried biomass and have much less variations in particle size compared to conventional wood chips. Conventional chipping of woody biomass followed by grinding and pelletizing may not be the most cost-effective way of preparing high-quality fuel. Instead, it may be better to comminute, assort, and dry the biomass in a way that produces wood chips whose combustion properties are more comparable to those of pellets (Table 1). Sieving and drying have been suggested as ways to upgrade chips [27]. Optimal chipping could simplify upgrading downstream in the product chain. Factors that determine the particle size distribution of chips include chipper type, tree species, and blade wear, and it can also be influenced by the choice of chipping screen [29–31].

Dried wood chips with limited variation in particle size which have been upgraded for the small- and medium-scale market have been referred to as "pellet chips" [30], a term which will henceforth be used as there is no established term to distinguish them from more moist chips with wider size distributions. Pellet chips could either be used directly in less sensitive small- and medium-scale combustors (replacing pellets) or as a raw material for producing fuel pellets to be consumed in more distant markets.

The cost of drying contributes significantly to the overall cost of production and is considerably lower (per unit dried mass) on larger scales because the investment usually increases with scale according to a power law, with an exponent of less than 1 [32]. In temperate climates, heat plants and combined heat and power plants usually have excess combustion capacity at certain times of the year due to seasonal variation in temperature. This excess capacity could be used to dry fuel and thereby obtain additional revenue from existing investments.

There are differences in size distribution and density between pellets and pellet chips, resulting in differences in terms of their production, transport, storage, and combustion properties [33]. Some stages of the production processes for pellets and pellet chips are very similar, such as raw material handling and storage, drying, and the loading of the product. Others are required only for pellet production, that is, grinding, pelletizing, and cooling. Naturally, for various practical and economic reasons, only a fraction of the potential market will be available to a new supplier. However, provided that a fuel can be comminuted, dried, and transported at a competitive cost and is suitable for use in existing combustors, there exists a market opportunity. For any site, the profitability of fuel production will be determined by the raw material cost, the production cost (especially the cost of drying and the availability of excess heat or combustion capacity), and by the distribution of potential users. When selecting a suitable site, the combined effects of these factors must be considered.

2. Objectives

The purpose of the study reported herein was to assess the use of logging residues as a dried fuel of narrow particle size distribution (pellet chips) in northern Sweden. More

Table 1: Properties of pellets and chips according to standard [16] and the Fuel Handbook [55]. MC: moisture content, LHV: lower heating value.

	Pellets (8 mm)	Chips
Particle size	Ø 8 mm ± 0.1 mm, 3.15 mm ≤ Length ≤ 40 mm	3.15 mm ≤ Length ≤ 6 mm
Fines	≤3 mm, 12% wt	≤3.15 mm, 1% wt
MC, % wt (as delivered)	<10	<10
Ash content, % wt (dry basis)	<0.7	<0.7
Volatile content,* % wt (dry basis)	81	84
LHV, MJ kg^{-1} (at 10% MC)	17.0	17.0
C	49.6–53.13	49.6–53.13
H	5.8–6.2	5.8–6.2
O	38.1–40.8	38.1–40.8
N	0.3–0.8	0.3–0.8
S	0.04–0.06	0.04–0.06
Cl	0.02–0.03	0.02–0.03
Bulk density ($t \cdot m^{-3}$ solid)	0.550–0.700 Assumed in this study: 0.720 (at 5.5% MC) [33]	Not specified by standard, 0.220 (at 26% MC) assumed in this study [33]

* For wood fuel.

specifically, the objective was to determine how the following factors influence the relative cost-effectiveness of producing pellets and pellet chips:

(i) the cost of harvesting and transporting forest residues;

(ii) the nature of the existing energy plants (and their potential for pellet production), their capacity, and production costs;

(iii) the distance to potential markets (end-users) and transport costs.

3. Material and Methods

3.1. Study Design. The study focused on the production of dried fuel from logging residues and the associated supply costs. The influence of the choice of location and the choice of product on economic viability was assessed. Three different locations in Sweden of a hypothetical fuel production facility were considered. It was assumed that the harvested biomass would be chipped at the landing and transported to a central site for further processing, with the chips being dried on site at the production facility. It was further assumed that the chip particle size distribution would be sufficiently homogeneous for the dried chips to be combusted in a reasonable proportion of existing pellet-fueled small- and medium-scale combustors, thus qualifying them as "pellet chips." After drying, the chips were either ground and pelletized before being stored and transported to users or stored directly without further processing. The following alternative locations in the county of Västerbotten, northern Sweden, were compared: (1) Vännäs (a coastal location), (2) Lycksele (in the interior of the region), and (3) Vilhelmina (close to a mountainous region) (Figure 1). The population densities of the municipalities of Lycksele, Vilhelmina, and Vännäs were 2.2, 0.88, and 16 inhabitants per km^2, respectively. Vännäs is located in the more densely populated coastal region, 30 km away from the region largest town (Umeå, with a population of 114 000).

Raw material costs were estimated from National Forest Inventory (NFI) data in conjunction with specific information about the three locations. The production costs for pellets and pellet chips were estimated, using data on investments and operating costs from the literature [34] and considering opportunities for integration with existing energy plants at the proposed sites (Sections 3.2–3.8). Potential markets for the fuels produced and costs for transport from the three sites were estimated based on public statistics for the region (Section 3.9).

A sensitivity analysis of the total supply costs was performed in which the following parameters were varied by ±50%: raw material cost, electricity cost/electricity revenues, production cost, and transport costs. Production capacity was varied by ±15%.

3.2. Plant Sites. Sites for the hypothetical plants were chosen next to district heating plants at all locations. The Lycksele plant was a combined heat and power plant while those at Vilhelmina and Vännäs were district heating plants only. Due to seasonal variation in demand, some of the plants had excess combustion capacity that was available during some parts of the year and could be used to generate heat for drying biomass fuel (Section 3.4). The Lycksele plant had an unusually high annual excess heat production capacity of 25 GWh because a nearby sawmill supplied by the plant had recently been shut down [35].

The Vilhelmina heat plant had a combustion capacity of 20 MW and delivered 58.5 GWh of heat annually. Its

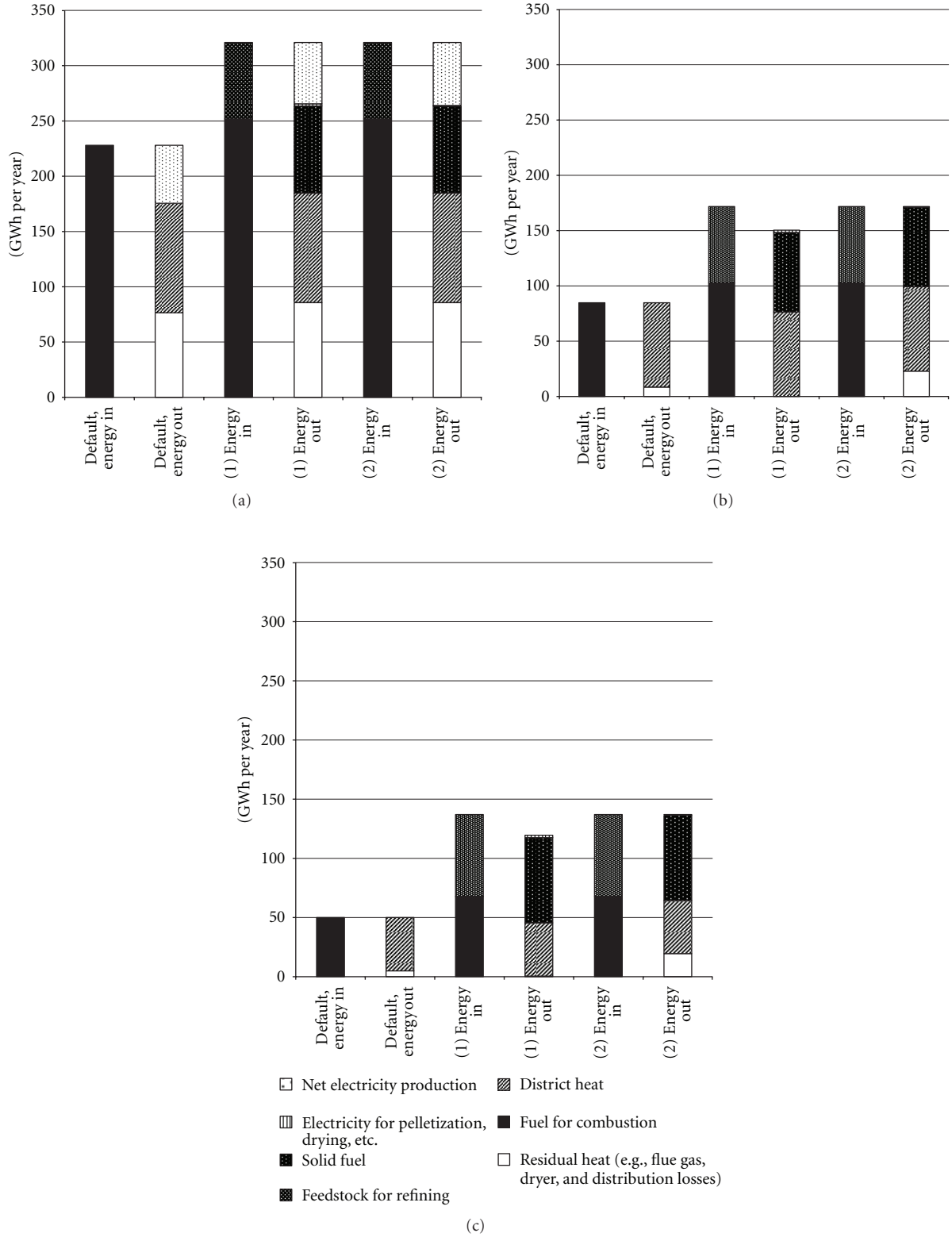

Figure 1: Energy balances for the three plant sites—Lycksele (a), Vilhemina (b), and Vännäs (c)—under the current regime (default), for pellet production (1) and for pellet chip production (2).

Table 2: Methods for calculating the marginal costs for extraction and delivery of logging residues for the plant sites.

Cost	Parameter used to calculate cost	Method of calculation ($ OD t^{-1})
Forwarding to roadside, C_1	Forwarding distance d_f (km)	$C_1 = 16.9 + 24.5d_f$
Chipping at roadside, C_2		$C_2 = 21.7$
Hauling to plant, C_3	Hauling distance d_t (km)	$C_3 = 3.26 + 0.217d_t$
Administrative costs, C_4		$C_4 = 9.61$
Reimbursement to land owners, C_5		$C_5 = 22.5$
Allocation costs for forwarders and chippers, C_6	Number of machine allocations (n_a OD t^{-1})	$C_6 = 327\ n_a$

primary fuels were bark (37.2 GWh), shavings (28.7 GWh), and stemwood chips (7.0 GWh). Flue gas condensation was used at the plant.

The Vännäs plant had a 6 MW boiler from which an additional 1–1.5 MW was recovered through flue gas condensation. A 3 MW boiler was used during the summer when heat demand was low. Various biomass fuels were used, including bark (33 GWh), stemwood chips (4.5 GWh), logging residues (0.5 GWh), and demolition wood. The maximum combined heat output of the plant boilers was insufficient to meet local demand when outdoor temperatures fell to −13°C or below. In such cases, the shortfall was made up using oil or electric heaters, with capacities of 2.9 GWh and 1.1 GWh, respectively [4, 36]. The town of Umeå provided a considerable local market for biomass fuels.

3.3. Raw Material Supply. Available amounts of raw material and fuel (logging residues) in the vicinity of the plants and the cost for extracting and transporting them to each plant were estimated using data from the NFI, according to a previously described procedure [21]. The NFI sample plots around each plant were used to estimate the age, growing rates, and distribution among biocomponents of the trees and to forecast the areas due to regeneration fellings according to present practice. The amounts of logging residues that could accordingly be expected were calculated (nature protection areas, wet areas, waterlines, and slopes with inclinations above 19.6° were not included, and from the remaining productive forest land, 40% of the logging residues were assumed to be left on the ground for practical reasons). It was further assumed that the raw material costs were dictated by the costs of extracting and transporting logging residues in the vicinity of the plants. The marginal cost C ($ OD t^{-1}) for the harvesting, processing, and transport of the logging residues was estimated as $C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6$ with C_1 to C_6 being the respective costs for forwarding to roadside, chipping at roadside, hauling the comminuted material to the plant, administrative costs, reimbursement to land owners, and allocation costs for forwarders and chippers (Table 2). C_1 to C_6 were calculated for the NFI plots in the vicinity of each plant site according to the previously described procedure [21]. The hauling distances d_t were calculated as the shortest distance from the plot to the plant site, multiplied by a winding factor of 1.3.

3.4. Drying and Refining. For all three plants, it was assumed that excess combustion capacity could be used when available and that the only additional expense incurred by the plant was the cost of the extra raw material required to generate the heat needed for drying. The heat demand (see Section 3.2) was assumed to have a seasonal distribution according to a generic duration curve, as detailed data on duration were not available [37]. This results in an uncertainty in the time available for drying, and thus of the required drying power and the investment needed in drying equipment. At Lycksele, it was assumed that the increased combustion needed to generate heat for the dryer in seasons when the plant was not operating at capacity was also used to increase electricity production. The amount of additional electricity produced was estimated from the temperature and pressure of the steam (87.9 bar above atmospheric pressure and 504°C, resp.). It was further assumed that at the Lycksele site, heat for the dryer was obtained by extracting steam from the turbine at the two pressures 1.9 bar total pressure and 0.4 bar and mixing them to obtain a temperature of 110°C. For all three plants, an annual solid fuel production of 15 000 OD t was assumed. As the same raw material was used, the differences between the fuels which are relevant to this study concern particle size and bulk density (Table 1).

The chosen drying device was a bed dryer, for which a drying temperature of 95°C would be sufficient. The MC of the raw material was assumed to be 50% wt and that of the dried material was assumed to be 10% wt. The operating parameters for the process were assumed to be the same as those for a low-temperature drying process used in a pellet plant at Grums, Sweden. The amount of heat required for drying was 1.67 times the drying enthalpy of the moisture evaporated [38]. Due to the relatively small scale of the hypothetical setup, recovery of the latent heat in the steam was not considered. The production options for the sites were summarized in Table 3.

3.5. Prices. The price of electricity was set at the average value for 2009 on the Nordpool spot market (51.3 $ MWh^{-1}) and was converted into USD using the 2009 exchange rate of 7.65 SEK USD^{-1} [39, 40]. The Lycksele plant received public support for producing green electricity, yielding an income of USD 38.3 MWh^{-1} [41]. As the cost data in [34] were in 2004 Euros, they were converted into SEK at a rate of 9.13 SEK $€^{-1}$ and then converted into today prices using the official consumer price index [40, 42].

3.6. Financial Assumptions. When calculating capital costs, an interest rate of 7% and a depreciation time of 15 years

Table 3: Overview of current heat and electricity production for the three sites and the three production options: default (no dried fuel produced), pellet production (10% MC), and pellet chip production (15% MC).

	Lycksele			Vilhelmina			Vännäs		
	Default	Pellet	Pellet chips	Default	Pellet	Pellet chips	Default	Pellet	Pellet chips
Heat delivered (GWh year^{-1})	99.4	99.4	99.4	58.5	58.5	58.5	39.0	39.0	39.0
Electricity production (GWh year^{-1})	52.5	—	—	0	0	0	0	0	0
Fuel and heating water consumption (GWh year^{-1})	227.6	—	—	75.1	—	—	42.2	—	—

were assumed, resulting in an annuity factor of 0.110. As a rough estimate, fixed operating and management costs were assumed to be 2% of the total value of the investment annually.

3.7. Investments. The major investment required to produce pellet chips is a dryer. Fuel pellet production requires a dryer and also a grinder and a pelletizer with a cooler. The costs of these investments were assigned by scaling the values reported in the data sources by a factor of 0.7 (Table 4).

Investment costs were estimated on the basis of data for a bed dryer installed at Gruvön [38] and a preceding study on pellet production [34]. For all three heating plants, it was assumed that the existing combustion capacity was sufficient for fuel drying and that no additional investment was needed. However, the sites had different drying capacities. Indirect costs (notably, for the construction of buildings for fuel handling and storage) were assumed to amount to 37% of the costs for the dryer, grinder, and pelletizing equipment [34]. It was further assumed that the dried fuel could be stored in sufficient quantities for continuous operation of the grinding, pelletizing, and cooling equipment and that little excess capacity was needed for either of these items.

3.8. Costs of Operations, Management, and Electricity. The fixed operating and management costs were assumed to be 10% of the value of the investment for the hammer mills and pelletizing equipment due to high wear, and 2% of the investment for the other equipment [32, 34]. The variable operating and management costs for raw material handling, operating the chippers and dryers, and handling and packaging the finished fuel were set to 8.10 \$ OD t^{-1}.The electricity consumption for grinding and pelletizing was set to 92 kWh t^{-1} of pellets [34]. For the bed dryer, an electricity consumption of 37.8 kWh kg^{-1} of moisture evaporated was assumed [38].

3.9. Transport Costs. To compare the distances over which the finished fuel would have to be transported to customers for the three sites, the geographical distributions of the relevant regional markets were estimated. Three market segments were considered: (1) small- and medium-scale district-heating plants using pellets or briquettes; (2) public buildings using heating oil; (3) other users of heating oil (excluding industrial, agricultural, forestry, and residential uses). For segments (2) and (3), it was assumed that the oil was primarily used for space heating and that there were no technical obstacles to replacing the oil burners with pellet burners. Residential uses were not considered because the bark and foliage contents of logging residues would be likely to cause dust problems on that scale.

Transport distances to small- and medium-scale district heating plants within a radius of 250 km from each site were computed on a digital map [43]. The cumulative transport distances were estimated independently for each of the sites. It was assumed that 50% of the pellets/briquettes combusted in each district heating plant could be supplied by a single site and that 10% of the oil consumed by segments (2) and (3) could be converted to biomass combustion using fuel supplied by the same site. The consumption data used were for 2009 [44].

It was assumed that pellets would be transported using dedicated bulk transport trucks with a maximum payload of 37.5 t (10% MC). For pellet chip transport, general-purpose bulk trucks with a volume of 135 m^3 were assumed. The bulk densities of pellets and pellet chips were assumed to be 0.33 t m^{-3} for fresh pellet chips (50% MC), 0.19 t m^{-3}for dried pellet chips (15% MC), and 0.68 t m^{-3} for pellets (at 10% MC) [33]. Consequently, the transport cost for pellets was 65% of the production cost for pellet chips. Differences in costs for different types of trucks were not considered. The transport cost (\$ t^{-1} km^{-1}) for dried pellet chips was assumed to be identical to the previously discussed raw material transport cost, with the difference that exact data on the road distance were available, making the use of a winding factor unnecessary.

4. Results

4.1. Raw Material Supply. For each of the three plant sites, the total amounts of logging residues required to produce 15 000 OD t of either fuel pellets or pellet chips were calculated (Table 5).

4.2. Production Processes. At all three sites, it was assumed that additional logging residues would be combusted in the existing heating plants to generate heat for drying (Figure 1). Some of this energy was stored, in that it increased the heating value of the solid fuel produced for sale. In the case of Lycksele, some of this heat was also used to increase the plant net electricity production (by about 6% with pelletization and 8% without). The rest of the energy from the additional combustion was lost as low-temperature heat, either from the dryer or from the smokestack of the heating plant.

4.3. Costs for Production and Transport to Users. The transport costs from the Vilhelmina plant were significantly

Table 4: Required investments for each of the three plants.

	Lycksele		Vilhelmina		Vännäs	
	Pellet	Pellet chips	Pellet	Pellet chips	Pellet	Pellet chips
Dryer						
Reference cost (million US$)	2.35	2.35	2.35	2.35	2.35	2.35
Reference steam capacity (t h^{-1})	8.72	8.72	8.72	8.72	8.72	8.72
Steam capacity (t h^{-1})	2.67	2.67	3.09	3.09	5.22	5.22
Investment (million US$)	1.03	1.03	1.14	1.14	1.01	1.01
Hammer mill						
Reference cost (million US$)	0.079	0.079	0.079	0.079	0.079	0.079
Reference capacity (1000 t $year^{-1}$)	3.00	3.00	3.00	3.00	3.00	3.00
Capacity (t $year^{-1}$)	2.14	0.00	2.14	0.00	2.14	0.00
Investment (million US$)	0.06	0.00	0.06	0.00	0.06	0.00
Pelletizing, cooling equipment						
Reference cost, million US$	0.76	0.76	0.76	0.76	0.76	0.76
Reference capacity (t h^{-1})	9.00	9.00	9.00	9.00	9.00	9.00
Capacity (t h^{-1})	2.14	0.00	2.14	0.00	2.14	0.00
Investment (million US$)	0.28	0.00	0.28	0.00	0.28	0.00
Investments, process equipment (million US$)	1.37	1.03	1.14	0.79	1.35	1.01
Indirect costs (37%)	0.51	0.38	0.42	0.29	0.50	0.37
Total costs (million US$)	1.87	1.41	1.56	1.09	1.85	1.38

Table 5: Amount of logging residues required, average hauling distance (km), and average cost for logging residue provision ($OD t^{-1}) for the production of 15 000 OD t of either fuel pellets or pellet chips.

Plant site	Total amount of logging residues (OD t yr^{-1})	Average hauling distance (km)	Resulting average cost ($OD t^{-1})
Lycksele	44 000	18	100
Vilhelmina	20 000	27	98.6
Vännäs	20 000	21	93.7

higher than those for the other two sites (Figure 2). The presence of a substantial market in close proximity to Vännäs resulted in a low initial transport cost for this site, although the difference compared to Lycksele was smaller for higher production capacities.

Production costs were the highest at the Vännäs site (Figure 2). This was primarily due to the relatively low capacity of its existing heat plant, which would mean that drying heat could only be produced during a shorter part of the year compared to the other sites. Consequently, handling the quantity of logging residues considered in this study would necessitate a relatively large drying capacity, resulting in higher costs. At Lycksele, the increased electricity production improved the profitability of the operation. It was relatively expensive to extract and transport raw material to the Vilhelmina plant because it is in a region that has a low average temperature and therefore has a comparatively low productivity per hectare.

The cost of transporting fuel to consumers from Vilhelmina was considerably greater than the average, while that for Vännäs was considerably lower than the average. For all three sites, the difference between the total costs for pellets and pellet chips were small. The only site at which pellets were the most profitable option was Vilhelmina. However, the relative influence of the various costs differed from site to site, with transport costs generally having a greater impact for pellet chips.

4.4. Sensitivity Analysis. It was apparent that the total cost was most sensitive to the raw material cost (Figure 3), with the production cost being less important. The raw material costs could be reduced in various ways, for example, by adopting improved technologies for early thinning, handling of logging residues, and stump extraction. The raw material cost would increase if stem wood was used, although this could potentially yield a more valuable final product.

The production costs were quite sensitive to the financial assumptions A lower rate of interest, for example, 5%, and a longer depreciation time, for example, 25 years rather than 15, would reduce capital costs by 35.4%, reducing the production cost by 18 to 20%. Such a low interest rate may be relevant for public policy considerations. Conversely, investments by private companies may require interest rates well over the assumed 7%.

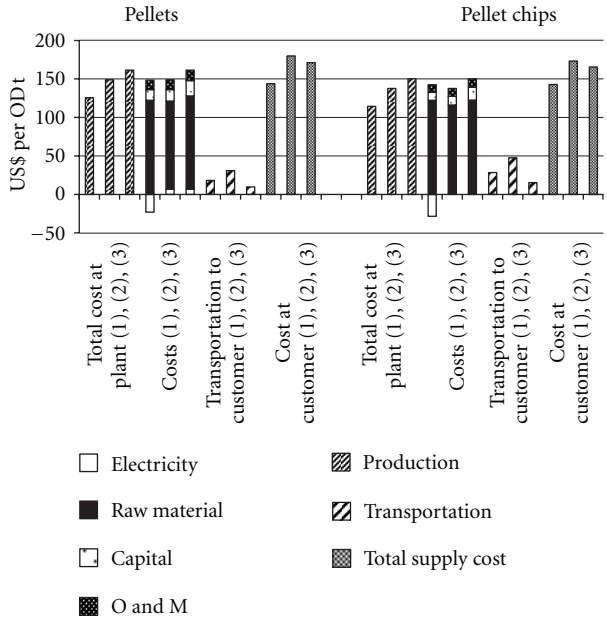

Figure 2: Supply costs for pellets (left) and pellet chips (right) when produced at (1) Lycksele, (2) Vilhelmina, and (3) Vännäs. Each plant was assumed to have a capacity of 15 000 oven-dry tonnes (OD t), with logging residues used as the raw material.

5. Discussion

Pellet chip production would only be economically viable if their market price exceeded their total production and transport costs of 140–185 \$ OD t^{-1} (26.7–35.2 \$ MWh^{-1}). For comparative purposes, the price for pellets used in medium-scale heat plants is around 216 \$ OD t^{-1} (41.3 \$ MWh^{-1}) [45]. It should be noted that the estimates discussed in this paper cover the costs of all operations from harvesting to delivery, with no analysis of how any profit would be distributed among different actors (such as the forestry, transport, and energy companies involved).

5.1. Harvesting and Transport of Raw Material. In this work, chipped logging residues were used both as a fuel for heat and power generation and as a raw material for manufacturing pellets and pellet chips. The supply cost of chipped logging residues proved to be the most important component in the production cost of pellets and pellet chips. It is known from the literature that the costs of procuring raw materials significantly affect the profitability of production [34]. Raw materials with lower bark and needle contents are likely to be more expensive than logging residues. For example, the reported price of chipped energy wood at the roadside was 98 \$ t^{-1}, compared to 85 \$ t^{-1} for chipped logging residues [46]. On the other hand, if a product with lower ash concentrations is produced, the market price of refined fuel for the small-scale market is considerably higher than the prices offered by operators of district heating plants (the price offered for pellets by small-scale residential users was about 280–390 \$ OD t^{-1} in 2009) [45, 47]. Identifying the most profitable process therefore necessitates a compromise. Cheaper raw materials such as whole trees, tree sections, and logging residues tend to be more ash-rich and yield a lower-value product, while more expensive raw materials with less bark and foliage yield high-value products.

There is great potential for increasing the cost-effectiveness of the harvesting and forwarding of logging residues, stumps, and wood from precommercial thinnings, since the technologies used at present are far from mature. Another possibility would be to reduce the amounts of needles, leaves, and bark in cheaper wood assortments, for example, through storage before chipping or mechanical separation before or after chipping. Several methods have been demonstrated for removing foliage, including separation using screens [48, 49] and aerodynamic methods [50].

5.2. Plant Capacity, Plant Location, and Production Cost. The production cost (excluding raw material and transport costs) for pellet chips was 8.4 to 10.1% lower than that for pellets. This was primarily due to lower capital costs, lower maintenance costs for high-wear equipment (pellet chip production does not require grinding and pelletizing equipment), and lower electricity consumption. The total cost for producing and transporting pellet chips was slightly lower than that for pellets at all sites other than Vilhelmina, which is relatively distant from its markets. It was observed that for lower production capacities and shorter average transport distances (the Lycksele and Vännäs cases), the reduced production cost of pellet chips was more important than their higher road transport costs compared to pellets. For higher production capacities and longer average transport distance (the Vilhelmina case), transport costs became more important, making pellets more competitive.

Drying is the most important plant operation in terms of production costs because it requires large amounts of heat and electricity. Recovering heat from the dryer by condensing the steam could potentially make the process more economical, especially on larger scales. Another way to reduce the heat load would be to allow the biomass to drying during storage. This could be done before comminution, after coarse comminution (e.g., chunking), which result in good storage properties [51–53] or after chipping. The use of low-temperature drying systems [54] could conceivably also reduce drying costs and make small-scale production more economical, reducing average transport distances. If drying could be conducted in modified cargo containers, handling costs would be minimized, reducing operational costs. Drying at small-scale district heating plants, as suggested by Yrjölä [27], would also reduce costs as no central drying location would be needed. However, more information is needed on the costs of drying systems of the type studied by Yrjölä. More detailed information will be required to accurately assess the scope for integrating fuel drying into existing district heating plants. Important factors include the plant annual excess heating capacity, the length of time during which this excess heat is available, and the existing infrastructure for processes such as fuel handling. The nature of the plant local markets also has a significant impact.

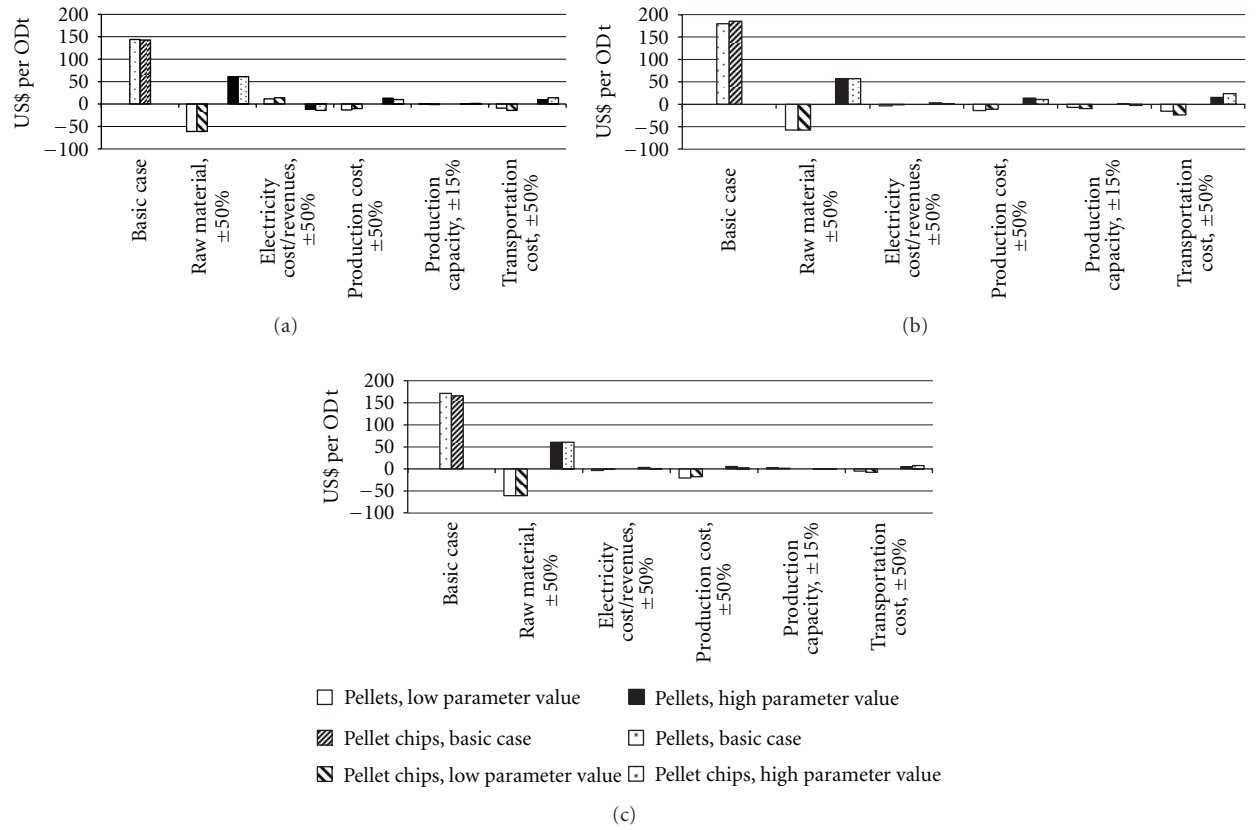

Figure 3: Results of the sensitivity analysis for the three plant sites—Lycksele (a), Vilhelmina (b), and Vännäs (c)—for pellet production (1) and pellet chip production (2). The following parameters were varied: raw material cost, electricity cost/electricity revenues, production cost, transport costs and product price (±50%), and productive capacity (±15%).

It is important to exploit existing combustion capacity rather than having to invest in new combustors. When existing generating capacity is available, the use of drying heat for electricity generation greatly reduces net production costs. Increasing the annual utilization time for the drying equipment reduces the investment needed for a given amount of dried material. If less heat is needed for drying, the utilization time for the dryer can be increased for a given duration curve, further reducing the dimensions of the dryer.

The heat load would also be reduced if slightly higher MC in the product could be accepted. Drying to 15% MC (below fiber saturation and sufficient to prevent the deterioration of the pellet chips by biological processes [55]) would reduce the need for drying heat by about 7% and would thus reduce the quantity of fuel consumed by the plant. This would make it possible to use a smaller dryer and less heat, which would reduce production costs and also increase the dryer annual utilization time. For Vilhelmina and Vännäs, the net effect of producing a fuel with a 15% MC would be to reduce production costs by 2–3% relative to those incurred at 10% MC (25.9–26.2 \$ MWh^{-1} rather than 26.2–26.6 \$ MWh^{-1}).

However, at Lycksele, the reduced demand for drying heat would reduce the amount of electricity generated, with the net result that increasing the MC of the fuel would not be profitable. For the other two sites, increasing the MC of the fuel would increase the number of potential locations for the dryer because smaller dryers can be operated with smaller sources of excess heat. An MC of 15% can be achieved with a simpler drying process and a cooler heat source compared to those required for an MC of 10%. These factors could increase the cost savings for producing fuel with an MC of 15% well beyond the 2–4% mentioned above. If a sufficient number of users have some drying capacity, or if small-scale flue gas condensation equipments were to become widely available at low cost, this result could be further improved.

While the economic yields of pellet production and pellet chip production are similar, an important difference is that dispensing with grinding and pelletization reduces the minimum investment required by 25 to 35%, if the assumptions made in this work hold. Provided that a market exists, risk-averse producers (who are likely to demand rates of return on invested capital that are substantially greater than 7%) may therefore find it preferable to manufacture pellet chips rather than pellets. The simpler production process for pellet chips would also reduce the risk of the enterprise and the amount of specialized know-how needed for production.

5.3. End Market and Product Transport. For the production scale considered in this study, the different transport properties of pellets and pellet chips were of limited importance.

There were two reasons for this. First, the transport cost was only 12.6–25.4% of the total cost for the delivered product. Second, limitations on the maximum weight of the trucks payloads mean that the higher bulk density of pellets cannot be fully exploited. Under the assumed conditions, the lower production costs for pellet chips compensated for this difference. One option that was not considered is increasing the bulk density of chips through compression. It has been reported that applying a pressure of 0.3 MPa to green pine chips increased their density to 0.280 OD t m^{-3}, which is about 40% higher than that without compression [56].

Only transportation by road was considered in this work. However, once the cargo has been loaded, rail transport is cheaper than road by a factor of 16 per t and km. For instance, at a loading cost of 4.3–5.7 \$ t^{-1}, the road transport cost considered in this work would make reloading worthwhile for distances above a few tens of km. Sea transportation has even lower marginal costs [57]. Thus, by using rail and sea transport, the range of markets available for a given location could be expanded significantly.

It was assumed that pellet chips could be fed into and burned in a significant proportion of existing medium- and small-scale combustors without modification or with only very slight modification. In cases where pellet chips could be sold to the small-scale market as well as the medium-scale market (which cannot be taken for granted, as small-scale equipment is more sensitive to fluctuations in feeding rate and operated by nonprofessionals) production could be more profitable. Better control technology may make the equipment less sensitive to fluctuations [28].

For pellet chips to be competitive with pellets, they would probably have to be significantly less expensive to buy. Lower cost of pellet chips compared to pellets would also be necessary to motivate consumers to convert existing oil- or electricity-based heating systems to use dried biomass fuels. Reducing the prices of pellet chips relative to pellets would make their production less profitable than the market price for pellets would suggest. The influence of price on demand was not considered in this work. It will be necessary to study the feeding and combustion properties of pellet chips in different types of equipment to identify any modifications needed to cope with the differences in fuel properties. Equipment manufacturers would have an important role to play in any such work. It will also be important to examine how demand is affected by fuel price and the different properties of pellet chips compared to pellets in order to accurately estimate the market price of the refined fuel. The increased market size accessible via sea and rail transportation should also be investigated, focusing on communities such as those along the interior railways in northern Sweden.

6. Conclusions

The supply costs (including raw material and transport costs) for producing 15 000 OD t of either wood pellets or small dried wood chips (pellet chips) annually have been estimated for three sites in Northern Sweden. The estimated cost of pellet production is 144–176 \$ OD t^{-1} (27.4–33.5 \$ MWh^{-1}) while that of pellet chips is 143–173 \$ OD t^{-1} (27.2–33.0 \$ MWh^{-1}). Assuming that the products can be sold at a price of 216 \$ OD t^{-1} (41.3 \$ MWh^{-1}, the current price for refined fuels used in heating plants in northern Sweden [46]) pellet chip production should be economically viable under the circumstances considered. For plants with low production capacities, pellet chips are expected to be more economical than pellets because their reduced production costs outweigh their greater road transport costs. The opposite is true for sites with greater productive capacities that are more distant from their markets. The capital costs for pellet chips were 17–27% lower than those for pellets, making pellet chip production more attractive to risk-averse producers.

The estimated costs for harvesting, forwarding, chipping, and transporting logging residues (including the cost of the additional fuel burned in the energy plant) were 114–122 \$ OD t^{-1} of fuel produced, making the raw material cost the most important component of the total cost of production and transportation. Raw material costs could be substantially reduced by developing improved methods for thinning and stump harvesting operations.

If the practical issues can be solved, it would be far more profitable to produce fuel for small-scale residential heating, which is much more expensive than that for medium-scale applications (the price of small-scale fuel is 390–410 \$ OD t^{-1}, compared to about 240 \$ OD t^{-1} for medium-scale). This is true even though the raw materials for small-scale fuel production (which include e.g., wood from early thinnings) are more expensive because of the need for low particle emissions. Cost-effective processes for foliage and bark separation could make it possible to cater to this market using cheaper raw materials (e.g., logging residues from regeneration fellings).

Improved methods for compacting and transporting chips could shift this market niche towards larger production capacities. Further development of small-scale low-temperature drying techniques would reduce the optimum process capacity, improving the competitiveness of pellet chips. To quantify the size of the market for pellet chips, it will be necessary to study the feeding and combustion properties of equipment designed for use with pellets and to determine how they would have to be modified for use with pellet chips. In particular, it will probably be necessary to increase their fuel feeding volume flows to compensate for the lower bulk density of pellet chips.

The feasibility of integrating fuel drying with existing combined heat and power plants and small-scale district heating plants should be studied in more detail, focusing on the specific circumstances at individual plants and sites. Important factors include the length of time during which excess heat is available, the properties of the steam generated, the potential drying capacity, and the availability of suitable raw material (energy wood from early thinning in particular). Storage of raw materials prior to comminution and drying should be investigated as a means of reducing their MC and the abundance of alkali-rich needles and leaves. Finally, it will be important to identify every heat source that could be used for fuel drying at a given site; even less intense

heat sources could potentially be used in low-temperature drying systems of the type described by Nordhagen [56].

Acknowledgment

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Research Article

Effect of Removal of Woody Biomass after Clearcutting and Intercropping Switchgrass (*Panicum virgatum*) with Loblolly Pine (*Pinus taeda*) on Rodent Diversity and Populations

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Plant-based feedstocks have long been considered viable, potential sources for biofuels. However, concerns regarding production effects may outweigh gains like carbon savings. Additional information is needed to understand environmental effects of growing feedstocks, including effects on wildlife communities and populations. We used a randomized and replicated experimental design to examine initial effects of biofuel feedstock treatment options, including removal of woody biomass after clearcutting and intercropping switchgrass (*Panicum virgatum*), on rodents to 2 years post-treatment in regenerating pine plantations in North Carolina, USA. Rodent community composition did not change with switchgrass production or residual biomass removal treatments. Further, residual biomass removal had no influence on rodent population abundances. However, *Peromyscus leucopus* was found in the greatest abundance and had the greatest survival in treatments without switchgrass. In contrast, abundance of invasive *Mus musculus* was greatest in switchgrass treatments. Other native species, such as *Sigmodon hispidus*, were not influenced by the presence of switchgrass. Our results suggest that planting of switchgrass, but not biomass removal, had species-specific effects on rodents at least 2 years post-planting in an intensively managed southern pine system. Determining ecological mechanisms underlying our observed species associations with switchgrass will be integral for understanding long-term sustainability of biofuels production in southern pine forest.

1. Introduction

Plant-based feedstocks have long been considered viable, potential sources for biofuels, which are defined as liquid fuels derived from biological materials [1] that could displace fossil fuel consumption. However, concerns with production effects on prices of food crops, the carbon footprint of large-scale production, potential land-use change, and effects on biodiversity may outweigh gains in carbon savings or other benefits [1, 2]. Therefore, additional information is needed related to sustainability of biofuels production and to understand environmental impacts of growing biofuel feedstocks, including impacts on biodiversity [3–5].

Source landscapes for biofuel feedstocks have expanded from agricultural to forested as technologies have developed to transform cellulosic portions of woody plants into liquid fuels at a production scale. In managed forests, biofuels typically have been produced by harvesting biomass including forest residues (i.e., tops, stumps, limbs, or unmerchantable trees that remain after harvesting and removing crop trees) or by planting short rotation woody species, such as aspen (*Populus* spp.) or eucalyptus (*Eucalyptus* spp.) [6, 7]. However, more recent efforts also have examined whether perennial grasses such as switchgrass (*Panicum virgatum*), a species native to eastern North America, could be intercropped between rows of crop trees in pine (*Pinus* spp.) plantations

so that both traditional forest products and cellulosic energy crops could be produced on the same land base. Intercropping biofuels on managed forests may avoid concerns related to land-use change or the food versus fuel debate while still producing a carbon-neutral source of energy [1, 8]. Recently, there has been increasing interest in intercropping switchgrass within intensively managed pine stands within the southeastern United States with pilot projects being conducted to assess feasibility. For example, in 2008, Catchlight Energy LLC, a Chevron/Weyerhaeuser Joint Venture (http://www.catchlightenergy.com/), was formed in part to assess the large-scale viability of such a management system. However, environmental effects of producing biofuels from forests, either from harvesting residual woody biomass or by intercropping perennial grasses, have not been well studied [1, 6, 9].

Rodents are model species for understanding ecological effects of anthropogenic activities for a multitude of reasons [10–12]. They contribute to species and functional diversity of the animal community [13] and are ecosystem engineers that create, modify, and maintain habitat structures (such as burrows) that influence nutrient cycling, soil aeration and habitat use by other animal species [14]. Rodents directly influence distribution and abundance of many species through their use of a variety of food sources (e.g., plants, lichen, fungi, and invertebrates) and as prey for many vertebrate predators [13].

Abundances of small mammals are influenced by changes in habitat structure, including removal of woody debris [15, 16] and cover of grasses [17, 18], so biofuels production may affect population dynamics and habitat relationships of rodents. Population abundance can be influenced by changes in habitat structure and quality, and a range of demographic parameters determines population abundance. The primary influences on population abundance are apparent survival and recruitment, which together indicate reproductive success, mortality, immigration to and emigration from a population. Additionally, adult sex ratio is important because it helps determine the effective population size. Thus, population abundance can be influenced by habitat structure, and with supporting demographic data, can be used to infer habitat quality [19]. Community composition and diversity of small mammals also vary with habitat structure [20, 21] suggesting that changes to habitat associated with biofuels production could also affect rodent diversity and abundance.

To better understand effects of producing biofuels from forested landscapes on animal communities and populations, we examined initial outcomes of a range of biofuels treatment options, including a biomass removal harvest and intercropping of switchgrass, on rodent community structure and population demographics. Population demographic parameters we examined included population abundance, recruitment, survival, and sex ratio for two years following treatment application. We hypothesized that rodent population abundance and community diversity would be greater in treatments where habitat heterogeneity was the greatest. We also hypothesized that population metrics related to habitat quality, including recruitment, survival, and male : female ratios would reflect greater habitat quality in treatments where more nest sites were available, such as treatments without a biomass removal harvest. This study is the first that we are aware of to experimentally examine a range of biofuels options and their effects on rodent communities and populations.

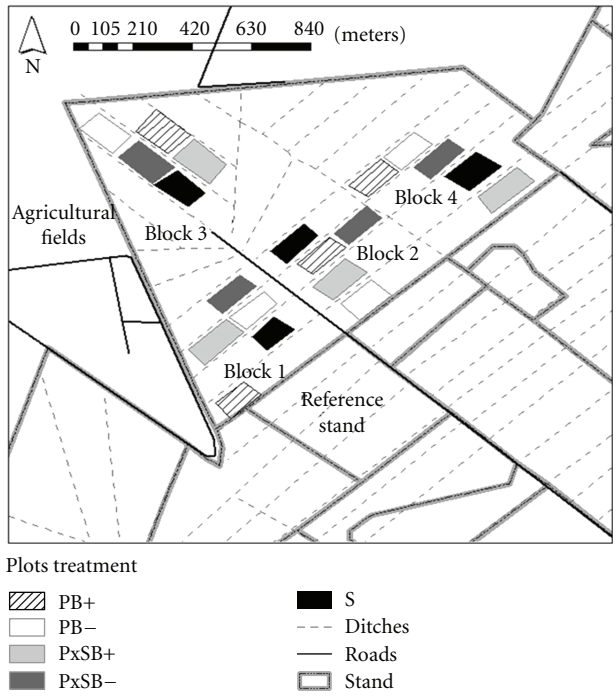

Figure 1: Map of study area, established and maintained by Catchlight Energy LLC, located in timberlands owned and managed by Weyerhaeuser Company in Lenoir Co., NC. Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass.

2. Methods

2.1. Study Area and Experimental Design. Our study was conducted in the southeastern coastal plain on the Lenoir 1 Sustainability Study Site, established and maintained by Catchlight Energy LLC on land owned and managed by Weyerhaeuser Company in Lenoir County, North Carolina, USA. The region is sandy bottomland forest dominated by agriculture and intensively managed loblolly pine (*Pinus taeda*) forests. The study site was a 72-ha loblolly pine plantation established in 1974 with a site index of 70 for loblolly pine at 25 years (by 25 years of growth, loblolly pine trees can be expected to reach 70-feet (21.3 m) in height due to site potential). Ground water levels were maintained via linear ditches that occurred along forest edges and paralleled each other through interiors of study site blocks (Figure 1).

Within the study site, a 33.6 ha research area was divided into 20 experimental plots that were clear-cut harvested, site prepared, and replanted with loblolly pine seedlings and/or switchgrass in 2008-09 (Figure 1). The experimental design was a randomized complete block with plots as the

experimental unit (4 replicates) and study sites as blocks (4 study blocks and 5 treatments per block). Plots averaged 1.11 ha in size (range: 0.76–1.39 ha: Figure 1). Within a block, experimental plots were randomly assigned one of the following five treatments:

2.1.1. Pine with Residual Woody Debris in Place, (Pine Biomass+, PB+). Treatment plots had standard mechanical site preparation (V-shearing of stumps and roots, subsoiling, and bedding at 6.1 m between rows). Loblolly pines planted in December 2008 were centered on raised beds and spaced 1-2 m apart. Residual woody debris was left on site.

2.1.2. Pine with Residual Woody Debris Removed, (Pine Biomass−, PB−). Standard mechanical site preparation occurred (V-shearing of stumps and roots, subsoiling, and bedding at 6.1 m between rows) and pines were planted on beds 1-2 m apart. Residual woody debris was removed from the plot with an excavator to simulate a biomass harvest.

2.1.3. Pine and Switchgrass Intercropped with Residual Woody Debris in Place (Pine × Switchgrass, Biomass+, P × SB+). Site preparation and planting of pines followed the pine biomass + treatments. Switchgrass was machine planted in June 2009 in the alleys between rows of planted pines.

2.1.4. Pine and Switchgrass Intercropped with Residual Woody Debris Removed, (Pine × Switchgrass, Biomass−, P × SB−). Site preparation and planting of pines followed the pine biomass treatments. Residual woody debris was removed with an excavator to simulate a biomass harvest. Switchgrass was machine planted in June 2009 in the alleys between rows of planted pines.

2.1.5. Switchgrass Only, (S). Site preparation included excavation to remove residual woody debris, V-shearing, and root raking to establish a suitable planting surface. Switchgrass was machine-planted May–July 2009 across the entire plot.

Habitat structure of each treatment was assessed using two 30 m transect lines on each study plot (Figure 2) in October 2010. To estimate canopy coverage, vegetation, or woody debris that crossed transect lines and covered a minimum length of 10 cm along the line were measured using point interception methods [22, 23]. Percent coverage was calculated as the linear distance a habitat feature intersected the transect line divided by transect line length (30 m) and averaged across two transect lines per plot. Mean height of each habitat feature that intersected a transect line was estimated to the nearest 10 cm. Height was calculated as mean height of each habitat variable on a transect line, averaged across two transect lines on each study plot.

2.2. Rodent Live Trapping. We established trapping grids (30 m × 60 m) approximately 20 m from the edge of each study plot using four parallel trap lines with 10 m between traps. Each trap line was composed of six Sherman live traps (H.B. Sherman Traps Inc., Tallahassee, Florida, USA) and one randomly assigned Longworth (Rogers Manufacturing Co., Peachland, British Columbia, Canada).

We set traps at sunset (1700–2030) and checked them at sunrise (0600–0830) for three consecutive nights (henceforth referred to as a trapping period). We baited with a mixture of sunflower seeds and rolled oats. We conducted 8 trapping periods from 15 July to 9 December, 2009, and 6 trapping periods from 19 July to 14 November, 2010. We marked all rodents with a unique numbered ear-tag (Monel Numeric size 1005-1; National Band and Tag Co, Newport, Kentucky, USA). Upon capture of each rodent, we recorded ear-tag number, species, sex, age-class, reproductive condition, and mass (g). We considered *P. leucopus* to be adults if they had completed their post-juvenile molt [24] and *S. hispidus* to be adults if they weighed >80 g [25]. We based age classes of other species on a combination of body mass and pelage characteristics. All rodent trapping, marking, and handling techniques were approved by the North Carolina Wildlife Resources Commission (Permit Numbers: 09-SC00162 and 10-SC00162) and the UNCG Institutional Animal Care and Use Committee (Protocol Numbers: 09-09 and 10-04).

We calculated community diversity at the plot scale with multiple metrics, including species richness (number of species captured in a plot/year), the Shannon Diversity Index, and the Fisher' α Diversity Index. We calculated Shannon Diversity Index as H′ using number of unique individuals, for each species, captured in a year [26] using Ecosim7 [27]. We calculated Fisher's α Diversity Index for study plots using number of unique individuals, for all species, captured in a year as $S = a + \ln(I + (n/a))$ where S = species richness, n = number of unique individuals, and a = Fisher's α. We used Estimate *S* 8.2 [28] with 1000 runs, strong hash encryption, and randomized samples without replacement to determine Fisher's α Diversity Index.

We calculated population abundance and apparent survival for all adults in the populations using Program MARK [29]. We used Pollock's robust design model (Huggins closed capture estimator—see [30, 31]) to estimate population abundance during each trapping period and population survival during each intertrapping interval [32]. We used the Huggins close capture estimator because it is conditional on only animals captured and is, therefore, a more stable estimator for small sample sizes [30]. Data were grouped by species and year for analysis; the best model for each grouping was chosen based on AICc values.

In addition to examining community diversity and population abundance, we also examined sex ratio and recruitment because these demographic parameters can be influenced by habitat quality [19]. We determined sex ratio and recruitment using Program MARK. Adult sex ratio was calculated as number of adult males divided by number of adults in each population as estimated by Pollock's robust design models (Huggins closed capture estimator) with sex as a group variable. Recruitment (births and immigration) was calculated using a robust design Pradel survival and recruitment model, with Huggins closed captures estimator [33]. Due to small sample sizes when data were separated by species and plots, model selection was limited to those models with constant recruitment over time. Therefore, reported

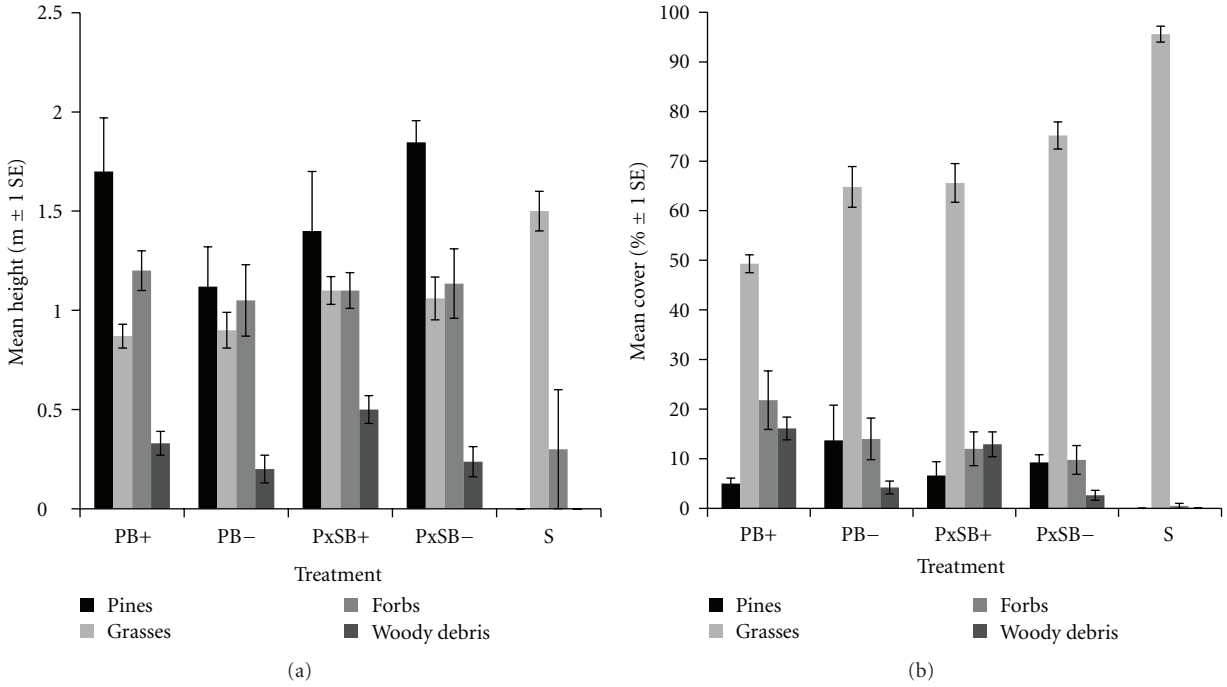

Figure 2: Mean (a) height (m; ±1 standard error) and (b) cover (%; ±1 standard error) of pines, grasses, forbs, and woody debris in treatment plots at the Lenoir 1 Sustainability Study Site, in Lenoir Co, NC. Mean percent cover and mean height represent the mean value of four replicate plots based on measurements taken in October 2010. Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass.

recruitment estimates represent recruitment per existing member for each plot. Parameterization of encounter probabilities (p and c) for each year-species combination matched the best fit model from the adult population abundance models.

2.3. Statistical Analyses. All dependent variables were calculated for each plot that represented an area of approximately 1,800 m^2. All data are presented as mean ± 1 standard error unless otherwise noted. We tested variables for normality using a Kolmogorov-Smirnov test and homogeneity of variance using a Levene's test. Where appropriate, we transformed variables that violated tests for normality or homogeneity of variance with log (+1), rank, square root, or square root-arcsin transformations.

We tested the hypothesis of no differences among treatments in community metrics (i.e., richness, Shannon Diversity Index, Fisher's α Index), abundance, recruitment, survival, and sex ratio among treatments using analysis of variance (ANOVA) or a Kruskal-Wallis test when parametric assumptions were not met. We examined relationships among population abundance and treatments by rank transforming population abundance and using an ANOVA because this facilitated a repeated measures approach [34]. For the three rodent species for which we could calculate abundance, we used repeated measures ANOVA with treatment as the between-subject factor and trapping period as the within-subject factor. In cases where the repeated measures ANOVA tests did not meet assumptions of sphericity, we used a Greenhouse-Geisser correction factor [35]. For posthoc comparisons among treatment groups, we used Tukey's analyses for ANOVA procedures and Mann-Whitney U pairwise comparisons for Kruskal-Wallis procedures. We used an alpha level of 0.05 for all statistical tests and we conducted analyses with SPSS 16.0 (SPSS 2007, Chicago, Ill, USA).

3. Results

In 2009, we trapped small mammals on 77 nights (15,366 trap nights), capturing 648 unique individual rodents (267 *Peromyscus leucopus*, 248 *Mus musculus*, 122 *Sigmodon hispidus*, and 11 *Reithrodontomys humulis*) 1,806 times. In 2010, we trapped on 54 nights (11,044 trap nights) capturing 1,634 unique individual rodents (1,030 *S. hispidus*, 310 *M. musculus*, 297 *P. leucopus*, 15 *R. humulis*, and 6 *Oryzomys palustris*) 3,594 times. In 2009 and 2010, treatment did not influence species richness or diversity (Table 1). Sample sizes were too small for analyses for *R. humulis* and *O. palustris*.

In 2009, there was a significant effect of trapping period on *M. musculus* population abundance ($F_{7,105} = 7.81$, $P < 0.001$) whereby a relatively small population of *M. musculus* in early trapping rounds increased through trapping periods 4 and 5 (Figure 3). In addition, there was a treatment effect on *M. musculus* where population abundance was less in PB+ plots than P × SB− plots ($F_{4,15} = 4.29$, $P = 0.02$; Figure 4). *M. musculus* population abundance was greater in treatments that contained switchgrass than treatments

Table 1: Mean (±1SE) values of species richness, Shannon Diversity Index, and Fisher's α by treatment in 2009 and 2010. Rodents were captured and released on site at the Lenoir 1 Sustainability Study Site, in Lenoir Co., NC, during 15 July–9 December, 2009 and 19 July–14 November, 2010. Statistical results are from comparisons using a 1-way ANOVA or Kruskal-Wallis test when parametric assumptions were not met. Kruskal-Wallis test statistics are reported as χ^2 estimates. Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass.

Year	Treatment	Species Richness	Shannon Diversity Index	Fisher's α
2009	PB+	3.25 ± 0.25	0.75 ± 0.10	0.75 ± 0.07
	PB−	2.75 ± 0.25	0.62 ± 0.19	0.63 ± 0.08
	P × SB+	3.25 ± 0.48	0.92 ± 0.11	0.72 ± 0.13
	P × SB−	3.25 ± 0.25	0.99 ± 0.09	0.72 ± 0.09
	S	3.50 ± 0.09	0.84 ± 0.15	0.76 ± 0.09
		$\chi^2 = 3.20$, df = 4, $P = 0.53$	$F_{4,19} = 1.20$, $P = 0.34$	$F_{4,19} = 0.31$, $P = 0.87$
2010	PB+	3.00 ± 0.0	0.78 ± 0.09	0.55 ± 0.01
	PB−	3.50 ± 0.29	0.91 ± 0.07	0.66 ± 0.07
	P × SB+	3.50 ± 0.29	0.86 ± 0.14	0.65 ± 0.08
	P × SB−	3.75 ± 0.25	0.76 ± 0.15	0.69 ± 0.07
	S	3.50 ± 0.29	0.89 ± 0.08	0.67 ± 0.07
		$\chi^2 = 4.61$, df = 4, $P = 0.33$	$F_{4,19} = 0.40$, $P = 0.80$	$\chi^2 = 1.02$, df = 4, $P = 0.91$

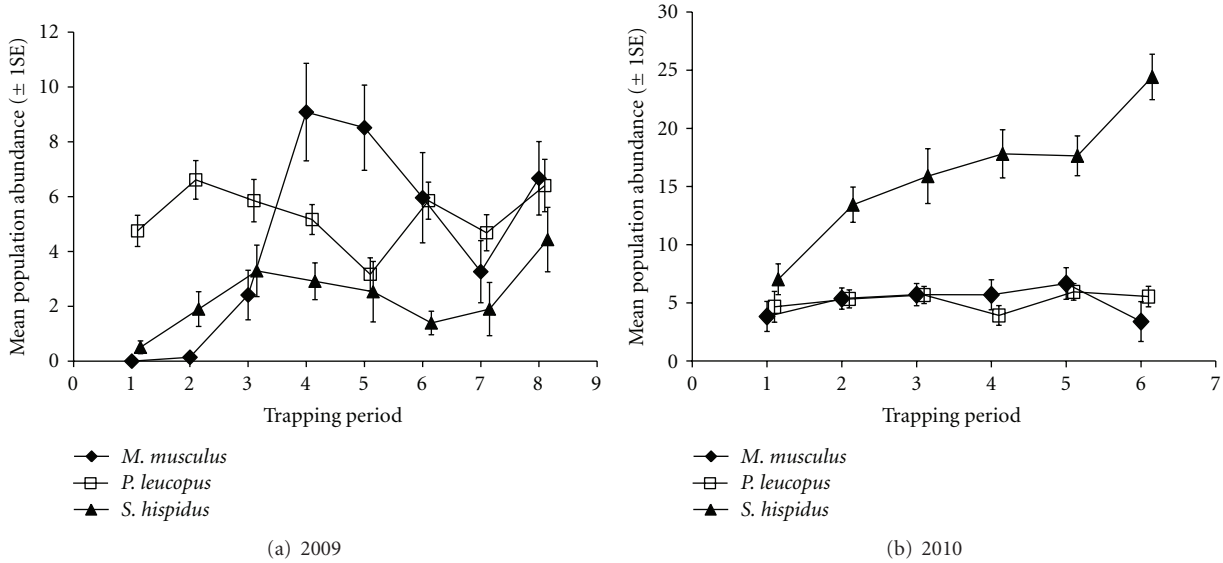

Figure 3: Population abundance (mean abundance ± 1 standard error; $n = 4$) for *Mus musculus, Peromyscus leucopus,* and *Sigmodon hispidus* by trapping period in (a) 2009 and (b) 2010 at the Lenoir 1 Sustainability Study Site, in Lenoir Co., NC. Axes vary between plot (a) and (b) to improve readability. Although not shown, 18 *Reithrodontomys humulis* were captured in 2009: 1 in period 2 (P2), 3 in P3, 2 in P4, 2 in P5, 5 in P6, 3 in P7, and 2 in P8. Sixteen *R. humulis* were captured in 2010 (3 in P3, 3 in P4, 3 in P5, and 7 in P6). Additionally, 6 *Oryzomys palustris* were captured in the last trapping periods of 2010. Rodents were captured and released during 15 July–9 December, 2009 and 19 July–14 November, 2010.

that did not, although not all pairwise comparisons were significant (Figure 4). *P. leucopus* population abundance did not differ among trapping periods ($F_{7,105} = 0.13$, $P = 1.00$; Figure 3) nor treatments ($F_{4,15} = 0.88$, $P = 0.50$; Figure 4). *S. hispidus* population abundance did not differ among trapping periods ($F_{3.49,52.38} = 1.21$, $P = 0.32$; Figure 3) nor treatments ($F_{4,15} = 0.53$, $P = 0.72$; Figure 4).

Population abundances were not influenced by trapping period in 2010 (*M. musculus*: $F_{5,75} = 0.21$, $P = 0.96$; *P. leucopus*: $F_{2.73,40.90} = 0.03$, $P = 0.99$; *S. hispidus*: $F_{1.72,40.89} = 0.11$,

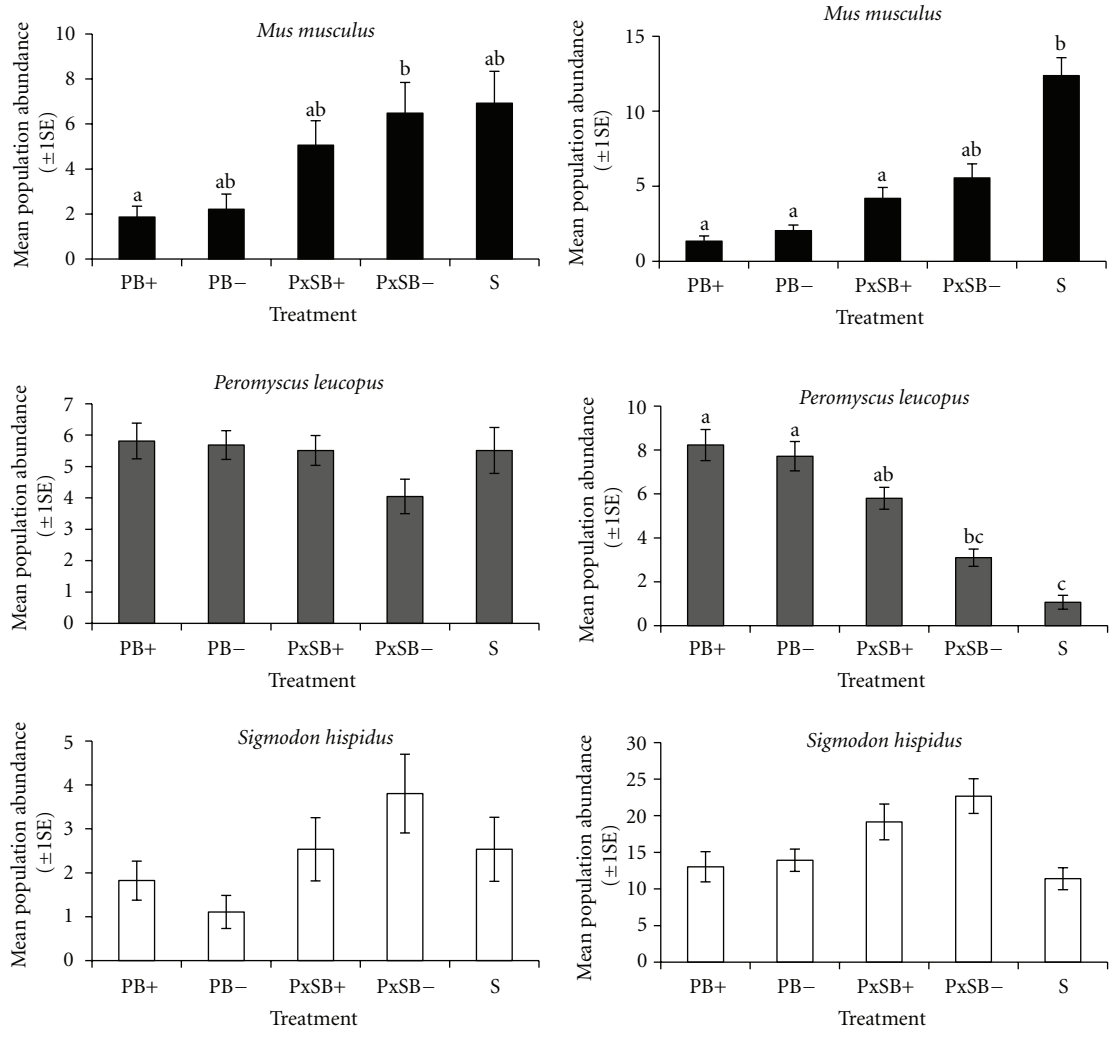

Figure 4: Population abundance estimates from Program MARK (mean number of adult individuals/plot, ± 1 standard error; $n = 4$) for *Mus musculus, Peromyscus leucopus,* and *Sigmodon hispidus* by treatment in (a) 2009 and (b) 2010 at the Lenoir 1 Sustainability Study Site, in Lenoir Co, NC. *y*-axes vary between plot (a) and (b) to improve readability. Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass. Treatments with different letters are significantly different ($P < 0.05$; Tukey's post hoc tests). Rodents were captured and released during 15 July–9 December, 2009 and 19 July–14 November, 2010.

$P = 0.94$; Figure 3). *M. musculus* population abundance was greatest in switchgrass only plots ($F_{4,15} = 8.25$, $P < 0.001$; Figure 4). In contrast, population abundance was the lowest for *P. leucopus* in switchgrass only plots and the greatest in plots without switchgrass (PB+ and PB−), although not all pairwise comparisons showed significant differences ($F_{4,15} = 13.61$, $P < 0.001$; Figure 4). *S. hispidus* population abundance did not differ among treatments ($F_{4,15} = 1.40$, $P = 0.28$; Figure 4).

There was no influence of treatment on recruitment of *M. musculus, P. leucopus,* or *S. hispidus* in either year (Table 2). Survival of *P. leucopus* was less in the pure switchgrass treatment than in treatments without switchgrass in 2010 (PB−, PB+; Table 3). Treatments also influenced sex ratio where there were fewer *M. musculus* males in PB+ than PB− treatments in 2010 (Table 4).

4. Discussion

Our results suggest that community composition of rodents did not change due to switchgrass intercropping or biomass removal treatments. However, there were species level responses to switchgrass whereby more *P. leucopus* were in plots without switchgrass and more *M. musculus* in plots with switchgrass. Additionally, decreased apparent survival of *P. leucopus* in switchgrass suggests that individual *P. leucopus* that did move into switchgrass was either less likely to survive or more likely to permanently emigrate from those treatments. This finding contrasts with higher apparent survival of *P. leucopus* in PB− and PB+ treatments (treatments without switchgrass), where they experienced either decreased mortality or decreased likelihood of permanent emigration from those treatments.

Table 2: Mean (±1SE) recruitment estimates (new individual via birth or immigration/existing member/plot) by treatment (calculated in Program MARK). Rodents were captured and released on site at the Lenoir 1 Sustainability Study Site, in Lenoir Co., NC, during 15 July–9 December, 2009 and 19 July–14 November, 2010. Statistical results are from comparisons using a 1-way ANOVA or Kruskal-Wallis test when parametric assumptions were not met. Kruskal-Wallis test statistics are reported as χ^2 estimates. Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass.

Year	Treatment	*M. musculus*	*P. leucopus*	*S. hispidus*
2009	PB+	0.24 ± 0.14	0.03 ± 0.01	0.10 ± 0.07
	PB−	0.44 ± 0.15	0.03 ± 0.00	0.73 ± 0.25
	P × SB+	0.27 ± 0.19	0.03 ± 0.00	0.06 ± 0.23
	P × SB−	0.10 ± 0.01	0.03 ± 0.01	0.44 ± 0.23
	S	0.20 ± 0.14	0.03 ± 0.01	0.79 ± 0.77
		$F_{4,19} = 0.80$, $P = 0.54$	$F_{4,19} = 0.19$, $P = 0.94$	$\chi^2 = 4.14$, df = 4, $P = 0.39$
2010	PB+	0.22 ± 0.16	0.02 ± 0.00	0.05 ± 0.01
	PB−	0.22 ± 0.12	0.03 ± 0.00	0.04 ± 0.00
	P × SB+	0.07 ± 0.02	0.03 ± 0.00	0.04 ± 0.01
	P × SB−	0.20 ± 0.11	0.21 ± 0.18	0.03 ± 0.00
	S	0.06 ± 0.01	0.24 ± 0.19	0.05 ± 0.01
		$\chi^2 = 3.64$, df = 4, $P = 0.46$	$\chi^2 = 5.73$, df = 4, $P = 0.22$	$\chi^2 = 3.96$, df = 4, $P = 0.41$

Table 3: Mean (±1SE) survival estimates for intertrapping period intervals by treatment (averaged across time and plots within treatment; calculated in Program MARK). Rodents were captured and released on site at the Lenoir 1 Sustainability Study Site, in Lenoir Co., NC, during 15 July–9 December, 2009 and 19 July–14 November, 2010. Statistical results are from comparisons using a 1-way ANOVA or Kruskal-Wallis test when parametric assumptions were not met. Kruskal-Wallis test statistics are reported as χ^2 estimates. Within a year-species pairing, means with different letters are significantly different from one another (Tukey's post hoc tests). Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass.

Year	Treatment	*M. musculus*	*P. leucopus*	*S. hispidus*
2009	PB+	0.46 ± 0.03	0.93 ± 0.04	0.57 ± 0.06
	PB−	0.51 ± 0.04	0.92 ± 0.04	0.39 ± 0.03
	P × SB+	0.56 ± 0.05	0.92 ± 0.04	0.53 ± 0.06
	P × SB−	0.57 ± 0.05	0.93 ± 0.03	0.53 ± 0.05
	S	0.66 ± 0.05	0.87 ± 0.05	0.60 ± 0.06
		$F_{4,15} = 0.85$, $P = 0.51$	$F_{4,15} = 0.14$, $P = 0.97$	$F_{4,12} = 1.29$, $P = 0.33$
2010	PB+	0.49 ± 0.07	0.98 ± 0.00[a]	0.93 ± 0.04
	PB−	0.50 ± 0.06	0.99 ± 0.00[a]	0.95 ± 0.03
	P × SB+	0.67 ± 0.07	0.93 ± 0.04[a]	0.96 ± 0.03
	P × SB−	0.59 ± 0.07	0.75 ± 0.07[ab]	0.99 ± 0.00
	S	0.81 ± 0.06	0.56 ± 0.06[b]	0.97 ± 0.01
		$F_{4,14} = 1.02$, $P = 0.43$	$F_{4,15} = 5.30$, $P = 0.007$	$F_{4,15} = 1.28$, $P = 0.32$

Rodent species captured in this study were expected to be found inhabiting pine forests in the southeast [15, 17, 36, 37]. *Peromyscus leucopus, S. hispidus, R. humulis,* and *M. musculus* were the only species captured in study plots in the first year of study and were >99% of the individuals captured in the second year of study (6 *O. palustris* were captured during November 2010).

The most abundant species captured shifted from *P. leucopus* in 2009 to *S. hispidus* in 2010. Both years of the study experienced similar weather, and there were no discrete weather events that would explain the patterns of population abundance we saw between years. Rather, shifts in species relative population abundance between years is likely due to successional changes, and has been observed in other studies of young pine plantations in the southeastern USA, and in secondary succession of both forest and grassland habitat types [36, 38, 39]. *Sigmodon hispidus* prefers grassy understory [40, 41], which was not available on study plots until 2010. This shift from *P. leucopus* to *S. hispidus* being the most abundant species suggests the rodent community responded to changes that occurred in habitat structure between site preparation at the beginning of year one and treatment establishment.

Our treatments varied along two resource axes: residual pine biomass (i.e., coarse woody debris; CWD) and switchgrass presence. Our results suggest that retention of biomass did not influence rodents within the first two years postsite preparation in this system because, overall, treatments with

Table 4: Mean (±1SE) values of sex ratio (proportion males) from adult population abundance estimates calculated in Program MARK. Rodents were captured and released on site at the Lenoir 1 Sustainability Study Site, in Lenoir Co., NC, during 15 July–9 December, 2009 and 19 July–14 November, 2010. Statistical results are from comparisons using a 1-way ANOVA or Kruskal-Wallis test when parametric assumptions were not met. Kruskal-Wallis test statistics are reported as χ^2 estimates. Within a year-species pairing, means with different letters are significantly different from one another (Mann-Whitney U pairwise comparisons with Bonferroni correction). Treatments: PB+ = Pine Biomass+; PB− = Pine Biomass−; P × SB+ = Pine × Switchgrass Biomass+; P × SB− = Pine × Switchgrass Biomass−; S = Switchgrass.

Year	Treatment	*M. musculus*	*P. leucopus*	*S. hispidus*
2009	PB+	0.72 ± 0.09	0.65 ± 0.04	0.49 ± 0.12
	PB−	0.57 ± 0.11	0.57 ± 0.05	0.44 ± 0.12
	P × SB+	0.65 ± 0.08	0.60 ± 0.04	0.58 ± 0.09
	P × SB−	0.61 ± 0.07	0.61 ± 0.06	0.38 ± 0.19
	S	0.52 ± 0.08	0.62 ± 0.04	0.74 ± 0.09
		$F_{4,19} = 0.35$, $P = 0.84$	$\chi^2 = 0.27$, df = 4, $P = 0.99$	$F_{4,19} = 0.63$, $P = 0.65$
2010	PB+	0.44 ± 0.12[a]	0.62 ± 0.04	0.63 ± 0.04
	PB−	0.81 ± 0.08[b]	0.55 ± 0.03	0.55 ± 0.04
	P × SB+	0.40 ± 0.09[ab]	0.79 ± 0.04	0.43 ± 0.04
	P × SB−	0.60 ± 0.06[ab]	0.60 ± 0.07	0.43 ± 0.05
	S	0.64 ± 0.04[ab]	0.42 ± 0.13	0.61 ± 0.05
		$\chi^2 = 11.03$, df = 4, $P = 0.026$	$F_{4,19} = 0.96$, $P = 0.46$	$F_{4,19} = 2.02$, $P = 0.14$

biomass removal had similar rodent abundances compared to treatments without biomass removal. A recent meta-analysis indicated little or no consistent response of mammal diversity to CWD and suggests that small mammal response to CWD is very context dependent. We were not able to find a relationship between small mammal metrics and removal of biomass in this study, which is consistent with other studies in the southeastern USA. At this time, it is unclear if a greater range of removal levels or a greater range in CWD amounts among treatments would have caused a stronger small mammal response [42]. Although biomass provides important habitat structure (i.e., nest sites, foraging substrate, and cover from predators) for rodents, it is likely that other factors such as presence of switchgrass (i.e., a potential source of food and cover) exerted a greater influence during early succession in this managed pine forest.

Presence of switchgrass changed habitat structure and resources available to the rodent community in young managed pine stands during the first two years of growth [43]. Differences in habitat structure among treatments with and without switchgrass were reflected in rodent population responses within the first year of study and became more pronounced in the second year of the study. While there was no effect of treatment on sex ratio or recruitment, population abundance and survival data suggest that *P. leucopus* was negatively affected by switchgrass presence. During the second year of study, *P. leucopus* adults were found in greatest abundance in PB+ and PB− treatments (nonswitchgrass treatments) and had greater apparent survival (mortality and permanent emigration) in these plots. Our results suggest that individual *P. leucopus* in plots with switchgrass (P × SB− and S) were either less likely to survive or more likely to permanently emigrate from the habitat. In contrast, *P. leucopus* in PB+ and PB− habitat experienced either decreased mortality or decreased likelihood of permanent emigration from the habitat. *Peromyscus leucopus* is typically an early successional species that is more abundant in open habitat types than areas with greater understory foliage cover [36, 44]. In our study, plots with switchgrass contained dense switchgrass cover. Our results suggest that switchgrass-dominated understories may not provide sufficient resources to support *P. leucopus* and/or that *P. leucopus* may be outcompeted by *M. musculus* in these treatments. However, additional research is needed to determine if this effect is temporary, if it changes with further stand development, and the causal mechanisms of this effect.

In contrast to our findings for *P. leucopus*, the population abundance of *M. musculus* was positively affected by switchgrass. During the first year of study, there were more *M. musculus* in the P × SB− and S plots than the other plots, and by the second year of study, there were over twice as many adults captured in switchgrass only plots than any other treatment. Additionally, *M. musculus* abundance in the intercropping treatments was intermediate to either S or PB+/PB− treatments. However, there was no effect of treatment on the apparent survival or recruitment (*per capita* births and immigration) of *M. musculus*. Therefore, while more *M. musculus* individuals were found in switchgrass treatments, the proportional population dynamics were similar among treatments—*M. musculus* were not more or less likely to survive, reproduce, immigrate or emigrate from any treatment. Yet in the second year, the adult populations of *M. musculus* in PB− were male dominated, the populations in PB+ had even sex ratios and the switchgrass treatments were intermediate between the two pine treatments. These findings suggest that female *M. musculus* may have been differentially affected by the presence of biomass in their less preferred habitat.

Mus musculus is an introduced, invasive species that can increase in abundance rapidly when required resources become available [44]. In the first year of our study, *M. musculus* abundance increased across trapping periods from

July–December 2009. Appearance of *M. musculus* in study plots in late August 2009 occurred simultaneously with harvest of corn (*Zea mays*) fields located adjacent to the north and east borders of our study area (Figure 1). Based on initial captures, abundance of *M. musculus* adults increased, suggesting an initial immigration event occurred on the study site from adjacent agricultural fields. Additional support for the immigration of *M. musculus* onto the study site from agricultural fields comes from our trapping data that shows individuals were first captured at trap stations close to the adjacent corn fields.

There was no treatment effect on population abundance of *S. hispidus* in either year of our study. Additionally, there was no treatment effect on *S. hispidus* recruitment, apparent survival, or sex ratio. However, population abundances in the second year of our study were approximately four to ten times greater than the population abundances in the same treatments in the first year of our study, and while not significant, *S. hispidus* population abundances were numerically greatest in P × SB− plots during both years. *S. hispidus* is associated with early successional or disturbed habitat types that have greater understory cover [17]. Furthermore, *S. hispidus* can out-compete other rodent species for resources in habitat types with greater understory foliage cover [36, 45, 46], Our results suggest that in more complex habitat, and as habitat heterogeneity increased from the first to second year of the study, *S. hispidus* was able to out-compete other species and become dominant. However, understanding effects of competition versus successional change in community structure would require additional studies.

During both years of our study, few *R. humulis* were captured, which was unsurprising given that it is a relatively rare species in pine forests [36]. Nevertheless, we captured *R. humulis* individuals in all treatment options at low numbers suggesting that for at least two years postpreparation, presence of switchgrass does not influence abundance of this species relative to nonswitchgrass plots. This result was surprising because we expected *R. humulis* to increase in presence of switchgrass due to increased availability of seeds during autumn and granivorous habits of *R. humulis*. Lack of response of *R. humulis* abundance suggests this species does not respond rapidly to changes in resource abundance or may be locally rare in managed pine forests in our study area. Data from other studies in the coastal plain suggest the former; *R. humulis* are among the most commonly captured species in the southeastern coastal plain [17, 37, 46] but are captured at relatively low rates after initial stand establishment [37].

Our results suggest either that *P. leucopus* is more competitive in plots with pine and *M. musculus* is more competitive in plots with switchgrass or that switchgrass does not provide suitable resources for *P. leucopus* and plots with pine do not provide suitable resources for *M. musculus*. Evidence from studies of mammalian diversity in pine plantations suggests that, although *M. musculus* is present, it is not usually the most abundant small mammal species present (e.g., [36, 45]). However, the potential mechanisms underlying our observed patterns, especially the clearly opposite responses of *P. leucopus* and *M. musculus* to switchgrass treatments, require further investigation. Field experiments involving competitor exclusion or limited-resource provision could be used to determine ecological mechanisms underlying the responses of *P. leucopus* and *M. musculus* to the presence of switchgrass in the future.

5. Implications

(1) Our results suggest residual biomass removal has no influence on rodent community structure or population demographics in an intensively managed, coastal plain southern pine system.

(2) In our study, switchgrass has a positive influence on the invasive *M. musculus* and a negative influence on the native *P. leucopus*. Moreover, intercropping switchgrass with pine does not appear to completely offset effects of switchgrass, at least for *P. leucopus*. However, other native species, such as *S. hispidus,* were not influenced by presence of switchgrass. In the short term, switchgrass can affect abundance of native and invasive rodent species. Determining ecological effects underlying associations is important for long-term implications.

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Research Article

The High Input of Soil Organic Matter from Dead Tree Fine Roots into the Forest Soil

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The spatial and temporal dynamics of tree fine roots were investigated in six boreal forests types in Eastern Sweden, close to the Swedish Forsmark and Laxemar nuclear power plants. Four dry and two wet forest types were included in the study. The amount of live and dead fine roots in terms of dry weight was estimated in soil cores. The live/dead ratios of fine roots (<1 mm in diameter) decreased with depth; very low ratios were observed in two wet forest sites. The proportions of dead fine roots to the total amounts of fine roots in the mineral soil horizons of those wet sites were 63 and 86%. The corresponding proportions in the mineral soil in dry forest sites were 45 and 45% and 49 and 48% at Forsmark and Laxemar, respectively. Sequential soil core sampling demonstrated a high variation in live and dead amounts of fine roots during the growth period. A high accumulation of carbon from dead tree fine root was found in all six forest types, in particular in the wet forest sites, but also in deeper soil horizons. Consequently, substantial amounts of organic matter from dead fine roots are continuously accumulated in the soil in boreal forests.

1. Introduction

Tree fine roots of forest trees are for their function forced to penetrate dry soil volumes often against mechanical resistance in densely packed soil layers. In spite of those difficulties, tree root systems explore the uppermost parts of the soil profile with a network of growing root tips. For an example, the root system of a 13-year-old Scots pine (*Pinus sylvestris*) reached an area of about 5 m from the tree stem and expanded about 0.4 m yr^{-1} [1, 2]. The high tree density in this forest stand (1095 ha^{-1}) made it clear that the uppermost parts of the soil profile must have been completely interwoven by tree fine roots.

The lateral roots in a nearby 120-year-old Scots pine stand (tree density = 393 ha^{-1}) reached 15–20 m from the tree trunks [3]. The root system of those mature Scots pine trees had expanded about 0.1 m yr^{-1}during the 120-year period leaving an area of about 300 m^{-2} penetrated by tree roots. The wide-spread network of fine roots on the structural roots increases the total surface area and length of the root system [4].

The white coloured area of the root tips behind the region of cell elongation is most active in the uptake processes [5, 6]. This absorption zone is often covered by mycorrhizal fungi or root hairs [7]. The seasonal change in the number of root tips seems to be very well correlated with the changes in the amount and length and surface area of living fine roots [8]. Fine roots are short lived in their effectiveness; death and decay of dead fine roots often take place within a few weeks.

The energy cost of forming and maintaining the fine root system of a single tree is very high [9–13].The amount of carbon allocated to the root systems is substantial [2, 8, 9, 12, 14–17]. The starch content in living fine roots (<1 mm in diameter) may reach as much as 30% of the dry weight [18]. Live fine root ramifications are constantly replaced and a substantial amount of dead fine-root tissues are formed.

Fine root production and litter formation of fine roots are important components of nutrient and carbon cycles in forest ecosystems [2, 8, 12, 14, 16, 17, 19–25]. Calculating carbon allocation to tree fine roots and turnover time is therefore essential in order to understand the patterns of carbon cycling in forest ecosystems.

The most commonly used methods of estimating fine-root production in forest ecosystems involve the measurements of live and dead amounts of fine roots in terms of dry weight from sequential soil cores. The contribution of

different diameter classes to root biomass and turnover rate may vary [4, 15]. The most substantial turnover rate is to be found in fine roots. Some fine roots are transferred to long-living large-diameter roots [13, 15].

The live/dead ratio of fine roots is a valuable vitality criterion in the soil profile [26]. Persson and Ahlström [27] used the live/dead ratio of fine roots to quantify changes in the "vitality" of fine roots in nitrogen manipulated Norway spruce catchment areas. The fluctuations in the amount of live and dead fine roots during the growth period in these forest areas suggested that climatic alterations were the most important underlying sources of variation. Soil temperature and soil water conditions seem to be the most important factors influencing fine-root growth. The most substantial decomposition takes place in the upper soil layers where high temperature, supplies of air, water, and food allow microorganisms to thrive [28, 29].

The effects of anoxic conditions on the spatial and temporal distribution on the tree fine roots have recently been identified [15, 26, 30]. The live/dead ratio of fine roots may be reduced in water saturated forest soils as a result of oxygen deficiency, a low rate of decomposition, and a substantial accumulation of decomposing organic matter from dead fine roots [31–33].

The boreal forests are in many ways able to keep plant remains from decomposing, thus preventing the release of carbon into the air. Most carbon is accumulated in poorly and very poorly drained soils. A high share of forested wetlands is to be found in the boreal forest region [34–36]. In boreal forests tree fine roots are exposed to large seasonal variations of soil moisture, nutrient availability, and soil temperature [37, 38]. In water-saturated forest stands the accumulation of dead fine roots is expected to be very high.

We hypothesized that soil water saturation plays an important role in regulating the amount of deposed organic matter from dead fine roots. A low live/dead ratio of fine roots is expected in water-saturated forest stands as a result of the high accumulation of dead root tissues. Soil carbon from dead tree roots plays a key role in the global carbon cycle and is an important component in climate models. Humans have, and will likely continue to have, significant impacts on the size of this pool by forest management practices forest such as forest harvesting, clear-cutting, ploughing, and drainage.

2. Material and Methods

Investigations were carried out in six different forest types in areas surrounding two Swedish nuclear power plants at Forsmark and Laxemar [15, 26]. The forest sites at Forsmark were of coniferous *Calluna-Empetrum* type, coniferous fern type, and *Alnus* swamp of herb type [39]. A distinct hummock and hollow microtopography was developed at the *Alnus* forest of swamp herb type at Forsmark.

The sites at Laxemar were of herb rich oak forest type, coniferous *Vaccinium myrtillus* type, and *Alnus* shore forest type. The soil type varied between leptosol/regosols) gleysols at Forsmark and histosols/gleysol at Laxemar (see Table 1). Stone/boulder volumetric content (%) and soil moisture conditions differed considerably between the different sites [26].

The tree density (the number of trees ha^{-1}) was 1340, 780, and 3340 at the Forsmark and 200, 400, and 1600 at the Laxemar sites, respectively. The mean tree height was 16.3, 19.8, and 18.5 m at the Forsmark sites and 17.1, 21.0, and 11.6 m at the Laxemar sites, respectively. The mean tree height of the trees was 16.3, 19.8 and 18.5 m at the Forsmark and 17.1, 21.0, and 11.6 m at the Laxemar sites, respectively (Table 1). The basal area (m^2/ha) of the trees was 22.5, 27.0, and 17.9 at the Forsmark sites and 15.0, 15.5, and 17.5 at the Laxemar sites, respectively. The specific basal area was occupied by different tree species.

The *Alnus* swamp forest site at Forsmark consisted besides *Alnus glutinosa* (Table 1; basal area = 7.3 m^2 ha^{-1}) of *Betula verrucosa*, *Picea abies,* and *Pinus sylvestris* (total basal area = 10.3 m^2 ha^{-1}). The *Alnus* shore forest at Laxemar consisted of *Alnus glutinosa* (basal area = 17.5 m^2 ha^{-1}). The coniferous *Calluna-Empetrum* site, the coniferous fern site at Forsmark and the coniferous *Vaccinium* site at Laxemar were dominated by *Picea abies* (basal area = 22.5 and 15.5 m^2 ha^{-1}) and the herb rich oak forest at Laxemar by *Quercus robur* (basal area = 15.0 m^2 ha^{-1}). The average thickness of the humus layer was 15.3, 5.2, and 15.3 cm at the Forsmark sites and 11.5, 5.5, and 5.3 cm at the Laxemar sites.

In total 32 soil cores were taken in each forest site from the four corners of a quadrate covering 200 m^2, 8 taken randomly in each corner (north, east, south, and west) [15, 26]. Each soil sample was taken as deep as possible, namely, to a depth where stones and larger blocks prevented further penetration by the soil corer.

Soil cores were sampled in the middle of October 2004 for the Forsmark sites and in the end of April 2005 for the Laxemar sites. During the winter months the upper part of the soil profile was deep frozen, and only limited growth of the fine roots could take place. The soil cores were randomly distributed within the hummock and hollow microtopography pattern at the Alnus forest of swamp herb type at Forsmark. Half of the soil core samples were taken in the hummocks and the other half in the hollows. In all other forest sites no stratification was applied.

Additional sequential soil core sampling was carried at the coniferous fern forest type at Forsmark on in total 4 sampling occasions [26]. Besides the first sampling in the middle of October in 2004, samplings were carried out in the middle of April, in the beginning of August and in the end of October in 2005 [15]. The depth distribution of fine roots was measured, at intervals of 0-2.5 (H1), 2.5-5 (H2), and 5–10 cm (H3) of the LFH horizon and in 10 cm segments (M1-M3) for the mineral soil profile down to 30 cm.

A cylindrical steel corer, with an inner diameter of 4.5 cm, was used for soil core sampling. In total 32 soil cores were taken, each soil core sample was taken to a depth where stones and larger blocks prevented further penetration by the soil corer. Only few root fragments were found in the deepest soil layer. The uppermost 0–2.5 cm layer consisted of humus in all investigated sites.

The soil samples were transferred into plastic bags and transported to our laboratory and stored in a cold storage

Table 1: Site and stand characteristics at Forsmark and Laxemar. *Picea abies* = *P. a.*, *Pinus sylvestris* = *P. s.*, *Betula verrucosa* = *B. v.*, *Alnus glutinosa* = *A. g.*, *Quercus robur* = *Q. r.*

Stand characteristics	Coniferous, *Calluna empetrum*	Coniferous fern	*Alnus* swamp herb	Herb rich oak forest	Coniferous *Vaccinium myrtillus*	*Alnus* shore forest
Soil moisture class[1]	Fresh	Fresh/moist	Moist	Fresh	Fresh	Moist
Soil type[1]	Leptosol	Regosol/Gleysol	Gleysol	Histosol/Gleysol	Histosol	Histosol
Tree age	59–60	80–88	85–95	112	55	34
Number of trees /ha	1340	780	3340	200	400	1600
Tree height (m)	16.3	19.8	18.5	17.1	21.0	11.6
Diameter at breast height (dbh in m)	0.21	0.26 (*P. a.*)	0.31 (*P. a*)	0.36	0.32	0.14
Basal area (m^2/ha)	22.5 (*P. a.*)	20.5 (*P. a.*) 6.5 (*B. v.*)	5.3 (*B. v.*) 7.3 (*A. g.*) 3.0 (*P. a.*) 2.3 (*P. s.*)	15.0 (*Q. r.*)	15.5 (*P. a.*)	17.5 (*A. g.*)

[1] [40, 41].

at −4°C; a temperature that did not damage the live tissue and caused no change in ion concentrations [42]. The roots were sorted out from the soil cores immediately after thawing. In order to distinguish live roots from dead roots distinct morphological characteristics were used [43].

Live fine roots (<1 mm in diameter) were defined as roots with a varying degree of brownish/suberized tissues, often well branched, with the main part of the root tips light and turgid or changed into mycorrhizal root tips [43, 44]. In cases when there was a difficulty to judge if a root fragment was live or dead, it was cut lengthwise with a sharp dissection knife and the judgement was based on the colour between cortex and periderm. The stele of live roots was white to slightly brown and elastic. In roots considered as dead, the stele was brownish and easily broken, and the elasticity was reduced. Dead root fragments with a length <1 cm were regarded as soil organic matter. The dry weight was estimated for all root fractions after drying in an oven at 65°C to constant dry weight (at least for 24 hours).

The fine-root production and turnover rates were calculated from significant (Student's t-test) increments of live, dead, and live + dead fine roots at the coniferous fern forest at Forsmark. Comprehensive descriptions of calculation methods used are to be found in [8]. By turnover rate, in this context, was meant the annual fluxes in the live, dead, or in the live + dead fine-root compartment. Root turnover rate (yr^{-1}) was calculated from the annual increments in live, dead and, live + dead fine roots divided by the average amounts in those categories during the year of sampling.

From these calculations only minimum estimates of turnover rate can be obtained since the sampling frequency (only four sampling occasions) covered only some of the major fluctuations, but certainly not all increases. The risk for overestimation due to the random variations in the means is low with a low number of sampling occasions and a high number of samples on each sampling occasion [8].

3. Results

A substantial variation with depth in the total amount of live and dead tree fine roots was observed at the different forest sites (Figure 1). High amounts of dead fine roots were indicated in the mineral soil horizons. The proportion of dead fine roots varied at all sites and in all horizons from 6 to 88% (Table 2). The highest proportions of dead fine roots were found in the two *Alnus* forest sites at Forsmark and Laxemar, which were both classified as "moist," with a high topographic wetness index (cf. Table 1). The live/dead ratio of fine roots (<1 mm in diameter) varied in all sites from 14.1 in the uppermost 2.5 cm of the humus layer to 0.2 in the deepest parts of the mineral soil horizon (Table 2). The live/dead ratio is calculated only for soil cores with both live and dead fine roots.

Low amounts of live fine roots were found in the uppermost 2.5 cm of soil of the moist *Alnus* shore forest at Laxenar compared with the same soil segments at other forest sites (Figure 1 and Table 2). The total amounts of fine roots were very low at the latter site and substantial amounts of dead fine roots were found in the total soil profile. At the moist *Alnus* swamp forest at Forsmark, a more substantial proportion of live fine roots were observed in the total soil profile, resulting in a comparatively high live/dead ratio, in particular in the humus layers (Table 2).

The rooting density ($g\,dm^{-3}$) was low at all sites in the mineral soil horizons compared with in the humus layers except for in the coniferous fern forest at Forsmark (Figure 1). A low live/dead ratio of fine roots was found in the deepest soil horizons, where the rooting density was very low (Table 2). Extremely low rooting density was observed in the mineral soil horizons at the *Alnus* swamp forest at Forsmark, at the herb rich oak forest at Laxemar and at the *Alnus* shore forest. The soil corer was driven in all sites to depths in the mineral soil horizon (at least 2 dm) where only

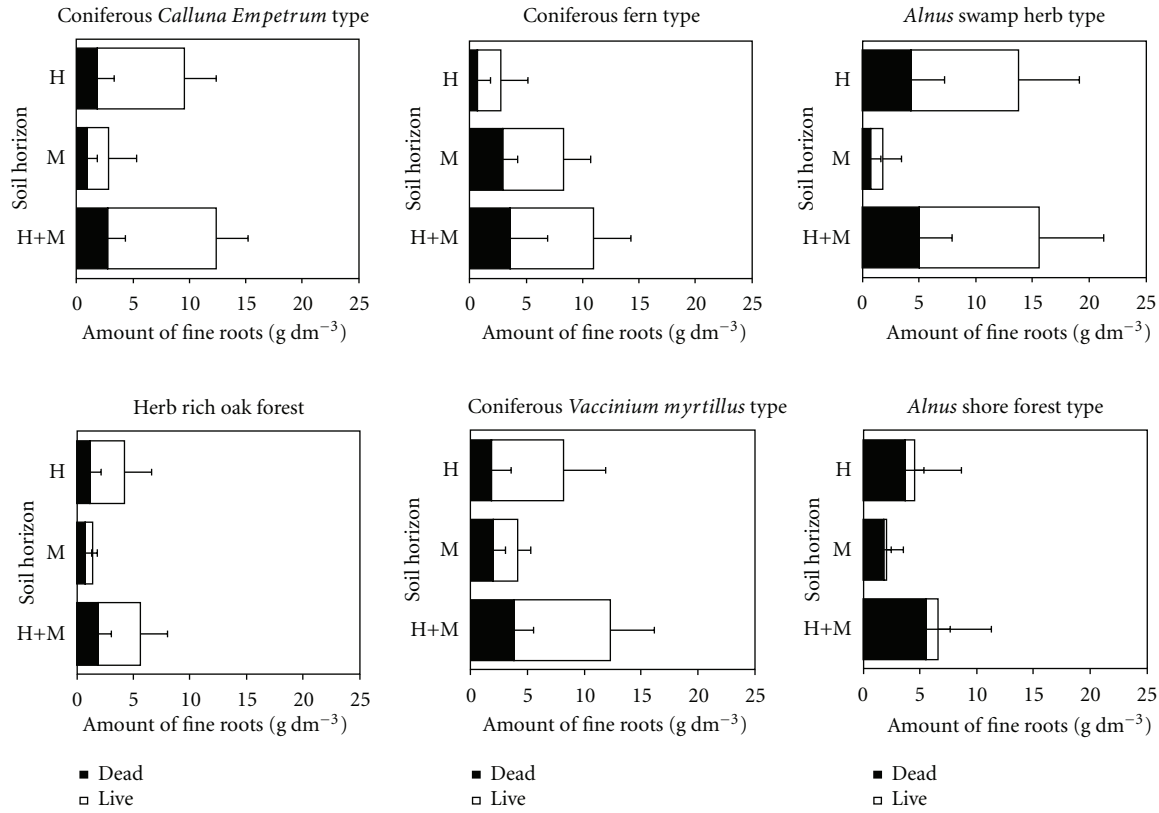

Figure 1: The amount of live and dead tree fine roots (g dm^{-3}; <1 mm in diameter) in the humus layer (H) and in the mineral soil horizon (M) compared with in the total soil profile (H+M) at different Swedish forest sites.

limited amounts of live or dead fine-root fragments were observed (Table 2).

The mean amount of live tree fine roots in the humus layer in relation to the total amount of live + dead fine roots in the soil profile was 48, 7, and 48% for the three Forsmark sites and 35, 25, and 6% for the three Laxemar sites, respectively (Figure 1, Table 2). The related amount of dead fine roots in the humus layer was 13, 2, and 30% for the Forsmark and 13, 2, and 28% for the Laxemar sites, respectively. Proportionally more live than dead fine roots were observed at all sites in the humus compared with in the mineral soil horizon, except for at the *Alnus* shore forest site at Laxemar (Figures 1 and 2). The density estimates (Figure 1; g dm^{-3}) give a more correct picture of the extensive distribution of live fine roots in the humus layer than simply the distribution per unit area in different soil layers (Figure 2 and Table 2; g m^{-2}).

The proportion of dead fine roots (<1 mm in diameter) of the total amount of fine roots in the humus layer (Table 2) was high in both moist *Alnus* forest at Forsmark and Laxemar sites (38 and 82%, resp.). A distinct hummock and hollow microtopography was developed at the *Alnus* forest of swamp herb type at Forsmark and tree fine roots were more frequently found in the uppermost aerated parts of hummocks. The tree layer consisted of a mixture of *Betula verrucosa*, *Picea abies*, and *Pinus sylvestris* (Table 1). At the water-saturated *Alnus glutinosa* shore forest at Laxemar, no

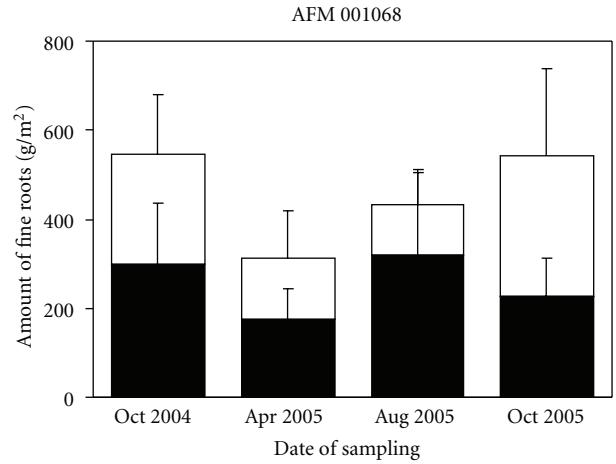

Figure 2: The amount of live (unfilled bar) and dead (black bar) fine roots (<1 mm in diameter) on the four sampling occasions in the coniferous fern site at Forsmark during 2004-2005. Mean values ±SD.

hummocks were found and anaerobic conditions reached even the uppermost parts of the soil horizon.

Substantial variations in live and dead amounts of fine roots and live/dead ratios were observed in the coniferous fern site at Forsmark during the sampling period confirming

Table 2: The distribution of live and dead amounts of tree fine roots (<1 mm in diameter), live/dead ratios, and dead (%) at different depths (H = humus; M = mineral soil) at the forest sites: Forsmark-1 (Coniferous, *Calluna Empetrum type*), Forsmark-2 (Coniferous fern type) and Forsmark-3 (*Alnus* swamp herb type) and Laxemar-1 (herb-rich oak forest), Laxemar-2 (Coniferous *Vaccinium myrtillus* type), and Laxemar-3 (*Alnus* shore forest type) forest sites. The live/dead ratio is calculated from the mean amounts of live and dead tree fine roots. Estimates are given as mean values ±SD (n = 31-32).

Site	Horizon	Tree roots ($g\,m^{-2}$)			
		Live	Dead	Live/dead ratio	Dead (%)
Forsmark-1	H 0–2.5	48 ± 42	3 ± 9	13.3	6
	H 2.5–5	64 ± 29	15 ± 22	4.2	19
	H 5–10	60 ± 63	21 ± 25	2.9	26
	H 10–15	9 ± 20	9 ± 21	0.9	50
	H 15–20	2 ± 9	2 ± 12	1.0	50
	M 0–10	71 ± 96	58 ± 63	1.2	45
	M 10–20	13 ± 59	10 ± 21	1.3	43
Forsmark-2	H 0–2.5	30 ± 35	4 ± 5	7.5	12
	H 2.5–5	4 ± 12	4 ± 11	1.1	50
	H 5–10	2 ± 6	3 ± 10	0.6	60
	M 0–10	228 ± 138	136 ± 70	1.7	37
	M 10–20	51 ± 67	73 ± 60	0.7	59
	M 20–30	2 ± 8	5 ± 15	0.4	71
Forsmark-3	H 0–2.5	56 ± 58	11 ± 11	5.1	16
	H 2.5–5	46 ± 36	23 ± 21	2.0	33
	H 5–10	55 ± 52	51 ± 40	1.1	48
	H 10–15	28 ± 35	25 ± 33	1.1	47
	H 15–20	13 ± 30	9 ± 16	1.5	41
	H 20–25	3 ± 9	6 ± 22	0.5	67
	M 0–10	29 ± 73	45 ± 55	0.6	61
	M 10–20	6 ± 11	14 ± 21	0.4	70
Laxemar-1	H 0–2.5	24 ± 28	7 ± 10	3.4	23
	H 2.5–5	34 ± 37	15 ± 16	2.3	31
	H 5–10	21 ± 28	8 ± 12	2.6	28
	M 0–10	57 ± 42	48 ± 34	1.2	46
	M 10–20	3 ± 7	9 ± 23	0.3	82
Laxemar-2	H 0–2.5	102 ± 61	18 ± 23	5.6	15
	H 2.5–5	48 ± 52	17 ± 21	3.0	26
	H 5–10	10 ± 29	11 ± 30	0.9	52
	M 0–10	132 ± 69	71 ± 48	1.8	35
	M 10–20	51 ± 49	71 ± 37	0.7	58
	M 20–30	25 ± 49	31 ± 32	0.8	38
	M 30–40	4 ± 10	26 ± 34	0.2	87
Laxemar-3	H 0–2.5	14 ± 17	47 ± 79	0.3	77
	H 2.5–5	5 ± 9	38 ± 57	0.1	88
	H 5–10	1 ± 4	7 ± 19	0.1	33
	M 0–10	17 ± 25	115 ± 104	0.1	87
	M 10–20	7 ± 16	35 ± 40	0.2	85
	M 20–30	3 ± 8	21 ± 33	0.1	84
	M 30–40	2 ± 8	10 ± 14	0.2	83

Table 3: The amount of live, dead, and live + dead fine roots (<1 mm in diameter) and differences on different sampling occasions, annual means, Σ annual increases of fine roots and turnover rate of live, dead, and live + dead fine roots at a fresh/moist coniferous fern forest site at Forsmark.

Sampling number	Live	Dead	Live + dead
(1)	317 ± 196	226 ±88[a]	543 ± 205
(2)	113 ±79[a]	321 ±184[a]	434 ± 212
(3)	150 ± 112	180 ±62[b]	330 ±136[a]
(4)	248 ±134[a]	299 ±136[b]	546 ±212[a]
Annual means	207	257	463
Σ Annual increases	135	214	216
Turnover rate	0.7	0.8	0.5

Sampling took place on 4 sampling occasions: October 20th, 2004 (1), April 18th, 2005 (2), August 2nd, 2005 (3), and October 28th, 2005 (4). Estimates are given as mean values ±SD ($n = 32$). Significant increases are marked by [a] and [b]. Differences are significant at $P = 0.05$ (Student's t-test).

a high turnover rate in live, dead, and live + dead fine roots (Table 3). Low amounts of dead fine roots were found at the remaining sites at Forsmark and Laxemar, in particular in the upper well-oxidized parts of the humus layer. Although, no sequential soil coring was carried out at the two moist *Alnus* forest sites, high turnover rates of live fine roots must explain the high accumulation rate of dead fine roots. Thus, anoxia may play an important role in regulating the rate of organic matter accumulation in forest soils.

4. Discussion

The methods used of estimating fine-root production and mortality should involve the measurements of live and dead dry weight of fine roots from soil cores in undisturbed soil horizons. The often reported discrepancy in the estimates of root litter formation in data from sequential coring may partly be due to imprecise definition of vitality and size classes of the fine roots. In our case distinct morphological characteristics were used in order to separate live and dead fine roots [8, 43]. In roots considered as dead, the stele was brownish and easily broken, and the elasticity was reduced [43]. Dark coloured tissues are frequently found in live fine roots and the colour in itself is not a reliable criterion of vitality. Depending on the pattern of cell death, several root functions can cease even before cell dies [45].

Substantial variations in live and dead fine roots and live/dead ratios usually occur in tree stands confirming our calculations of turnover rates [4, 17, 23, 27, 39, 46–50]. The dead amounts of fine roots normally do not persist for long in well-oxidized conditions, decay or complete disappearance is accomplished in a few days only [8, 49, 51]. Under anoxic conditions there is an accumulation of dead fine roots, since the decomposition will be reduced [33, 52, 53]. Under long-term anoxic conditions, for example, the case, at the *Alnus* swamp forest of herb type at Forsmark and at the *Alnus* shore forest at Laxemar, an accumulation of dead fine roots was observed.

Fine roots respond quickly to environmental changes and are rapidly penetrating favourable the soil horizons. We know that fine roots are sensitive to drought and that their live/dead ratios are decreasing with less water availability in the soil [54–57]. In water-saturated forest ecosystems the primary production of fine roots may exceed the decomposition of dead roots, also leading to a decreased live/dead ratio [32, 58, 59]. In many cases death takes place as a result of ageing, reduced carbohydrate supply, the influence of different climatic stress factors such temperature changes and frost [49, 60]. Increased fine-root herbivory especially in nutrient-rich patches is furthermore expected to significantly influence the carbon cycling patterns [61].

Although our sampling occasions were few, our data from the coniferous fern site at Forsmark suggest that substantial increases/decreases in live, dead, and live + dead fine roots will take place during the growth period (Table 3). The annual above-ground litter fall (mainly *Picea abies* needles) was 135 g m^2 compared with the annual below-ground fine-root litter supply of 257 g m^2 [62] (Table 3). Our study suggests that the annual above-ground tree litter fall from leaves/needles is less important in terms of dry weight than the annual belowground formation of fine-root litter.

Available information in the literature suggests a fine-root production with a seasonal pattern different from needle or leaf production [26, 63, 64]. Fine roots respond quickly to environmental changes and their life span is relatively short. Our investigation confirms that the growth pattern of the fine roots depends on where in the soil profile they are developed and that the live/dead ratio is decreasing with depth (Table 2).

"Vitality" in terms of live/dead ratios of fine roots should be expected to be high in the humus layer, since the extensive mycorrhizal infection in that layer makes the fine roots functional over a prolonged period of time [65–68]. Although no distinct seasonal pattern is reported in the literature a high growth and death rate of fine roots should be expected during the summer months [8, 69]. A high death rate was observed during the winter month and early spring (Table 3). Dead fine roots are decomposed quickly in well-oxidized soil layers ensuring a high live/dead ratio of fine roots.

Detritus from above-ground and below-ground plant tissues constitutes the primary source of carbon for soil organic matter [28]. The presence of soil organic matter improves the nutrient availability and reduces soil strength. Tree fine roots may play a more important role for the formation of soil organic matter than the needles/leaves [8, 22, 26, 70–73]. In strongly seasonal climates, the length of the growing season often increases the lifespan of needles/leaves, but fine roots may stay alive less long.

Sequential coring data at the ecosystem scale suggest an annual production of fine roots, frequently higher than the average amount of live fine-roots [8, 17, 22, 26, 74–78]. Most observations on fine-root turnover are underestimates and the costs and benefits of exudation, root hairs and the mycorrhizal fungi is not yet sufficiently clarified [43]. Techniques for obtaining root data are still in a formative stage. As more research is conducted on root methods, techniques will become more refined and standardized. Obtaining root data is essential for all kind of long-term field experiments, because plant responses may occur in the shifts in carbon allocation between above- and below-ground plant components.

Decomposition of fine roots is determined mainly by the interactions between soil temperature and oxygen accessibility [79]. Other factors regulating the fate of dead fine roots in the soil are the soil pH, the availability of decomposer organisms, and litter quality [22, 80, 81]. Only few studies have considered the interactions between all these factors [32, 33, 35, 52, 53, 71, 79, 82–84]. Estimates of root respiration to the total CO_2 efflux range from 10% to 90%, with considerable methodological uncertainties [35, 84].

The high amount of dead fine roots accumulated in our two anoxic forest sites unveils a high turnover rate of live fine roots. The changes between anoxic and well-oxidized soil conditions in a forest soil may cause death of both fine roots and mycorrhiza [33, 52]. The effects of anoxia on the metabolic cost on the plant root system and the mycorrhizal infection have so far received limited attention [32, 59, 85]. Uncertainties in the belowground carbon balances limit the establishment and improvement of policies regulating the atmospheric CO_2 concentrations.

Trees constitute major reservoirs of carbon in terrestrial ecosystems; large amounts of carbohydrates are annually transported from the shoots to the roots and stored in the root systems [4, 5, 9, 11, 13, 21, 25, 48, 64, 72]. High amounts of live and dead fine roots are found in forest ecosystems [8, 12, 15, 55, 80]. The vitality of the fine roots seem to depend on where in the soil profile they are developed; it is therefore essential, while studying the distribution of fine roots in forest ecosystems, to relate to the natural soil-horizons [15, 46]. The often well-developed organic-rich humus layer in the forest soil most effectively buffers the root system against drought and nutrient deficiencies [15, 69]. Few studies have so far examined patterns in live/dead ratios of fine roots in relation to soil water and mineral nutrient availability during the growth period [15, 24, 74]. Fine roots of trees in many ways are indicators of environmental change, soil nutrient status, and forest health [14, 16, 47].

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Review Article

Cogasification of Coal and Biomass: A Review

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Recently, there has been significant research interest in cogasification of coal and various types of biomass blends to improve biomass gasification by reducing the tar content in the product gas. In addition, ash present in biomass catalyzes the gasification of coal. However, due to the fibrous nature of biomass and the large difference in gasification temperature of coal and biomass, cogasification in existing systems presents technical challenges. This paper documents research studies conducted on the cogasification of various types of coal and biomass using different types of gasifiers under various sets of operating conditions. In addition, the influence of cogasification on upstream and downstream processing is presented.

1. Introduction

Coal gasification is an established technology [1, 2]. Biomass gasification has been the focus of research in recent years to estimate efficiency and performance of the gasification process using various types of biomass such as sugarcane residue [3], rice hulls [4], pine sawdust [5], almond shells [6], almond [7], wheat straw [8], and food waste [9]. However, only a handful of peer-reviewed journal articles are available on woody biomass gasification [10–13]. Recently, there has been significant research interest in cogasification of various biomass and coal mixtures such as Japanese cedar wood and coal [14] coal and saw dust [15], coal and pine chips [16], coal and silver birch wood [17], coal, pine, and polyethylene [18], and coal and birch wood [19]. Cogasification of coal and biomass has some synergy [20]. The process not only produces a low carbon footprint on the environment, but also improves the H_2/CO ratio in the produced gas which is required for liquid fuel synthesis [14]. In addition, inorganic matter present in biomass catalyzes the gasification of coal. However, cogasification processes require custom fittings and optimized processes for the coal and region-specific wood residues.

While cogasification is advantageous from a chemical point of view, some practical problems have been associated with coal and biomass gasification on upstream, gasification, and downstream processes. On the upstream side, the particle size of the coal and biomass is required to be uniform for optimum gasification. Kumabe et al. [14] used particle size in the range of 0.5 to 1.0 mm for both coal as well as for biomass and Kezhong et al. [21] used particle size of 0.42 mm for biomass and 0.25 to 0.75 mm for coal. In addition, moisture content and pretreatment (torrefaction) are very important during up-stream processing.

While upstream processing is influential from a material handling point of view, the choice of gasifier operation parameters (temperature, gasifying agent, and catalysts) decide product gas composition and quality. Biomass decomposition occurs at a lower temperature than coal and therefore different reactors compatible to the feedstock mixture are required. Kumabe et al. [14] used a downdraft gasifier for gasification of Japanese cedar and Mulia coal, and Kezhong et al. [21] used a fluidized bed reactor for gasification of bituminous coal with pine dust and rice straw. Temperature variation among reactors can cause different compositions of syngas.

Feedstock and gasifier type along with operating parameters not only decide product gas composition but also dictate the amount of impurities to be handled downstream. Downstream processes need to be modified if coal is used with biomass in gasification. Heavy metal and impurities such as sulfur and mercury present in coal can make syngas difficult

to use and unhealthy for the environment. Also, at high temperature, alkali present in biomass can cause corrosion problems in downstream pipes. An alternative option to downstream gas cleaning would be to process coal to remove mercury and sulfur before feeding it to the gasifier.

The objective of this paper is to present a comprehensive review on up-stream, gasification and downstream processes, along with different types of gasifiers, feedstock materials, and conditions for cogasification.

2. Gasification Process

The general gasification process consists of a series of unit operations. The main unit operations are feedstock preprocessing (upstream processing), gasification, product gas cleanup, and gas utilization (downstream processing) [22]. Figure 1 shows the stepwise processes coal and biomass cogasification.

3. Upstreaming Process

3.1. Size Reduction. Coal and biomass require drying and size reduction before they can be fed into a gasifier. Size reduction is needed to obtain appropriate particle sizes; however, drying is required to achieve a moisture content suitable for gasification operations. In addition, densification of the biomass may be done to make pellets and improve density and material flow in the feeder areas.

In a biomass gasification study, Lv et al. [5] and Rapangnà and Latif [7] reported that gasification of small biomass particles (0.23 mm particles for pine saw dust and 0.28 mm for almond shells) resulted in low tar and high gas yields and high energy content. These improvements in yield and efficiency make sense, as smaller particles have larger surface area and porosity, for a given mass, which facilitates faster heat transfer rates and removal of gasification products from the solid surfaces. Kumabe et al. [14] used a particle size range of 0.5 to 1.0 mm for Mulia coal and Japanese cedar during cogasification. It was found that Mulia coal pulverized to a sieve size less than 106 μm had more sulfur in the product gas than that from the particles of sieve size ranging 0.5 to 1 mm. However, size reduction processes (e.g., hammer-milling, knife milling, or tub grinders) consume energy. The energy consumed during size reduction depends on many factors including biomass moisture content, initial size, screen size, and processing equipment properties. Mani et al. [23] tested the specific energy consumption for the size reduction of corn stover, barley straw, and switchgrass. Average specific energy consumed at 12% initial moisture content of the feedstock with a hammer mill screen size of 3.2 mm was measured as 27.09, 11.04, and 27.63 kWh/t for barley straw, corn stover, and switchgrass, respectively. Due to its fibrous nature, switchgrass had the highest specific energy consumption. In the size reduction of switchgrass by means of a hammer mill with a screen size of 5.6 mm, 44.9 kWh/t of energy was consumed [24]. Given the importance of forest residues for gasification, a similar study is needed to determine the influence of particle size and specific energy consumption for forest residues. This information will be critical to performing sustainability and economic analysis of the size reduction process.

3.2. Drying. McKendry [25] recommended that biomass moisture content should be below 10–15% prior to gasification. High moisture content reduces the temperature achieved in the gasification zone, thus resulting in incomplete gasification. Forest residues or wood has a fiber saturation point at 30 to 31% moisture content (dry basis) [26]. Compressive and shear strength of the wood increases with decreased moisture content below the fiber saturation point. In such a situation, water is removed from the cell wall which causes shrinkage of the cell wall. The long-chain molecules which make up the cell wall move closer to one another and bind more tightly. A high level of moisture, usually injected in form of steam in the gasification zone, favors formation of a water-gas shift reaction that increases hydrogen concentration in the resulting gas [15].

3.3. Torrefaction. The torrefaction process is a thermal treatment of biomass in the absence of oxygen, usually done at 250–300°C temperature to drive off moisture, decompose hemicellulose completely, and cellulose, partially [27]. Torrefied biomass has reactive and unstable cellulose molecules with broken hydrogen bonds. Torrefied biomass not only retains 79–95% of feedstock energy but also produces a more reactive feedstock with lower H/C and O/H content than the original biomass [27]. Torrefaction causes high production of H_2 and CO in the gasification process. A study showed that H_2 and CO production were increased by 7% and 20%, respectively, in gasification of torrefied Beachwood in an entrained flow reactor at 1400°C as compared to the original wood [28].

4. Cogasification Processes

While coal gasification chemistry is well established and it has been adopted for biomass gasification, the chemistry of gasification of coal-biomass mixtures has not been widely studied. Coal gasification follows a combination of the following reactions [15]:

$$2C + O_2 = 2CO \text{ (partial oxidation)}, \quad (1)$$

$$C + O_2 = CO_2 \text{ (complete oxidation)}, \quad (2)$$

$$C + 2H_2 = CH_4 \text{ (hydro-gasification/methanation reaction)}, \quad (3)$$

$$CO + H_2O = CO_2 + H_2 \text{ (water-gas shift reaction)}, \quad (4)$$

$$CH_4 + H_2O = CO + 3H_2 \text{ (steam reforming reaction)}, \quad (5)$$

$$C + H_2O = CO + H_2 \text{ (water gas reaction)}, \quad (6)$$

$$C + CO_2 = 2CO \text{ (boudouard reaction)}. \quad (7)$$

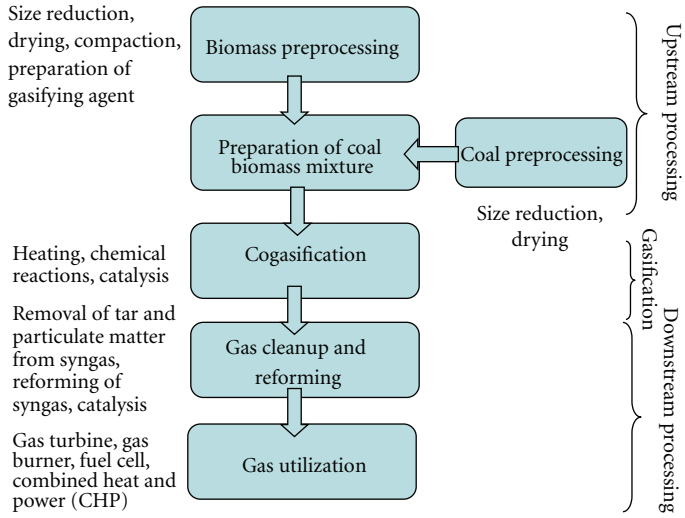

Figure 1: Various operations involved in the coal-biomass gasification process.

While coal is mainly carbon, biomass is a complicated mixture of complex compounds such as cellulose, hemicelluloses, lignin, extractives, and minerals. During gasification of biomass, minor oxidation (combustion) and major pyrolysis take place. The behavior of biomass pyrolysis shows drying (below 125°C), hemicelluloses, cellulose, and partial lignin decomposition (from 125 to 500°C), and degradation of the remaining lignin (above 500°C). In simple words, biomass produces char, condensable volatiles and tar, and gaseous products during pyrolysis. Char is mainly carbon, and it follows reactions 1 to 7 during gasification. All of the volatiles and some tars are thermally cracked and broken down into simple gaseous products during gasification. The remaining tar and some alkali minerals leave with the product gases. Kumar et al. [22], like many others, presented the complex biomass gasification process in a single equation:

$$\begin{aligned} CH_xO_yN_zS_s + \text{Air (79\% } N_2 \text{ and 21\% } O_2) + H_2O \text{ (steam)} \\ = CH_4 + CO + H_2 + H_2O \text{ (unreacted steam)} \\ + C \text{ (Char)} + \text{Ash} + \text{Tar}. \end{aligned} \tag{8}$$

While many researchers mentioned synergy of cogasification of coal and biomass, Pan et al. [16] presented a simplified cogasification reaction scheme. The backbone of this reaction scheme is that both coal and biomass undergo pyrolysis without interaction before entering into the gasification reactions. During the pyrolysis, complete de-volatilization of coal and biomass takes place, and condensable volatiles as well as tar rise along with air/steam away from the gasification zone leaving char behind. These volatile products never get a second chance to come in contact with fresh air/steam. Since methane and ethylene formation does not take place at atmospheric pressure, their presence in the product syngas is the result of pyrolysis. In the next step, gasification of the remaining char and residual coal takes place to form CO, CO_2, H_2, and other gases. The reaction scheme presented by Pan et al. [16] does not explain the synergic effect of cogasification which needs further investigation.

There are various factors which influence the cogasification process and the composition of the product gas. These factors include type of gasifier, gasification temperature, flow rates of coal-biomass mixtures and oxidizing agents (air and/or steam), type and amount of catalysts, proportion of biomass in the coal-biomass mixture, and the properties and type of biomass [14, 18, 21].

4.1. Gasifier Type. Both fixed bed and fluidized bed gasifiers have been used in cogasification of biomass with coal. Kumabe et al. [14] used a downdraft fixed-bed gasifier to study cogasification of Mulia coal and Japanese cedar biomass mixtures at 900°C; however, Pan et al. [16] and Vélez et al. [15] attempted cogasification on biomass and coal in fluidized bed gasifiers. Vélez et al. [15] gasified mixtures of biomass (saw dust, rice husk, and coffee husk) and coal in a fluidized bed gasifier at 1000°C. Vélez et al. [15] reported two operational problems. The first problem was defluidization of the fluidized bed gasifier caused due to agglomeration of low melting point ash present in the biomass. The second problem was clogging of the downstream pipes due to excessive tar accumulation.

Collot et al. [17] studied cogasification and co-pyrolysis of birch wood and coal in a fixed bed, possibly an updraft, as well as fluidized bed gasifiers. A major difference between fixed bed and fluidized bed reactors was that the product gas produced from fluidized bed gasification had 4.0 to 6.0% (by weight) tar content; however, the fixed bed reactor gave tar yields ranging from 25.5 to 26.1% (by weight) for cogasification of coal and silver birch wood mixtures (1 : 1 ratio by wt) at 1000°C temperature, 20 bar pressure, and 60 second holding time.

5. Factors Effecting the Cogasification Process

5.1. Feedstock Properties

5.1.1. Type of Biomass. Lignocellulosic biomass is mainly composed of several chemical constituents: cellulose and hemicellulose (60–80% dry basis), lignin (10–25%), and some extractives and minerals [29]. The proportion of these chemical species greatly influences the composition of the gasification products. In a gasification study, Hanaoka et al. [10] reported 97.7%, 92.2%, and 52.8% carbon conversion efficiencies for cellulose, xylan (hemicelluloses), and lignin, respectively. While the gasification products were similar for lignin and xylan, cellulose produced high amounts of CO_2 (carbon dioxide) and CH_4 (methane) in the product gas compared to lignin and xylan. In another study, Yang et al. [30] reported that lignin contributed to high H_2 (hydrogen) yields in the gasification products, almost four times higher than cellulose. Kezhong et al. [21] used two types of biomass, pine sawdust and rice straw, along with Shenmu coal. When 20% of each biomass (oven dried for 20 hours at 90°C) with 80% coal was gasified, H_2 composition in syngas gas increased from 17.66% for pine sawdust to that of 21.96% for rice straw. Three types of different biomass, rice husk, sawdust, and coffee husk, were used by Vélez et al. [15]. A mixture of 6% of coffee husk with subbituminous coal produced 14%, 8%, and 8.2% of H_2, CO_2, and CO, respectively. A mixture of sawdust with coal produced syngas composition of 10.7%, 10%, and 11.8% H_2, CO_2, and CO, respectively, and a mixture of coal and 6% of rice husk produced syngas composition containing 11.4% of H_2, 9.3% of CO_2, and 6.0% of CO. These results suggest that the type of biomass selected during the cogasification influences the product gas composition.

5.1.2. Proportion of Biomass in Coal-Biomass Mixtures. The proportion of biomass in the cogasification process influences product gas composition [14, 15]. Vélez et al. [15] prepared mixtures of coal and raw biomass on a weight basis whereas Kumabe et al. [14] mixed coal and raw biomass on a molar carbon basis. Mulia coal and Japanese cedar biomass were mixed and gasified in a downward draft fixed bed gasifier [14] at 1173 K temperature. The mixtures were prepared using varying proportions of biomass from 0 to 1 on a molar carbon basis and the influence of the amount of biomass was studied with respect to the molar ratio of H_2, CO, and CO_2 in the product gas. The study reported that the gas composition varied with variation in biomass ratio. As the biomass ratio increased from 0 to 1, H_2 composition decreased from 47.9 to 37.5 vol% and CO_2 content increased from 26.1 to 33.7 vol%. The other gas species like CO (22.1–23.9 vol%), CH_4 (2.6–4.6 vol%) and others (0.8–2.9 vol%) were independent of biomass ratio. The molar ratios of H_2/CO and H_2/CO_2 decreased from 2 to 1 with increase in biomass ratio from 1 to 2. Kezhong et al. [21] reported increase in hydrogen yield from 17.66% to 19.30% and CO_2 yield from 19.07% to 20.22% when the biomass ratio was increased to 20% to 33% during cogasification.

In the study conducted by Vélez et al. [15], the mixtures of 6 and 15% raw biomass (saw dust, rice husk, and coffee husk) with subbituminous coal were gasified in preheated steam and air. The authors concluded that the high proportion of biomass in the mixture increased hydrogen content in the product gas (up to 15%) but significantly decreased the energy efficiency of the process. Beside proportion of biomass, cogasification also depends on the type of coal used in the mixtures [16]. In a fluidized bed cogasification study of pine wood and two types of coals (low-grade coal and refuse coal), Pan et al. [16] reported that a minimum of 20% pine chip (by weight) for the low-grade coal and 40% pine chip (by weight) for the refuse coal were recommended for cogasification. Similar studies are required for forest residues and coal to gather region-specific experimental data.

5.1.3. Ash Content. The presence of ash in the gasification fuel is not good for fluidized bed gasification. Vélez et al. [15] mentioned that the low melting point of ash present in woody biomass led to agglomeration which caused defluidization problems. The ash caused sintering, deposition, and corrosion of the gasifier construction metal. Biomass containing alkali oxides and salts with ash content above 5% causes clinkering/slagging problems [25]. On the other hand, gasification was improved by adding wood waste with a low-grade coal, having an ash content of 32%. The improvement was due to the high volatiles, the low ash content, and the low sulfur in biomass which counterbalanced the negative effects of the high sulfur present in the coal [18].

It is very important to study the melting of biomass ash, its chemistry within the gasification bed (no bed, silica/sand, or calcium bed), and the fate of alkali metals when using fluidized bed gasifiers.

5.2. Air and Steam Flow Rate. When air and steam are used as gasifying agents, their accurate flow rates not only create correct stoichiometric gasification conditions but also provide sufficient reaction time, also called residence time, for heavy-molecular-weight volatiles and tar particles to break down into gaseous species. The terms equivalence ratio (ER) and superficial velocity (SV) are used to define air flow rate. ER is defined as the ratio of actual air flow to the air flow required for complete stoichiometric combustion of the gasification feedstock [21]. The term SV is defined as the ratio of actual air flow to the cross-sectional area of the empty gasifier which compensates for the gasifier dimensions. The amount of air supplied to the gasifier determines the degree of combustion and in turn the temperature of the combustion zone for a directly heated gasifier. However, excessive air might provide high conversion, but it will produce syngas with high CO_2 concentration and low calorific value.

In a cogasification study, Ponzio et al. [31] observed that high ER of 0.25 produced significantly higher yield for all the gases than low ER of 0.19. Similar results are also reported by Gil et al. [32] for gasification of pine wood chips. While studying the influence of particle size and reactor geometry in a fluidized bed gasification of coal and coal-derived char, Tomeczek et al. [33] observed that char required more

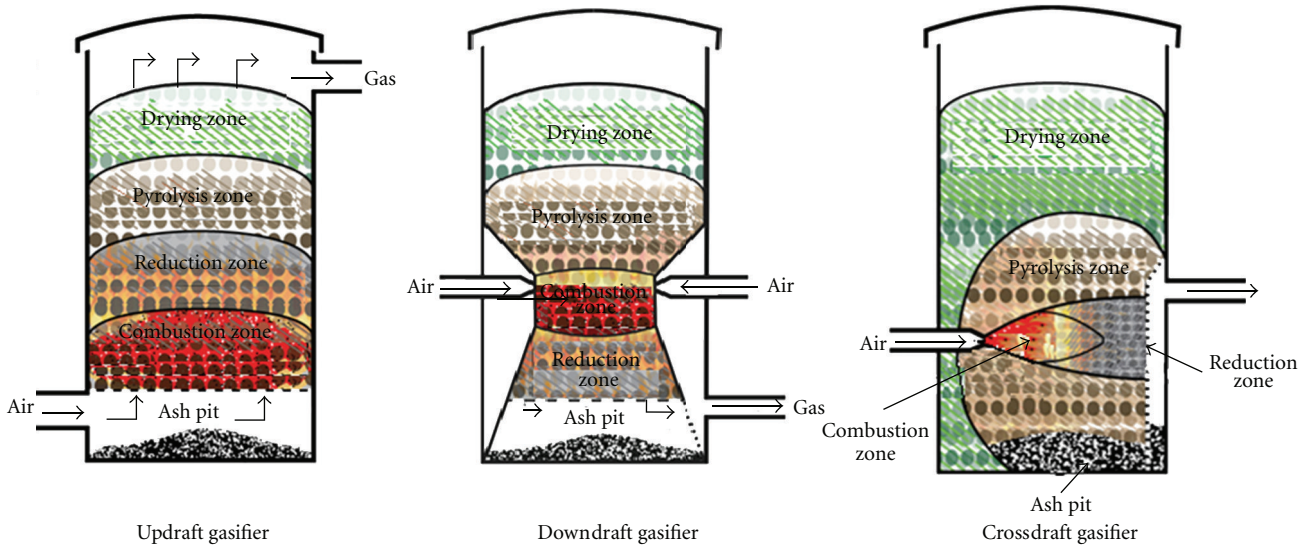

FIGURE 2: Different zones of gasification depending upon the types of gasifier. Image source: http://gekgasifier.com/gasification-basics/gasifier-types/.

residence time than coal to produce product gas of the similar calorific value. Pan et al. [16] observed that the superficial velocities of 0.76–1.45 m/s were too high or in other words residence times 1.7–3.5 s were too low, to achieve water-gas shift reaction equilibrium conditions. Kumabe et al. [14] used commercial Outokumpu HSC Chemistry 5.11 chemical equilibrium calculation software and determined that the air-fuel (O_2/C) of 0.5 mol/mol and steam ratio (H_2O/C) of 3 mol/mol of feed carbon were suitable to produce syngas favorable for synthesis of liquid fuels. Addition of steam favors the water-gas shift reaction and formation of hydrogen during gasification at high temperatures (750–800°C). Steam has also been used by some other researchers in the cogasification process [15, 16, 31, 34]. Vélez et al. [15] observed that a high steam-to-biomass ratio improved hydrogen formation as carbon present in biomass/coal preferred the water-gas and water-gas shift reactions. Ponzio et al. [31] observed a large amount of unreacted steam upon increasing the steam-to-feed ratio more than 53%. Pan et al. [34] used a steam-to-air ratio of 0.55 in their experiments. Kehzong et al. [21] found that when ER ratio was increased from 0.30 to 0.42, the total gas yield increased from 1.75 to 1.94 m^3/kg fuel however, the syngas gas yield decreased from 0.98 to 0.93 m^3/kg fuel at normal conditions of temperature and pressure, since more oxygen was provided for combustion. Similar results were obtained by Pinto et al. [18] upon cogasification of a coal and pine mixture.

5.3. Gasifier Temperature Profile. The temperature profile along the gasifier greatly influences the product gas composition and hence the calorific value of syngas, by affecting reaction chemistry of gasification (reactions shown by equations 1 to 7). Vélez et al. [15] observed that in the temperature range between 810°C and 850°C, the water-gas shift reaction had a strong role in increasing the hydrogen concentration in the syngas. The reaction also produced a maximum amount of CO_2 at 820°C. At 850°C, the Boudouard reaction dominated and consumed CO_2 produced through the water-gas shift reaction thereby increased the CO concentration in the product gas. Pan et al. [16] mentioned that attention must be given on the temperature profile to be maintained along the reactor during the design stage. Pan et al. [16] recommended considering long temperature zones for partial oxidation and water gas reactions because these reactions are very slow. In the updraft gasifier, the reactor might be divided into three main zones: the combustion zone at the bottom, the reduction zone in the middle, and the pyrolysis zone at the top. The location of these zones varies with the type of gasifier (Figure 2).

Pan et al. [16] maintained the average temperature between 840°C and 910°C during the cogasification experiments. High temperature in the reduction zone (above 850°C to 900°C) reduces the tar content in the product gas; however, high temperature in the combustion zone might cause sintering problems and defluidization of the bed [22, 34, 35]. Vélez et al. [15] maintained the maximum gasification temperature below 1000°C to avoid sintering. Pinto et al. [18] observed that methane and hydrocarbons were decreased by 30 and 63%, respectively, while H_2 concentration was increased by 70%, when temperature was increased from 750°C to 890°C. In the presence of steam flow rate of 5 kg/h steam and a gasification temperature at 890°C, H_2 (39.8%), CO (17.3%), CO_2 (20.4%), CH_4 (14.9%), and C_nH_m 7.6% (v/v) were produced. Pinto and colleagues recommended that a temperature range of 850 to 900°C should be used for cogasification of coal and pine. The temperature profile inside the directly heated cogasification reactor is also influenced by the proportion of biomass in the coal-biomass mixtures. Pan et al. [16] observed that the average temperature of the fluidized bed gasifier dropped by approximately 60°C when the proportion of pine chip was increased from 20 to 100% in the mixtures. Hence, the temperature profile is

specific to a particular coal-biomass mixture and the type of biomass.

5.4. Catalyst. The use of appropriate catalysts not only reduces reaction temperature but also improves the gasification rates. In addition, catalysts also reduce tar formation. Several studies reported the influence of a catalyst on biomass gasification [6, 35–39]. Lv et al. [35] and Tanaka et al. [39] fed mixture of feedstock and catalyst into the reactor of the gasifier. In a cogasification study performed on coal to assess the influence of switchgrass ash, Brown et al. [40] observed that addition of switchgrass ash to coal increased coal gasification by eightfold. Tanaka et al. [39] observed that NiO/Al_2O_3 catalyst produced product gas with H_2/CO ratio of 2, suitable for methanol synthesis, from the gasification of spruce and hemlock wood sawdust. Lv et al. [35] reported that H_2/CO ratio as high as 4.45 can be achieved by using dolomite and nickel-based catalysts. Rapagna et al. [6] observed that using dolomite or olivine catalyst as a bed material increased gasification by 50% and reduced tar yields by 20 times compared to sand. Asadullah et al. [36, 37] achieved negligible tar formation using $Rh/CeO_2/SiO_2$ catalyst in low-temperature gasification. Aznar et al. [41] observed that when the small pine wood chips were gasified in a nickel-based catalytic fluidized bed reactor with steam-O_2 mixtures followed by high-temperature (ICI 15-5 and BASF K6-11, 350–480°C) and low-temperature (BASF K3-110, 200–260°C) CO-shift reactors, an exit gas with 73 vol% of H_2 (dry basis) was obtained.

In a study of the cogasification of Puertollano coal mixed with pine, petcoke, and polyethylene (PE), Pinto et al. [42] found that the use of dolomite catalyst helped to reduce H_2S and to retain sulfur in solid phase by more than 90%. It also reduced the formation of gaseous chlorine. Dolomite as a catalyst was better than that of Ni-dolomite and G72-D (Zinc oxide) in terms of sulfur and chlorine retention. Catalysts have proven effects on gasification and quality of syngas.

6. Downstream Processing

Following upstream processing and gasification to produce the product fuel gas, it is very important to perform downstream processing of syngas such as cleaning particulate matter, alkali, nitrogen, and sulfur compounds and tar removal to produce a clean gas as required by following applications.

6.1. Particulate Matter Removal. Product gas particulate matter is mainly ash and char particles, and its quantity depends upon the type of gasifier [25]. Conventional cyclone separators can remove particles above 10 μm; however, some type of filtering device must be used to remove particles smaller than 10 μm. Some filters like ceramic filters, wet scrubbers, bag filters, and packed bed filters are 99.8% effective. All the filters which work below 450°C are clogged due to tar deposition [25]. Some ceramic filters can operate as high as 700°C and can be very effective for hot gas cleaning. Vélez et al. [15] used two cyclones connected in series to remove particles down to 5 μm in size from the product gas of cogasification. Pan et al. [16] used two cyclones followed by a filter and a condenser cooler for gas cleanup from a fluidized bed cogasification experiment.

6.2. Alkali Removal. Alkali elements (Na, K, Mg, Ca) and S present in the feedstock form oxides and vaporize at high temperatures (above 700°C) during gasification. These alkali oxides condense below 650°C and deposit on the downstream sections of the gasification system causing corrosion. In addition, alkali oxides deactivate catalysts used for tar removal. Salo and Mojtahedi [43] reported that the syngas produced from a pressurized fluidized bed gasification reactor at 850°C had concentrations of 1.2 ppm (by weight) for both Na and K compared to 0.05 ppm for the product gas produced at 430°C. Zevenhoven-Onderwater et al. [44] showed that a dolomite bed promotes volatilization of alkali components; however, a silica bed tends to bind most alkali released from the biomass by forming low-melting-point alkali silicates. These low-melting-temperature silicates cause problems with bed agglomeration.

Product gas must be cleaned for most end uses. Nitrogen, generally present as ammonia, is removed by wet scrubbing of the cold gas and by destroying ammonia using dolomite, nickel-based, and iron-based catalysts. Sulfur is converted to SO_2 or H_2S during gasification which can be removed using limestone, dolomite, or CaO.

6.3. Tar Removal. Tar consists of high-molecular-weight compounds exiting the gasifier with the product gas. Tar condenses below 450°C on downstream pipe lines, particulate matter filters, and some of it remains in the product gas in the form of a suspended aerosol. The amount of tar formed during the gasification depends upon the type of biomass, the gasification process, and the operating conditions. Most of the processes which utilize product gas require tar-free syngas. There are two ways to produce tar-free syngas. A first method requires improvements in the gasification technologies with optimized gasifier design, operating conditions, and proper selection of catalysts. The second method is to develop high-efficiency tar removal techniques [25].

It has been shown in previous sections that the gasification operating parameters such as biomass type, the gasifier temperature profile, the ER, the type of gasifying agent, and the steam-to-biomass ratio all influence tar content of the product gas. In addition, the use of a catalyst during gasification also reduces the tar content of the product gas. Tanaka et al. [39] observed no tar formation when a NiO_2/Al_2O_3 catalyst was used during gasification of wood. Pan et al. [34] introduced a secondary air injection at 850°C to crack the tar into lower-molecular-weight gaseous compounds. During the experiments, Pan et al. [34] were able to reduce tar concentration from $\geq 3.70\ g/m^3$ to $0.42\ g/m^3$.

Several attempts have been made to capture tar during downstream processing of syngas produced from the cogasification process [14, 31, 35]. Kumabe et al. [14] used an anisole of special grade chemicals, manufactured by Wako Pure Chemical Industries, Ltd., to dissolve tar. Ponzio et al. [31] used a solid-phase adsorption method to capture tars

Table 1: Summary of research articles on cogasification of coal and biomass.

Source	Type of feedstock	Gasifier type	Gasification conditions	Effect on syngas compositions and comments
Kezhong et al. [21]	(i) Shenmu bituminous coal (ii) Pine saw dust/rice straw	Fluidized bed	(i) Gasification agent—oxygen-rich air-steam (ii) Equivalent ratio (ER) increased from 0.31 to 0.47 (iii) Temperature 948–1026°C (iv) Steam/carbon ratio (F_s/F_c) = 0.83	(i) H_2 and CO decreased (ii) Total gas yield increased (iii) Syngas yield decreased (iv) Smaller ER is favorable to increase Syngas yield
			(i) Steam/carbon ratio (F_s/F_c) increased from 0.26 to 0.88 (ii) Temperature 921–1033°C (iii) Equivalent ratio (ER) = 0.4	(i) Bed temperature decreased (1033 to 921°C) (ii) H_2 and CO first increased and then decreased (iii) Steam/carbon ratio of 0.5 is preferred
			(i) Biomass/coal ratio increased from 0 to 33% (ii) Equivalent ratio (ER) = 0.34 (iii) Steam/carbon ratio (F_s/F_c) = 0.77 (iv) Temperature: 912–976°C	(i) Bed temperature increased (912 to 976°C) (ii) H_2 increased and CO decreased (iii) Slight decrease in Syngas yield
Pinto et al. [18]	(i) 60% coal (ii) 20% pine (iii) 20% polyethylene	Fluidized bed	(i) Temperature increased from 750 to 890°C (ii) Gasification agent—air, steam, and mixture of both (iii) Steam input rate = 5.0 Kg/h (iv) Air input rate = 4.4 Kg/h	(i) CO_2 decreased and H_2 increased (ii) Not much effect on char (iii) Energy conversion increased (iv) Gas composition (v/v) at 890°C: H_2: 39.4%, CO: 17.3%, CO_2: 20.4%, CH_4: 14.9% and C_nH_m—7.6%
			(i) (Oxygen/oxygen + steam) ratio increased from 0.02 to 0.28 (ii) Temperature: 850°C (iii) Feedstock input rate = 5.0 Kg/h	(i) 15% reduction in H_2 production (ii) 38% and 53% reduction in CH_4 and hydrocarbons (iii) Total gas yield decreased
			(i) (Steam + O_2)/fuel ratio increased from 1.1 to 1.9 (ii) Air input rate = 4.4 Kg/h (iii) Steam input rate = 5 Kg/h	(i) H_2 and CO_2 first increased and then decreased (ii) CO and CH_4 first decreased and then increased (iii) (Steam + O_2)/fuel ratio of 1.3–1.5 is preferred
Kumabe et al. [14]	(i) Mulia coal (ii) Japanese cedar	Fixed bed downdraft	(i) Air-steam gasification (ii) Biomass ratio increased from 0 to 1	(i) H_2 decreased and CO_2 increased (ii) Cold gas efficiency increased (iii) No effect on CH_4 concentration

Table 1: Continued.

Source	Type of feedstock	Gasifier type	Gasification conditions	Effect on syngas compositions and comments
Vélez et al. [15]	(i) Columbian coal (ii) Coffee husk (iii) Sawdust (iv) Rice husk	Fluidized bed	(i) Air-steam gasification (ii) Biomass ratio was increased from 6% to 15% (iii) Temperature <1000°C (iv) Steam/fuel ratio was increased	(i) Bed temperature decreased by 30°C with 15% biomass (ii) Energy efficiency decreased (iii) High H_2 concentration was obtained with increase in biomass ratio as well as steam/fuel ratio
Pan et al. [16]	(i) Pine chips (ii) Black coal (iii) Sabero coal	Fluidized bed gasifier	(i) Biomass ratio was increased: 0%, 25%, 40%, and 100% (ii) Air-steam gasification (iii) Temperature = 840–910°C	(i) CO increased (ii) H_2 first increased up to 25% of biomass and then decreased (iii) Overall thermal efficiency increased (40% to 68%) (iv) Carbon conversion efficiency increased (63% to 83.4%)
Couhert et al. [28]	(i) Beachwood (ii) Torrefied beachwood at 240°C (iii) Torrefied beachwood at 260°C	Entrained flow reactor	(i) Feedstock: beachwood and torrefied beachwood (ii) Temperature = 1200 and 1400°C	(i) CO_2 remained same (ii) H_2 was increased by 7% with torrefied wood (iii) CO was increased by 20% with torrefied wood

from the product gas. Lv et al. [35] used dichloromethane cooled to −10°C to condense and collect tar.

7. Environmental Benefits

Greenhouse emissions from coal gasification are higher than that from biomass gasification [45]. This could be due to the high carbon content and low volatile percentage in coal [14]. For measuring greenhouse emissions, the GHGI (greenhouse gas emission index) is used, which is defined as the lifecycle greenhouse gas emission associated with the energy products divided by the lifecycle greenhouse gas emissions associated with the fossil-fuel-derived products displaced [45]. In a study conducted to produce electricity and FT (Fisher Tropsch) liquids from coal and biomass, Lui et al. [45] found that GHGI was 1.71 for coal gasification which came down to 0.96 when a mixture of 40% biomass-60% coal was used as feedstock. From these results, it can be concluded that using biomass with coal is beneficial for the environment in terms of greenhouse gas emissions.

Cogasification combined with Fisher-Tropsch technology is used to produce liquids from coal and biomass. CBTL (Coal-Biomass to liquids) helps to reduce GHG emissions as compared to petroleum-derived diesel. NETL (National Energy Technology Laboratory) reported that the use of 30% switchgrass (Biomass) with coal for producing diesel (CBTL) with carbon capture and storage technology (CCS) produced 63% less GHG emission compared to a fossil-derived diesel. GHG emission can further be decreased up to 75% by using more aggressive capturing technique of auto-thermal reformer in CCS. This technique is economically competitive with fossil-based diesel if the cost of crude oil remains somewhere between $100 and $120/bbl [46].

8. Summary

A review of up-stream, gasification, and downstream processing is presented in this paper. A summary of literature review has also been presented in Table 1. Composition of product gas is effected by the various up-stream and downstream processes and other gasification parameters. Feedstock properties like particle size and moisture content of the biomass feed should be kept in range of 0.5 to 1.0 mm and 10–15%, respectively. Upstreaming processes like torrefaction of biomass help to increase H_2 and CO yield. The type of gasifier is selected according to the feedstock properties and the desired utilization of the syngas. If syngas is used for electric generation then a downdraft gasifier should be used because it releases gas at high temperature with low impurities and hence causes fewer side effects on the engine. Beside the gasifier, the type of gasifying agent is also important. The use of steam as a gasifying agent assists the water-gas shift reaction and produces H_2-rich syngas. In contrast, if air is used, then less H_2 is produced. Also, the use of catalysts affects syngas production. Dolomite catalysts help in increasing the gasification rate along with reducing the sulfur and chlorine. Once gas is produced, it contains impurities like particulate matter, alkali, and tars. These impurities must be removed before using the product gas. Particulate matter can be removed by attaching a cyclone separator at the gas exit, while alkalis and tars can be removed by using catalysts and secondary air injection in the gasifier system which helps in combustion of tars.

Despite much research in this field, cogasification of forest logging residue with coal has not yet been fully explored. The tar evolution profile from the cogasification of forest residue and coal requires further investigation to customize the design of the gasifier, its operating conditions, and tar removal system. Along with this, the use of an entrained flow gasifier for the cogasification of coal and biomass can also be a research opportunity for the future because different types of feedstock can be used in it. Moreover, it has other advantages like uniform temperature profile inside the reaction zone, short reactor residence time, and high carbon conversions.

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Research Article

Aboveground Forest Biomass Estimation with Landsat and LiDAR Data and Uncertainty Analysis of the Estimates

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Landsat Thematic mapper (TM) image has long been the dominate data source, and recently LiDAR has offered an important new structural data stream for forest biomass estimations. On the other hand, forest biomass uncertainty analysis research has only recently obtained sufficient attention due to the difficulty in collecting reference data. This paper provides a brief overview of current forest biomass estimation methods using both TM and LiDAR data. A case study is then presented that demonstrates the forest biomass estimation methods and uncertainty analysis. Results indicate that Landsat TM data can provide adequate biomass estimates for secondary succession but are not suitable for mature forest biomass estimates due to data saturation problems. LiDAR can overcome TM's shortcoming providing better biomass estimation performance but has not been extensively applied in practice due to data availability constraints. The uncertainty analysis indicates that various sources affect the performance of forest biomass/carbon estimation. With that said, the clear dominate sources of uncertainty are the variation of input sample plot data and data saturation problem related to optical sensors. A possible solution to increasing the confidence in forest biomass estimates is to integrate the strengths of multisensor data.

1. Introduction

It is well known that forest ecosystems provide an important carbon reservoir. Continued deforestation and forest degradation will result in the loss of forest biomass/carbon stocks magnifying the global negative effects of climate change. The policy and management decisions governing these resources will play a critical role in mitigating these effects, thus requiring a robust method of monitoring the spatial and temporal patterns of forest biomass. The rates of carbon emission are considered as the largest source of uncertainty in climate change scenarios due to the difficulty in spatial explicitly estimating the carbon stocks and dynamic changes. One solution is to develop robust approaches for estimating biomass/carbon changes in land cover using remotely sensed data. The past three decades have produced significant advances in estimating forest biomass including the application of different sensor data (e.g., Landsat, radar, and LiDAR) and the development of advanced techniques such as regression analysis, neural network, and process-based ecosystem models [1–12].

There are four critical issues associated with remote sensing-based biomass estimation methods: (1) sufficient number of available sample plots, (2) selection of suitable

metrics for biomass modeling, (3) use of suitable algorithms to establish biomass estimation models, and (4) use of suitable methods to conduct uncertainty analysis of the estimates. The literature is rich with examples that highlight these issues. Lu [5] has summarized the biomass estimation methods and discussed the potential methods to improve biomass estimation performance. The application of LiDAR, radar, and hyperspectral data for biomass estimation was reviewed by Koch [13], while Gleason and Im [14] summarized biomass estimation methods based on literature in the past ten years.

Landsat Thematic Mapper (TM) data with suitable spectral and spatial resolution and relatively long history of data availability have made it a primary data source for biomass estimation. However, it does have a critical limitation in that data saturation generates large uncertainty for sites with high biomass density or sites having complex forest stand structure [15]. LiDAR data has recently received more attention because it can overcome the data saturation shortcoming of Landsat providing more robust biomass estimations. The confidence of these measures has long been recognized as an important part in forest biomass estimation; however, research on biomass uncertainty analysis has only recently obtained sufficient attention due to the difficulty in collecting reference data. The objective of this paper is to briefly overview aboveground forest biomass estimation methods based on Landsat and LiDAR data and the methods for uncertainty analysis and to present case studies. This paper is organized as follows: Section 2 provides an overview of biomass estimation methods with Landsat TM and LiDAR data, and uncertainty analysis methodology; Section 3 provides the case study corresponding to each review topic; Section 4 provides conclusions and discusses the challenges.

2. An Overview of Biomass Estimation and Uncertainty Analysis Methods

2.1. Biomass Estimation with Optical Sensor Data. The remote sensing-based biomass estimation methods assume that forest stand information captured by sensors is highly correlated with aboveground biomass. According to this assumption, the keys for biomass estimation are to use appropriate variables and to develop suitable estimation models if sufficient sample plots are available. Many new variables such as vegetation indices and textures can be calculated from the multispectral bands [16–18]. Lu and his colleagues examined the relationships of aboveground forest biomass with Landsat TM spectral signatures and vegetation indices [16], and textural images [17] in the moist tropical regions of the Brazilian Amazon, and then extensively investigated the potential variables for biomass estimation. They found that a combination of spectral response and textural images can effectively improve biomass estimation performance, especially in the areas with complex forest stand structures [15]. They also found that the use of subpixel information offered better estimation results than per-pixel-based spectral signatures [19]. However, the complex forest stand structures and biophysical environments often result in data saturation in Landsat images that was a major source of uncertainty in biomass estimation [14, 15].

In addition to the selection of suitable spectral variables, the use of proper algorithms for establishing biomass estimation models is also critical. Common algorithms include multiple regression analysis, neural networks, and K-nearest neighbor (KNN) [5]. Multiple regression analysis may be the most frequently used approach for developing biomass estimation models [11, 12, 15, 20–25]. This approach will typically use the sample plot biomass measure as the dependent variable; spectral signatures, vegetation indices, and/or textures from Landsat TM image are used as independent variables. The regression models assume that the biomass variable is linearly correlated with spectral responses and that limited correlations exist between independent variables. This assumption is usually not met in practice because remotely sensed data are often highly correlated each other [16]. There is also an issue with the regression approach in that the selected variables may have a nonlinear relationship with forest biomass [26]. An alternative to these limitations is to use nonparametric approaches such as neural network and KNN.

Neural networks have universal approximation properties that are regarded as a more robust solution for complicated and nonlinear problems compared to conventional parametric approaches [27] and have been used for biomass or volume estimation [27–32]. In the KNN approach, it is assumed that the spectral responses of pixels are only dependent on the state of forests. The estimate of each location was computed as a weighted mean of K spectrally nearest neighbors by inverse distance weighting. This approach has been used to update national forest inventory databases in Nordic countries such as Finland and Sweden based on the combination of plot inventory data and Landsat images [33–38]. Both neural networks and KNN methods are not as extensively applied as multiple regression methods for biomass estimation. Both methods require a large number of observations and a good representation of the variation of forest variables limiting their applications.

Most forest biomass estimation based exclusively on TM images was conducted in the 1990s and 2000s. Newer sensors such as radar and LiDAR have recently offered an important new structural data stream for forest biomass estimations. Applications using these new datasets to estimate biomass have obtained increasing attention [8, 11, 12, 39–42]. The following section focuses on the overview of biomass estimation methods with LiDAR data.

2.2. Biomass Estimation with LiDAR Data. LiDAR remote sensing systems can be distinguished based on the way with which returned signals are recorded (discrete return or wave form), scanning pattern (profiling or scanning), platforms (airborne, spaceborne, or ground based), and footprint size (small footprint: ~1 m or smaller; medium footprint: ~10–30 m; or large footprint: ~50 m or larger). The most common configurations of LiDAR systems are (1) airborne discrete-return scanning LiDAR, (2) airborne discrete-return profiling LiDAR, (3) airborne small-footprint waveform

LiDAR, (4) airborne medium-footprint waveform LiDAR, and (5) satellite waveform systems.

Airborne discrete-return scanning LiDAR may be the most widely used LiDAR system for biomass estimation. Although airborne discrete-return LiDAR could be scanning or profiling, for simplicity we refer airborne discrete-return LiDAR to the scanning sensors specifically because the use of profiling systems has mainly been limited to researchers in NASA (e.g., [39, 43]). Because a LiDAR sensor can directly measure components of vegetation canopy structure, such as canopy height, previous research has indicated that the use of LiDAR data is a promising approach for biophysical parameter estimation [8, 44–47]. Lim et al. [45] had reviewed the application of LiDAR data to forest studies. More detailed review of using LiDAR data for biomass estimation was also provided by Koch [13] and Gleason and Im [14].

Previous studies often used regression models to estimate biomass based on the metrics derived from LiDAR data. Because most allometric equations for calculating biomass in the field are power models [48], biomass and LiDAR metrics are usually log transformed when fitting a regression model [45, 49, 50]. In this case, a simple linear regression corresponds to a simple power model, and a multiple regression model corresponds to a multiplicative power model.

For airborne discrete-return LiDAR systems, the metrics were usually extracted from the canopy height distribution of the point cloud (e.g., [45, 51]). LiDAR metrics can be calculated based on all returns or a specific type of returns (such as first returns). Although most studies have used all returns, there are a few studies that used LiDAR metrics derived from first returns for predicting biomass (e.g., [52, 53]). Kim et al. [53] found that the model using first returns improved the R^2 by 0.1 for predicting the total aboveground biomass in the mixed coniferous forest in Arizona compared to the one using all returns.

Instead of using point cloud, some studies extracted LiDAR metrics by first interpolating the canopy height of LiDAR point clouds to generate a canopy height model (CHM) and then derived height metrics from the CHM cells [49, 50]. CHM usually records the maximum canopy height within each grid cell. Therefore, the height metrics derived from CHM is more related to upper canopy instead of the complete vertical profile of vegetation structure. However, few studies have reported the difference between metrics derived from different returns of LiDAR point cloud and those from CHM for biomass estimation.

2.3. Uncertainty Analysis. Uncertainty analysis of biomass estimates from remote sensing-based methods has only recently received sufficient attention [54, 55]. In forest biomass/carbon estimation, there are many sources of uncertainties, such as biased sampling, plot location errors, measurement errors of tree variables (diameter and height), improper use of allometric equations for biomass calculation, uncertainties from biomass and carbon conversion factors and from geometrical and radiometric correction of remotely sensed data, and the selection of input parameters used in modeling algorithms. The keys to reduce uncertainties are to identify the sources causing the uncertainty, to model their accumulation and propagation and to quantify the amount of uncertainties contributed to the final output. Friedl et al. [56] summarized three primary sources: (1) errors introduced through the image acquisition process, (2) errors produced by the application of data processing techniques, and (3) errors associated with interactions between instrument resolution and the scale of an ecological process on the ground. The uncertainty of estimating forest carbon may be much higher than the change to be achieved in carbon sequestration through changes in forest management [57]. The sampling error, measurement error for tree height and diameter, and regression error for tree volume are often recognized as major error components [58].

The map accuracy is traditionally assessed by calculating correlation or root mean square error (RMSE) between estimates and observed values. However, the accuracy often varies spatially depending on the complexity of landscape, density of sampled data, and accuracy of the remotely sensed data used [59, 60]. Pixel-based uncertainty analysis is needed to account for spatial variation of uncertainties. Moreover, the assessment of map quality can be conducted by quantifying and assessing the impacts of various input variations on the variation of outputs or by estimating the amounts of various input and output uncertainties and then conducting an uncertainty budget, that is, portioning the output uncertainty into the input uncertainty components. The former is called sensitivity study and the latter called uncertainty analysis [57].

As a specialized form of sensitivity analysis, an uncertainty and error budget shows the impacts of individual input uncertainties and their groups on the quality of output estimates [61]. The goal for developing an uncertainty and error budget thus is to account for all major sources of uncertainties and further provide modelers with guidelines for reduction of uncertainties and provide policy makers with suggestions for risk assessment of decision making. For the purpose, the widely used methods include the Monte Carlo [62], Fourier Amplitude Sensitivity Test (FAST) [63, 64], Taylor series [65, 66], polynomial regression [67], and response surface modeling [68, 69]. Helton and Davis [70] summarized the advantages and disadvantages of these methods. Although these methods were originally developed for building uncertainty and error budgets for a spatial models, the methods can be improved and applied to conduct uncertainty analysis on a pixel-by-pixel basis [71–73]. One example is that Gertner et al. [74, 75] extended the polynomial regression method to carry out uncertainty and error budgets for spatially explicit estimates of soil erosion.

To date, there are only few reports on spatial uncertainty analysis and error budget of mapping forest biomass/carbon. For this purpose, Wang et al. [54] demonstrated a methodological framework by integrating an image-aided spatial cosimulation algorithm and a polynomial regression model. The cosimulation was used to combine forest inventory plot data with TM images and generate forest carbon maps with uncertainties of estimates, and the polynomial regression model was applied to establish the relationships

of input uncertainties with output uncertainties. They found that the variation of image data had more impact on the accuracy of forest carbon-predicted values than the sample plot data. Moreover, Wang et al. [55] investigated the impacts of plot location errors on accuracy of forest carbon estimates and concluded that the perturbations of plot locations statistically did not lead to biased population mean predictions of forest carbon but increased the RMSE of predicted values, and plot location errors smaller than 800 m did not lead to noticeably different spatial distributions of the predicted values.

3. Case Studies

This section provides three case studies to demonstrate the application of biomass estimation methods with Landsat TM and LiDAR data, respectively, and uncertainty analysis. The first case study estimates aboveground biomass using Landsat TM. The second case study estimates biomass using LiDAR data. The third case study illustrates the methods for conducting uncertainty analysis in order to understand the major sources influencing biomass estimation performance.

3.1. Case Study I: Aboveground Biomass Estimation with Landsat TM Image. Since the 1970s, the Brazilian Amazon has experienced high deforestation due to road-building, logging, agricultural, and cattle-raising expansion [76]. About 20–50% deforested areas in the overall Amazon basin are in certain stages of successional forests [77–80]. Accurate delineation of successional and mature forest biomass distribution becomes considerably significant in reducing the uncertainty of carbon emission and sequestration. It is also critical for understanding their roles in influencing soil fertility and land degradation or restoration and in environmental processes and sustainability [81]. This case study selected Machadinho d'Oeste in northeastern Rondônia, Brazil to examine the capability of using Landsat TM image for aboveground biomass estimation.

3.1.1. Methods. Fieldwork was conducted in July-August 1999. A detailed description of the field measurement and the calculation of aboveground forest biomass based on diameter at breast height (DBH) and tree height was provided in Lu et al. [19]. A total of 26 sample plots for secondary succession with data range of 24–160 T/ha and a mean value of 89 T/ha, and a total of 14 sample plots for mature forest with data range of 111–495 T/ha and a mean value of 248 T/ha were collected and used in this research. Based on the probability of tree height distribution in a sample plot, entropy was calculated and used to evaluate the complexity of forest stand structures [15].

The TM image, which was acquired on 18 June 1998, was geometrically rectified using control points taken from topographic maps at 1 : 100,000 scale (Universal Transverse Mercator, south 20 zone) with a RMSE of less than 0.5 pixels. An improved image-based dark object subtraction model was used to implement radiometric and atmospheric correction [82, 83]. The surface reflectance values after calibration were rescaled to the range of 0–100 by multiplying 100 for each pixel. Eight grey level cooccurrence matrix- (GLCM-) based texture measures (i.e., mean, variance, homogeneity, contrast, dissimilarity, entropy, second moment, and correlation) associated with five TM bands (bands TM 2, 3, 4, 5, and 7), and seven different sizes of moving windows (i.e., 5×5, 7×7, 9×9, 11×11, 15×15, 19×19, and 25×25) were tested in order to identify the best variables for biomass estimation [17].

The multiple regression analysis was used for biomass estimation in this study. The sample plot data were linked to image variables to extract the mean value for each sample plot based on a window size of 3×3 pixels. Because so many textural images were available but not all were needed in the biomass estimation, it was important to identify suitable textural images. Pearson correlation analysis was used to analyze relationships between biomass and TM-derived variables, including TM-spectral signatures and textures, and between the textural images each other. Only the textural images having significantly high correlation coefficients with biomass but having low correlation each other were selected and used for biomass estimation. The aboveground biomass from sample plots was used as a dependent variable and the selected TM-derived variables were used as independent variables. A stepwise regression analysis was used to develop the biomass estimation model. The coefficient of determination (R^2) was calculated to evaluate a regression model performance.

3.1.2. Resultant Analysis. The regression analysis results (Table 1) indicated that spectral signature led to much better estimation performance than textural images for secondary forest, but the result was inverse for mature forest. Neither spectral signatures nor textural images could effectively estimate mature forest biomass. A combination of spectral signature and textural images slightly improved secondary forest biomass estimation performance, but the improvement was considerable for mature forest biomass estimation. This research also indicated that textural image was a critical variable for mature forest biomass estimation, but not for secondary forest. As Figure 1 illustrated, if entropy was used to express the complexity of a forest stand structure, the entropy value was linearly related to secondary forest biomass, implying that the stand structure became complex as biomass increases in successional stages. However, the entropy value was similar for mature forests even if there was a significantly large range of biomass density (from approximately 110 to 500 T/ha in this study). This implied the data saturation problem in Landsat TM-spectral data due to the impact of forest stand structure in mature forest. In this case, use of spatial information based on textural measures was valuable to reduce the impacts of the forest stand structure, especially the heterogeneity of forest stands; thus, incorporation of textural images was necessary for mature forest biomass estimation.

3.1.3. Discussion and Summary. The aboveground forest biomass estimation based on TM image has indicated that

Table 1: A summary of regression analysis results in the western Brazilian Amazon.

Variables	Models	R^2	Beta value
Spectral signature	$AGB_{SF} = 667.72 - 13.92 \times f_{b4}$	0.75	
	$AGB_{MF} = 1024.14 - 54.96 \times f_{b5}$	0.16	
Texture	$AGB_{SF} = 164.62 - 2.27 \times f_{var}$	0.23	
	$AGB_{MF} = 134.57 + 19.29 \times f_{con}$	0.39	
Combination	$AGB_{SF} = 480.82 - 8.06 \times f_{b4} - 0.98 \times f_{var}$	0.76	−0.71 (sp), −0.24 (txt)
	$AGB_{MF} = 753.31 - 43.21 \times f_{b5} + 17.89 \times f_{con}$	0.50	−0.31 (sp), 0.65 (txt)

(1) AGB_{SF} and AGB_{MF} represent biomass estimates for successional forest and mature forest.
(2) f_{b4} and f_{b5} represent reflectance values of TM bands 4 and 5.
(3) f_{var} and f_{con} represent the textural image developed with the variance texture measure with TM band 4 and a window size of 15 × 15 pixels, and the textural image developed with the contrast texture measure with TM band 5 and a window size of 19 × 19 pixels.
(4) sp and txt represent the variables of spectral signatures and textures.
(5) R^2 is the coefficient of determination.

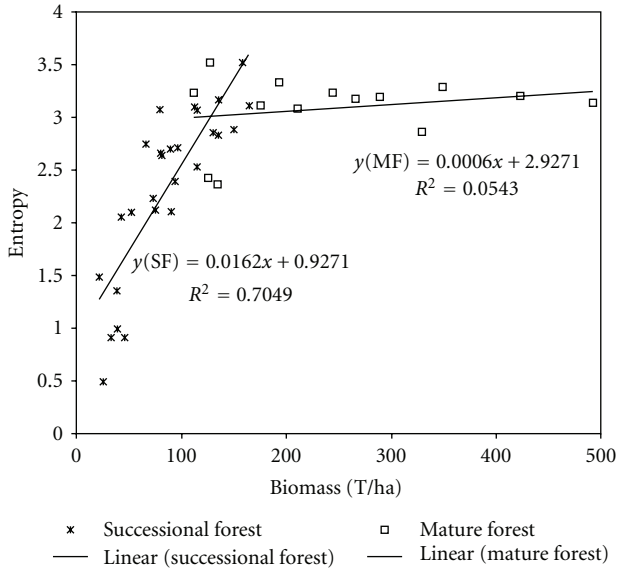

Figure 1: Comparison of aboveground biomass-entropy relationships in successional and mature forests in Machadinho d'Oeste in northeastern Rondônia, Brazil.

texture is an important variable for improving biomass estimation performance for the areas with complex forest stand structure. One critical step is to identify suitable textures but remains a challenge because textures vary with the characteristics of the landscape under investigation and images used. Identifying suitable textures involves the determination of appropriate texture measures, moving window sizes, image bands, and so on [17, 84, 85]. In practice, it is still difficult to identify which texture measures, window sizes, and image bands are suitable for a specific research topic, and there is also a lack of guidelines on how to select an appropriate texture [17].

This case study indicates that Landsat TM image can provide reasonable good estimation results for secondary forest biomass estimation, but the estimates have relatively poor for mature forests due to the data saturation problem in Landsat TM image. As shown in this case study, when biomass density is greater than approximately 150 T/ha in the moist tropical forest of the Brazilian Amazon basin, Landsat TM spectral signatures become insensitive due to the complex forest stand structure. The impacts of different biophysical environment on optical sensor data and different composition of vegetation species make it difficult in the model transferability, as previous research shown [15, 81]. It is important to develop reliable and stable variables from multispectral image. Spectral mixture analysis may provide an alternative because it can decompose the multispectral image into fractions having biophysical meanings [19].

The first case study shows the importance of Landsat TM image for successional forest biomass estimation, but incapability for mature forest because of data saturation problem caused by complex forest stand structure. Since LiDAR data can capture canopy height information, the use of LiDAR data may significantly improve biomass estimation performance. The second case study shows the application of LiDAR data for biomass estimation.

3.2. Case Study II: Biomass Estimation with LiDAR Data. Sierra Nevada in California is a mountain range as a home to many national resorts such as Lake Tahoe and Yosemite National Park. It is also a major source of water to the Central Valley, the most productive agricultural area in the United States. The vegetation in Sierra Nevada, including montane forests in higher elevation and woodland in lower elevation, plays a key role in regulating water and carbon cycling and providing critical ecological services. In this case study, LiDAR data were used to estimate vegetation biomass in the Sagehen Experimental Forest, which is approximately 32 km north of Lake Tahoe on the eastern slope of the Sierra Nevada. The major tree species in this area include white fir (*Abies concolor*), red fir (*Abies magnifica*), mountain hemlock (*Tsuga mertensiana*), lodgepole pine (*Pinus contorta*), Jeffrey pine (*Pinus jeffreyi*), sugar pine (*Pinus lambertiana*), and western white pine (*Pinus monticola*).

3.2.1. Methods. A total of 81 circular field plots with each of 0.05 ha were collected in 2006. A Trimble GeoXH handheld

GPS with Zephyr Geodetic antenna was used to remeasure the center of 81 individual plots. The average horizontal accuracy of the new GPS measurements was 0.1 m with the majority of less than 0.2 m, and, at the worse case, it was 1.5 m. All trees greater than 5 cm in DBH within each plot were measured with a nested sampling design. Canopy trees (DBH $\geq$ 19.5 cm) were tagged and measured within the whole plot; understory trees (DBH between 5 and 19.5 cm) were measured for one third of the plot. Tree measurements include species, DBH, tree height, canopy base height, vigor, and crown position. Allometric equations of individual tree species were selected from the literature [86, 87] to predict biomass of individual trees based on their DBH and, in some cases, height. The individual tree biomass was summed at the plot level to derive aboveground live tree biomass density in T/ha.

LiDAR data were collected on September 14–17, 2005 for the study area using an Optech ALTM 2050 system, which acquired up to two returns per pulse at a pulse frequency of 50 kHz, scan frequency of 38 Hz, and a maximum scan angle of 15°, creating a swath width of ~580 m. The point density was about 2–4 returns per square meters. The LiDAR point clouds were first filtered to generate a Digital Elevation Model (DEM) of 1 m cell size. The canopy height of individual points was calculated by subtracting the terrain elevation from the original Z values. A number of LiDAR metrics were generated based on LiDAR point heights within any given plot: mean (h_u), standard deviation (h_{std}), skewness (h_{skn}), and kurtosis (h_{kurt}); proportion of LiDAR points within different height bins (0 to 5 m, 5 to 10 m, …, 45 to 50 m, and >50 m, denoted as $p_{0\text{ to }5}$, $p_{5\text{ to }10}$,…, $p_{45\text{ to }50}$, and $p > 50$, resp.); percentile heights (5, 10, …, 100 percentile, denoted as h_5, h_{10},…, h_{100}, resp.); quadratic mean height (h_{qm}). To examine the impacts of laser returns on biomass estimation, we generated LiDAR metrics from point clouds based on first returns and all returns, respectively. Besides using point clouds, we also generated LiDAR metrics based on the 1-m Canopy Height Model (CHM) cells within individual plots. CHM was obtained by subtracting DEM from a DSM (Digital Surface Model), which was generated by interpolating the highest point within each cell. All of the above LiDAR data processing was conducted using the Tiffs (Toolbox for LiDAR Data Filtering and Forest Studies) software [88].

We first did log transformation for both biomass and individual LiDAR metrics and then fit linear models using stepwise regression to select the most statistically significant LiDAR metrics. The developed linear models were multiplicative in the original scale. A total of four models were developed depending on the data sources used to extract LiDAR metrics: (1) all LiDAR returns, (2) first returns only, (3) last returns only, and (4) CHM cells. Among the 81 plots used for model development, one plot had questionable GPS accuracy. Three plots were found to have large residuals (>3 standard residuals) in the regression models and had obvious mismatch between field measurements and LiDAR point clouds after carefully visual inspection. Therefore, these four plots were removed, resulting in a total of 77 plots in statistical analysis.

Table 2: Regression models and their statistics.

Data source	Independent variables	R^2	RMSE (T/ha)
All returns	$h_{\text{qm}}, h_{35\text{ to }40}$	0.76	82.1
First returns	$h_{\text{qm}}, h_{35\text{ to }40}$	0.75	83.5
Last returns	$h_{\text{qm}}, h_{40}, h_{35\text{ to }40}$	0.76	81.1
CHM cells	$h_{\text{qm}}, h_{35\text{ to }40}$	0.77	81.0

Note: h_{qm} is the quadratic mean height, $h_{35\text{ to }40}$ means the proportion of LiDAR points or CHM cells within the height bin of 35–40 m, and h_{40} means the 40th percentile of LiDAR points. R^2 and RMSE are the coefficient of determination and root mean square error, respectively.

3.2.2. Resultant Analysis. The LiDAR metrics chosen for the four regression models and their model fitting statistics are summarized in Table 2. Among the four models, the model based on CHM cells has the highest R^2, followed by the one based on last returns and the one based on all returns. The model based on first returns has the highest RMSE. However, the differences among these four models are too small (R^2: 0.75–0.77; RMSE: 81.0–83.5 T/ha) to be considered as significantly different. If all field plots are used to fit the regression model, the biomass model based on LiDAR metrics from all returns is

$$\text{Ln(AGB)} = 2.10 + 1.56\ \text{Ln}\left(h_{\text{qm}}\right) + 0.05\ \text{Ln}(h_{35\text{ to }40}), \quad (1)$$

where AGB is the aboveground live tree biomass in T/ha, h_{qm} is the quadratic mean height in meter, and $h_{35\text{ to }40}$ is the proportion of LiDAR points between 35 m and 40 m. The maximum canopy height of the field plots ranges from 15.7 m to 44.7 m with a mean value of 27.9 m. The above model indicates that if there are more points in the upper vertical stratum (higher $h_{35\text{ to }40}$ values), a plot will have higher aboveground biomass. The quadratic mean height h_{qm} is also a metric giving more weight to the higher canopy points [89]. The selection of these two metrics in the model agrees with the fact that the biomass of a field plot is highly influenced by larger and taller trees. Figure 2 shows the predicted biomass in comparison to the field biomass when the LiDAR metrics from all returns are used to develop the biomass model. For the 77 field plots, the average field biomass is 239.1 $\pm$ 166.4 T/ha and the maximum biomass is 808.9 T/ha. This figure clearly shows that LiDAR is able to predict biomass even for the plots of very high biomass.

3.2.3. Discussion and Summary. In previous studies, the coefficients of determination (R^2) of the statistical models for LiDAR-based biomass estimation typically vary from 0.6 to 0.9 depending on the specific vegetation conditions, the amount of field observations, and the specific approach used for statistical modeling. Our results are in the range of the coefficients from these studies and are close to those from similar forest conditions (e.g., [90]). Although previous research indicated that the use of first returns instead of all returns can improve R^2 by 0.1 [53], this study found a negligible difference (~0.01) to use first, last, or all returns for biomass estimation. This research also indicated no significant difference by using LiDAR metrics derived from point clouds or CHM (Table 2).

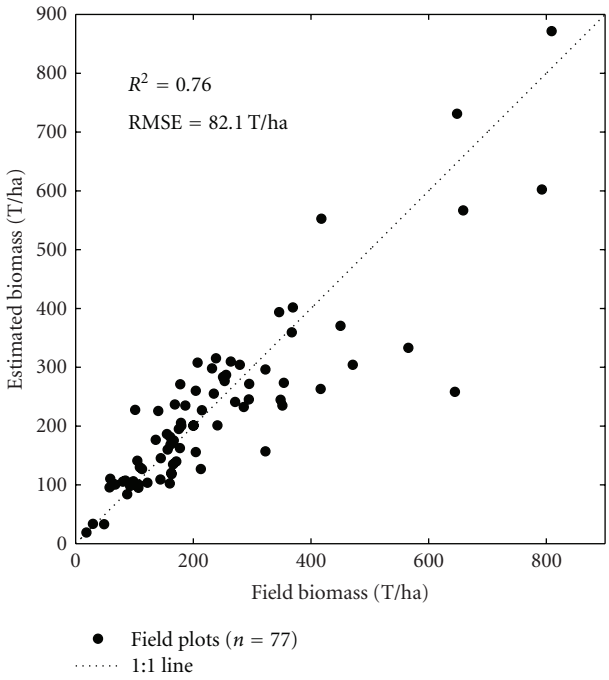

Figure 2: LiDAR-predicted versus field biomass over the 77 field plots in the Sagehen Experimental Forest in Sierra Nevada, California.

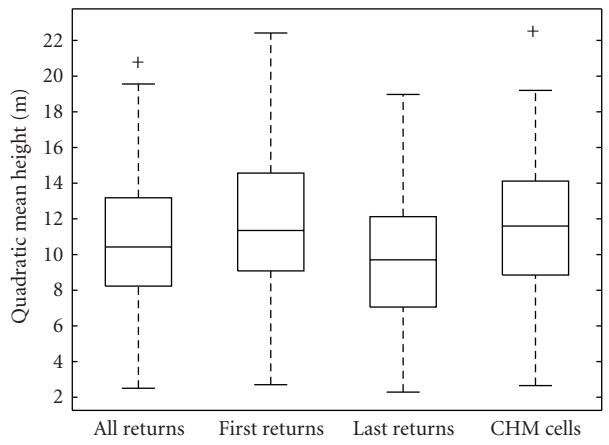

Figure 3: Boxplots of quadratic mean height derived from different LiDAR data sources.

Despite the models' performance is similar, it was found that there are significant differences among the LiDAR metrics from some data sources. Figure 3 shows the box plots of quadratic mean height calculated from all returns, first returns, last returns, and CHM cells, respectively. Table 3 summarizes the relevant P-values of the pair-wise two-sample t-tests. It was observed that the quadratic mean height from first returns was higher than the one from last returns on average at the 5% significant level (P-value: 0.001). This makes sense since a laser usually penetrates deeper into the canopy to generate another return after the first one if it is not completely blocked. Figure 4(a) shows an example of the LiDAR point cloud in one plot, with the first and last return linked by arrow-headed lines. It can be seen that there are large elevation differences between first and last returns for many laser pulses. Figure 4(b) shows the histogram of the differences between first and last returns for the same plot. Note that there are points with differences of 0.5 m–4 m, which is the so-called "blind-zone" of airborne LiDAR data.

Table 3: P-values of pair-wise two sample t-tests for quadratic mean heights derived from different data sources.

	First returns	Last returns	CHM cells
All returns	0.133	0.081	0.141
First returns	—	0.001	0.962
Last returns	—	—	0.001

The quadratic mean height from last returns is lower than the one from CHM cells on average at the 5% significant level (P-value = 0.001). This is also reasonable since CHM cells characterize the canopy surface height distribution while last returns correspond more to trunk, branches, and ground. The relevance of last returns to lower canopy elements such as branches and trunks, the major biomass components, might explain why the LiDAR metrics based on last returns have slightly better model performance (R^2: 0.76, RMSE: 81.1 T/ha) compared to the ones based on first returns (R^2: 0.75, RMSE: 83.5 T/ha). Again, this is a very small difference, and it is unclear whether this pattern will persist over other vegetation types.

Based on above observations, we conclude that different groups of LiDAR metrics (from all returns, first returns, last returns, or CHM cells) do not lead to significant difference in biomass estimation although they could be significant from each other by themselves. In other words, different group metrics are all sensitive to biomass variation in our study. Because our findings are different from the results from previous studies [53], more research is needed in the future along this line.

Although uncertainty analysis of the biomass estimation results is regarded as an important part in biomass modeling based on remote sensing methods, insufficient number of sample plots often make it difficult to conduct such analysis, as shown in much previous research and above two case studies. Therefore, the third case study in the following section shows the methods for conducting uncertainty analysis in a study area of Zhejiang province, China, in order to understand the major sources influencing biomass estimation performance.

3.3. Case Study III: Estimation and Uncertainty Analysis of Aboveground Forest Carbon. The third case study was conducted at Lin'An County, Zhejiang Province of East China for examining uncertainty of forest carbon estimates. Lin'An County has an area of 312,680 ha and is located in a subtropical zone with average annual temperature of 16.4°C and average annual precipitation of 1,628 mm. This is a mountainous area with an elevation range of 1770 m

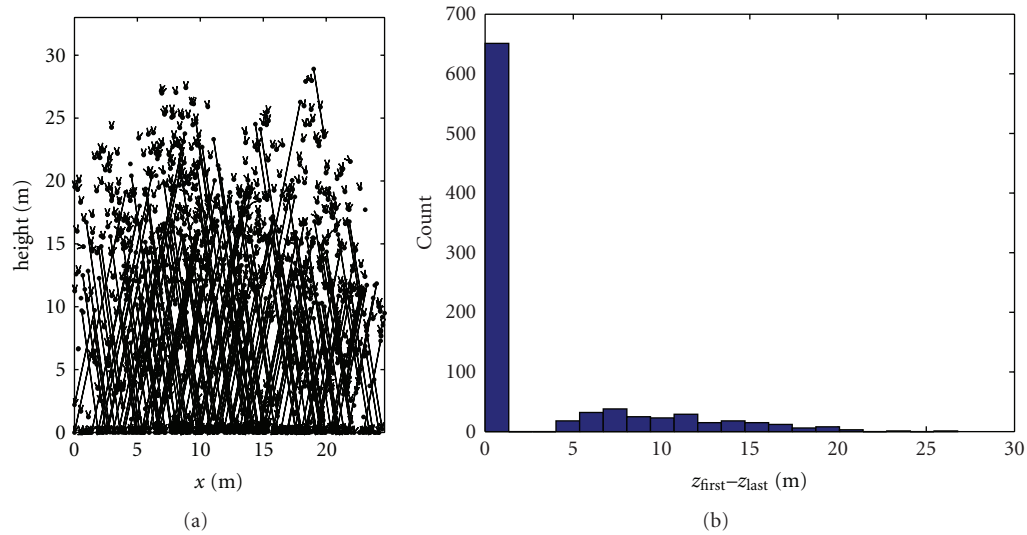

Figure 4: (a) LiDAR point cloud in one field plot with the first and last returns linked by arrow-headed lines, and (b) the histogram of the elevation differences between first and last returns for the same plot.

and characterized by plantation ecosystems consisting of coniferous forests, evergreen broad-leaf forests, deciduous and evergreen broadleaf-mixed forests [91].

3.3.1. Methods. A total of 766 plots covering 80% of the county which were measured in 2004 were used to generate an aboveground forest carbon map. Within each plot, tree DBHs and heights were measured. The plot tree volumes, including stump but excluding branches, were first computed by using the empirical models by species. The values of aboveground forest biomass and carbon were then obtained by using biomass expansion factors and carbon conversion factor [55].

A Landsat Enhanced Thematic Mapper Plus (ETM+) image, dated on August 3, 2004, was used for this study. This ETM+ image was geometrically rectified using a digital topographic map with the Universal Transverse Mercator (UTM) as reference coordinate system, and the resulting RMSE was less than one pixel. In order to improve relationships of the images with the aboveground forest carbon, six inversions of bands: $1/b1$, $1/b2$, $1/b3$, $1/b4$, $1/b5$, $1/b7$, and ten band ratios: $b1/b4$, $b2/b4$, $b3/b4$, $b5/b4$, $b7/b4$, $b8/b4$, $(b4 - b3)/(b4 + b3)$, $(b3 + b5)/b7$, $(b3 + b5 + b7)/b4$, and $(b2 + b3 + b5)/b7$, were calculated. Moreover, correlation matrix-based principal component analysis of six original ETM+ bands was made. The images that had the highest correlation with forest carbon were used to create estimates of forest carbon with an image-based cosimulation algorithm.

The 766 plots were divided into two groups by a random sampling. The first group of 600 plots (Figure 5(a)) was used to generate an aboveground forest carbon map by an image-based spatial co-simulation algorithm in which the plot data were combined with the ETM+ image [54]. The second group of 166 plots (Figure 5(b)) was applied to conduct the accuracy assessment and uncertainty analysis of the obtained estimates. In the algorithm, it is assumed that aboveground forest carbon is spatially autocorrelated [55, 92]. That is, the closer the locations, the more similar the values of aboveground forest carbon. The similarity becomes weaker and weaker as the distance between two locations increases. Once the distance reaches a threshold value, the similarity will disappear. This feature of aboveground forest carbon can be characterized by using variogram. The threshold value for the distance between two locations is called the range of spatial autocorrelation. The values of aboveground forest carbon are spatially dependent on each other within the range and independent outside of it. In addition, it is assumed that aboveground forest carbon is spatially cross-correlated with the image-spectral variables. The spatial autocorrelation of the forest carbon and spectral variables and cross-correlation between them provide the basis on which the predicted values of the forest carbon at unobserved locations can be generated from the sample plot data using the co-simulation algorithm.

The value of aboveground forest carbon at each location is regarded as a realization of this random process, and the realization can be created using the following co-simulation algorithm [54, 55]. The study area is first divided into square cells or pixels, and a random path to visit each of the pixels is set up. When each pixel is predicted, a neighborhood in which plot data are used is determined based on the range of spatial autocorrelation. Within this neighborhood, the sample plot data, previously simulated values if any, and collocated image data are employed to obtain a conditional cumulative distribution function. This function is determined by calculating a conditional mean and variance by an unbiased collocated simple cokriging estimator that weights the data values and spatial variability. The weights vary depending on spatial configuration of the

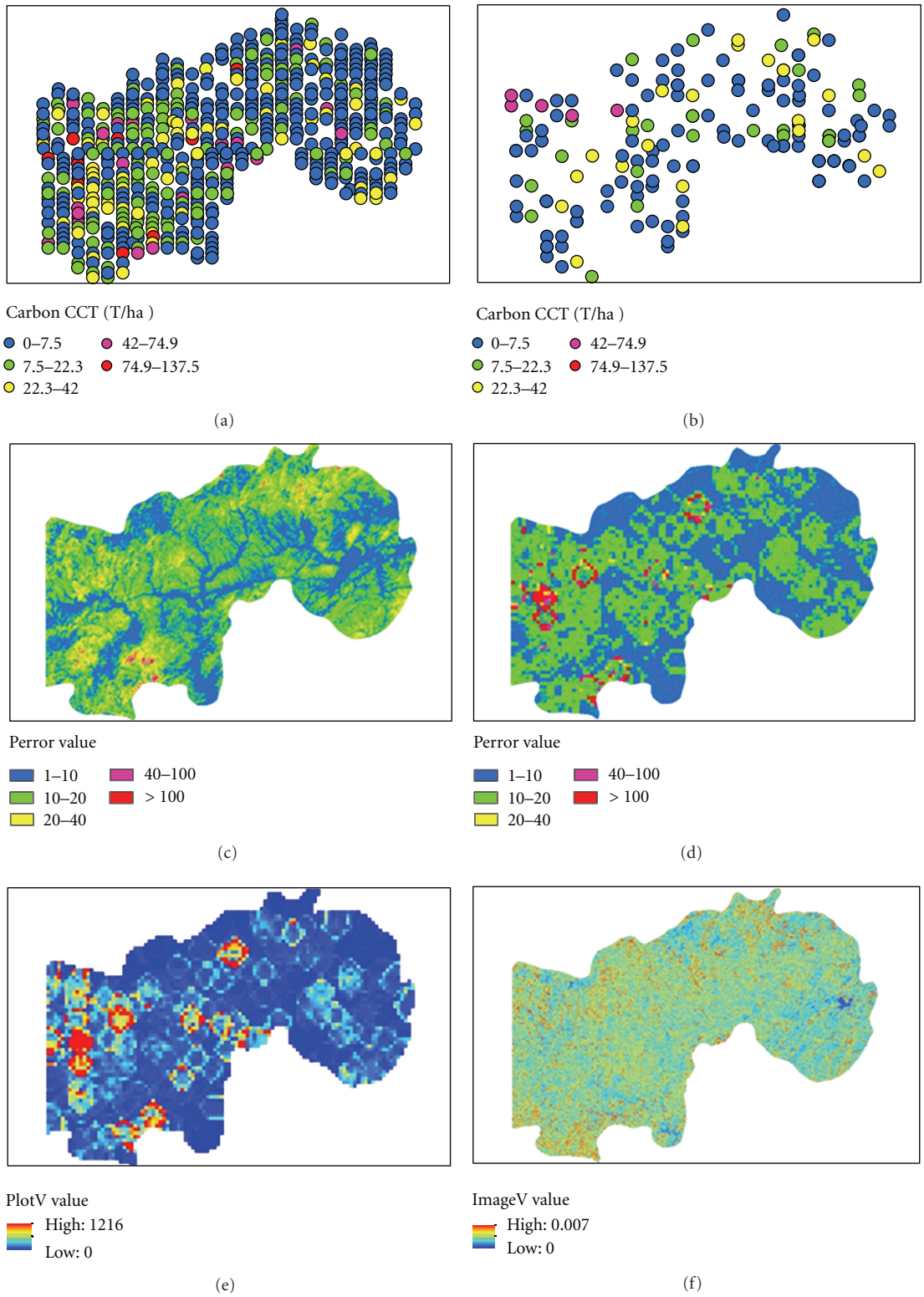

Figure 5: Continued.

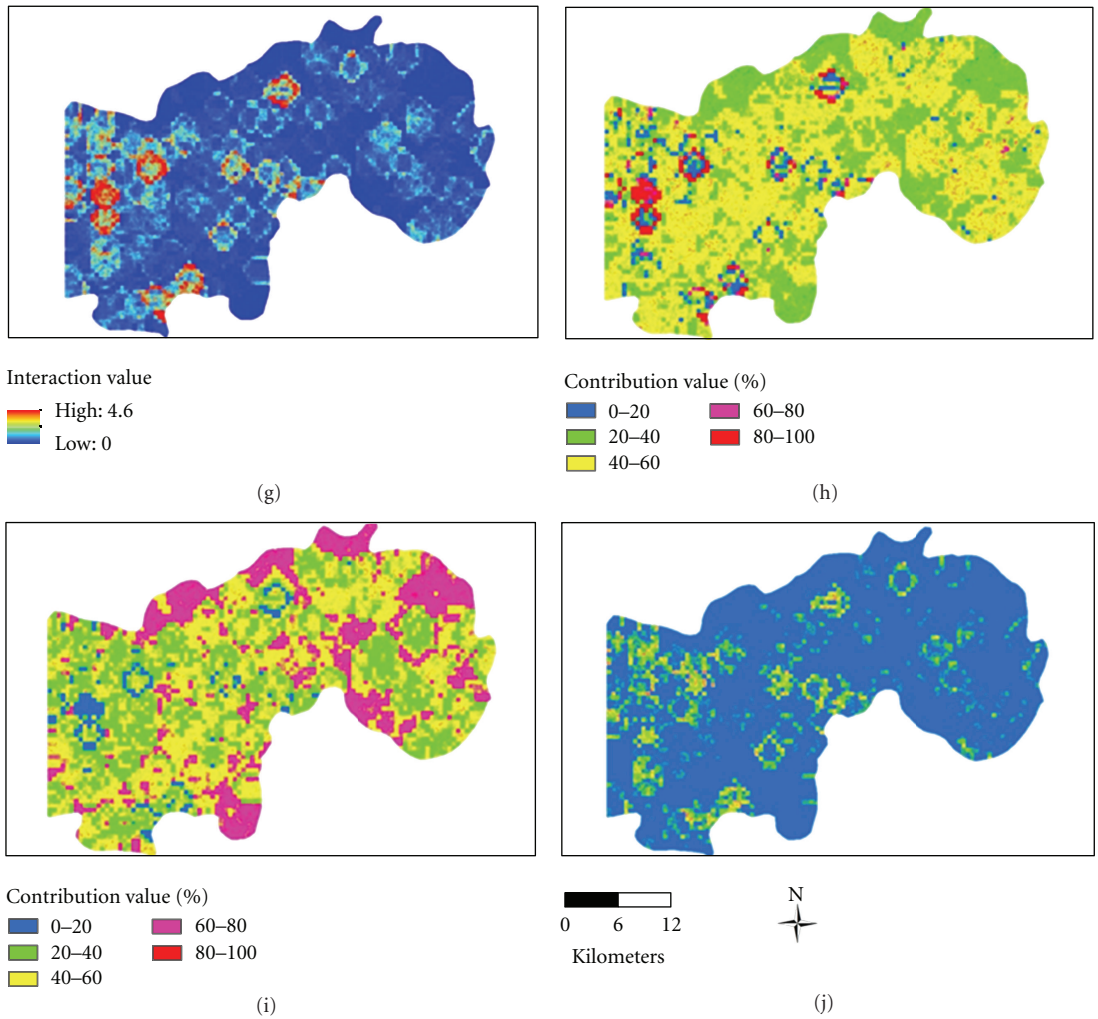

Figure 5: Aboveground forest carbon map obtained by combining forest inventory sample plot data and ETM+ images using image-based spatial co-simulation and its polynomial regression-based uncertainty analysis in Lin-An county, Zhejiang province of East China. [(a) forest carbon (T/ha) of sample plots used for development of algorithm; (b) forest carbon (T/ha) of sample plots used for test of results; (c) predicted forest carbon values (T/ha); (d) errors (T/ha) of predicted forest carbon values; (e) variance of input plot data; (f) variance of input image; (g) interaction of forest carbon and image variances; relative uncertainty contribution (%) from (h) the input plot data, (i) ETM+ image, and (j) their interaction].

data and predicted locations and their spatial autocorrelation and cross-correlation. Generally, the shorter the distance is, the greater the weight of the data is. From the distribution function, a value is then randomly drawn, regarded as a realization of the forest carbon at this location and also used as a conditional data for simulation of neighboring locations. A computer program is used to follow this random path to create a simulated value for each location. A map of the forest carbon is obtained after all pixels are visited. By setting up different random paths to visit each location and repeating the above process, more than one simulated values can be created. In this study, 400 simulated values for each pixel were obtained, and an E-type sample mean of the forest carbon was finally calculated and used as a predicted value.

An uncertainty and error budget method was developed based on the polynomial regression to explicitly model the propagation of uncertainties from inputs to output for the above mapping [54]. The advantages of this method are that it can model spatial and temporal uncertainty propagation and contributions from sampling, plot location errors, measurement errors, improper allometric equations, biomass and carbon conversion factors, and so forth, and it can also handle the effect of interactions among input variables and the effect of neighboring information. First, the various sources of uncertainties are identified and quantified. A polynomial regression is then developed to define the relationships of uncertainties between the inputs and output. Finally, the regression model is used to estimate the relative uncertainty contributions of the inputs to the uncertainty of the output. In order to clearly explain this method, in this study only the variances of the used field plot data and ETM+ images were considered as the input uncertainties

for estimation of each location. The output uncertainty was the absolute difference between the estimated and observed values of aboveground forest carbon for each of the 166 test plots.

3.3.2. Resultant Analysis. The sample mean, standard deviation, and coefficient of variation of aboveground forest carbon for the 600 plots that were used for development of the co-simulation algorithm was 11.23 T/ha, 18.08 T/ha, and 161.08%, respectively. That is, the forest carbon at the plot level varied greatly due to a great range of elevation, and diverse soil and topographic features in the mountainous area. The spatial distribution of the predicted forest carbon values in Figure 5(c) was consistent with that of the sample plot data in Figure 5(a). That is, where the sample plots have higher forest carbon values, the predicted values are also higher and vice versa. Based on the test sample of 166 plots, the Pearson correlation coefficient and RMSE between the estimated and observed values of the forest carbon were 0.7146 and 9.98 T/ha, respectively. This RMSE value was relatively large, which was caused by large variation of the forest carbon in this area.

In order to model propagation of uncertainty, a total of sixteen 1st to 4th order polynomial regression models with and without constant regression coefficients, and with and without interactions of uncertainties between the forest carbon and spectral variable were obtained by using the 166 test sample plots. It was found that the 1st order polynomial regression model without the interaction and the 3rd order polynomial regressions models with and without the interaction, but without the constant regression coefficient, provided more accurate prediction. All other models led to negatively predicted values of the output uncertainty for the extremely small and large input errors and thus had poor ability of predicting uncertainty. Let F_u, P_v, and I_v be the uncertainties of the output carbon, input plot variance and image variance, the models were expressed as follows:

$$F_u = 4.5349 + 0.07936P_v + 1007.191I_v, \tag{2}$$

$$F_u = 0.2768P_v + 9231.889I_v - 0.003657P_v^2 - 5840468I_v^2 + 0.00001315P_v^3 + 1280283000I_v^3, \tag{3}$$

$$F_u = 0.2452P_v + 10495.45I_v + 33.046P_v \times I_v - 0.003762P_v^2 - 7476639I_v^2 + 0.0000137P_v^3 + 1726692000I_v^3. \tag{4}$$

The values of regression coefficient R for models (2), (3), and (4) were 0.4147, 0.5033, and 0.5064, respectively. The regression coefficients were relatively low, mainly due to the great variations of the aboveground forest carbon, the input plot data and image variance, and the output uncertainties. Based on the model (4), the error map of the predicted values was calculated and illustrated in Figure 5(d). Its spatial distribution was mainly determined by the spatial patterns of the input variances from the field plot data in Figure 5(e) and less affected by the input variances of the used image (Figure 5(f)). In the areas where the variation of the forest carbon was large (Figures 5(a) and 5(c)), the error of the predicted values was also large (Figure 5(d)). The relative uncertainty contributions from the input variances of the plot data were larger than 40% at the most part of the study area (Figure 5(h)), especially in the areas where the variation of the forest carbon was large. Thus, the plot data variance was the main source of uncertainty. In the areas where the uncertainty contributions from the plot data variances were smaller, the uncertainties of the predicted forest carbon values were mainly determined by the variances of the used image (Figure 5(i)). The variance contributions from the interaction of the aboveground forest carbon with the image were smaller but positive, implying that the variances from both plot data and ETM+ image increased the uncertainty of the predicted values (Figures 5(i) and 5(j)).

3.3.3. Discussion and Summary. Although the co-simulation algorithm led to an aboveground forest carbon map that had a similar spatial distribution of estimates to that of the sample plot data, the overall relative RMSE of 88.9% was very large. This was mainly due to the large variation of the aboveground forest carbon in this case study. Developing robust polynomial regression models that can account for the relationships of input uncertainties with output uncertainties is a great challenge for uncertainty analysis of forest biomass/carbon estimates. It is often difficult to obtain a high-quality polynomial regression model in terms of regression coefficient or coefficient of determination due to large variations of input and output uncertainties, especially when outliers exist. Wang et al. [54] used a 4th-order polynomial regression with a regression coefficient of 0.4818. Although the regression coefficients of the obtained models were statistically significant in this case study, they were relatively small. The main reason was due to the large variations of the input plot data variances and image variances. In order to improve the quality of the models, in practice, the outliers can be removed using 2 standard deviations.

This case study led to a finding that the main source of the uncertainty for mapping aboveground forest carbon was the variances of the input field plot data and relatively the uncertainty contribution from the used image was small. Moreover, the interaction of the uncertainties from both the field plot data and image increased the uncertainties of the predicted values. Because of space limitation, this case study did not deal with other uncertainty sources including biased sampling, measurement errors of tree variables, uncertainties of allometric equation parameters for tree volume calculation, uncertainties from biomass and carbon conversion factors, uncertainties from geometrical and radiometric correction of remotely sensed data, and so forth. However, this case study did not lose its generalization as the demonstration of a methodology for mapping and uncertainty analysis of forest carbon by combining sample plot data and remotely sensed images. In future studies, more sources of uncertainties will be investigated.

4. Conclusions and Challenges

Landsat TM imagery having proper spectral and spatial resolutions and relatively long historical datasets, as well as world-wide data availability with free has been extensively applied for forest biomass/carbon estimation. The TM imagery is suitable for forest biomass estimation for the area with relatively simple stand structure such as secondary forest but does not work well for the area with complex forest stand structure such as mature forest in the moist tropical region of the Brazilian Amazon. Due to the complexity of atmosphere, vegetation phenology, and different vegetation types and structures, application of Landsat TM images for biomass estimation is often site dependent, which means that the algorithm developed in one study area cannot be directly transferred to other study areas [15].

Many factors, such as collection of sample plots, biomass calculation with allometric equations, selection of spectral variables, and use of modeling algorithms, affect biomass estimation results. The uncertainty analysis based on co-simulation algorithm indicates that the variation of input field plots is the major source inducing uncertainties of biomass estimates. For the areas with complex forest stand structure and vegetation species composition, data saturation on the optical sensor data is another important source resulting in large uncertainty in the moist tropical region. Since LiDAR data can capture forest canopy height, its use has proven to offer an alternative for improvement of biomass estimation. However, LiDAR is mainly used to estimate canopy height. Although canopy height is a very important variable for biomass estimation, biomass is also related to other forest stand parameters such as tree species composition and tree density. LiDAR or optical sensor data alone cannot provide sufficiently accurate biomass estimation results. It necessitates making full use of different sensor features inherited in LiDAR and TM images. Therefore, identifying suitable methods to integrate both data sources for biomass estimation is valuable. This involves the selection of suitable variables for use in modeling and of suitable algorithms to establish estimation models. Through the uncertainty analysis, it is possible to identify the major sources affecting biomass estimation performance, and then we can adopt suitable measures to reduce the uncertainties.

When multiscale remotely sensed images are used for mapping forest biomass/carbon, a great challenge we are facing is how to combine the images that have inconsistent spatial resolutions. Traditional data fusion algorithms such as RGB (red-green-blue) to HIS (intensity-hue-saturation) and Brovey transformation [93] do not work well because the spatial resolutions of the results are limited to the original images. Multi-scale image fusion approaches such as multi-scale Kalman Filtering [94] are needed. Another great challenge is how to match the multi-scale images with sample plot data when the images and data have inconsistent spatial resolutions and further scale up the spatial data from finer spatial resolutions to coarser ones when sample plots are smaller than pixels of maps that are required for decision making. The upscaling of spatial data is often necessary because generally the sizes of sample plots are smaller than $30\,\text{m} \times 30\,\text{m}$ because of cost limitation, while forest biomass/carbon maps at national scale are usually generated at spatial resolution of $1\,\text{km} \times 1\,\text{km}$. The challenge is mainly because the relationships of forest attributes with spectral variables vary depending on spatial resolution of data and a model that is developed based on the data at one spatial resolution cannot be used across resolutions. Wang et al. [54, 95] overcame this gap by developing an image-based spatial co-simulation algorithm in which the same distributions of spatial data are assumed when images and sample plot data are combined and scaled up from finer spatial resolutions to coarser ones.

Another challenge in forest biomass/carbon estimation is accuracy assessment and uncertainty analysis. Decision and policy makers need not only forest biomass estimates but also their measures of uncertainty. However, the latter is usually difficult to obtain. The challenge is mainly attributed to (1) high cost to collect independent sample plot data; (2) complicated landscapes and environments in which various soil and topographic factors lead to high variation of forest biomass/carbon; (3) multiple sources of uncertainties; (4) lack of algorithms that can be used to conduct uncertainty analysis. Wang et al. [54, 55] suggested four groups of uncertainty sources for forest biomass/carbon estimation. First of all, there are uncertainties of the used data, mainly including measurements errors of tree variables, plot location errors, image data errors due to remote sensing systems and atmospheric conditions, geometric errors due to mismatch of image and map coordinate systems, and so forth. The second group of uncertainty deals with variation of variables and parameters. For example, high variation of forest structures and complicated tree species composition will no doubt result in large uncertainties of forest biomass estimates. High variation of tree volume to biomass and biomass to carbon conversion factors will also lead to great uncertainties. Moreover, the uncertainties may also be due to uses of biased sampling methods, improper allometric equations for tree volume calculation, inaccurate interpolation algorithms, and so forth. In addition, knowledge gaps are another source of uncertainty.

Some of uncertainties may accumulate and propagate to the outputs through the estimation and mapping system of forest biomass/carbon and others may be cancelled out. Uncertainty analysis-modeling and quantifying the propagation of the input uncertainties to the outputs is thus a complicated process. Currently, robust approaches are still lacking. Larocquea et al. [96] discussed a theoretical framework to estimate error propagation for process-based models of forest ecosystem carbon cycle. Nabuurs et al. [57] compared the uncertainties of forest carbon estimates for a tropical and a temperate forest for model-based methods and found that carbon content, wood density, and current annual increment of stems were the parameters that exhibited the highest influence on carbon sequestration. Wang et al. [54] developed a general framework for uncertainty analysis of forest biomass/carbon estimates, and this study further demonstrated its application.

In this study, the first case study revealed data saturation of Landsat TM images for biomass estimation of mature

forest as one of uncertainty sources. The uncertainties can be attributed to both complex forest stand structures and inherent disadvantages of Landsat TM sensors. Because of its capability to capture canopy height information, the use of LiDAR data in the second case study implied the potential to improve biomass estimation performance by combining LiDAR and Landsat TM images. However, due to limitations of space and time, this study did not demonstrate the integration. Because of the insufficient number of sample plots, in addition, uncertainty analysis of this study was only conducted in the third case study. Thus, the important contribution of this study lies at providing the potential and suggestions for the future research direction.

In this study, an image-based spatial conditional cosimulation algorithm was used to map aboveground forest carbon in the third case study. This algorithm is based on spatial autocorrelation of variables and accounts for not only the local spatial variation of variables but also the uncertainties of the local estimates [54, 55]. In practice, the spatial autocorrelation of forest variables widely exist. The variables and the relationships between them also vary from place to place. Thus, this algorithm is very promising. Another similar choice is geographically weighted regression (GWR) that is a local form of linear regression [97]. GWR can be used to model spatially varying relationships and allows regression coefficients to vary spatially. In the first and second case studies of this research, however, a global regression modeling method was employed to map forest biomass, and the local variation and spatial autocorrelation of forest variables were not tested mainly because of limited sample plots. In the future study, it may be necessary to demonstrate the applications of GWR to these study areas.

Acknowledgments

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Research Article

Productivity and Cost of Integrated Harvesting of Wood Chips and Sawlogs in Stand Conversion Operations

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This study evaluated the operational performance and cost of an integrated harvesting system that harvested sawlogs and biomass (i.e., energy wood chips) in stand conversion clearcut operations. Douglas-fir (*Pseudotsuga menziesii*) trees were processed into sawlogs while whole trees of tanoak (*Lithocarpus densiflorus*), and sub-merchantable materials (small-diameter trees, tops and limbs) were fed directly into a chipper to produce biomass for energy production. A standard time study method was used to determine productivity and costs. Over 26 working days, the integrated system produced 1,316 bone-dry metric tonnes (BDTs) of sawlogs, and 5,415.89 BDT of chips, with an average moisture content of 43.2%. Using the joint products allocation costing method, the costs of the integrated system were $29.87/BDT for biomass and $4.26/BDT for sawlogs. Chipping utilization was as low as 41%, directly affecting production and cost of chipping operation. Single-lane, dirt, spur roads were the most costly road type to transport whole trees to a centralized processing site: transportation costs for biomass and sawlogs were increased by $0.08/BDT and $0.02/BDT, respectively, for every 50 meter increase in traveling distance. Diesel fuel price could raise total system cost for each product by $0.78/BDT and $0.08/BDT for each $0.10/liter increase.

1. Introduction

On the north coast of California many once-commercially-productive conifer stands are now over-run by tanoak (*Lithocarpus densiflorus*), which sprouts from stumps, out-competing merchantable conifer species. The transformation in species dominance from conifer to hardwood was the result of poor stocking success following earlier harvests. More than 16,187 hectares on private industrial forest land along the north coast of California are now classified silviculturally as rehabilitation stands due to understocking of conifers (<11.49 m^2 of basal area per hectare; Figure 1) [1]. Converting stand composition through clearcut practices, referred to as rehabilitation harvests, has been taking place in northern California, but is expensive due to the large volume of nonmerchantable forest biomass which needs to be removed. If local bioenergy markets are available, nonmerchantable biomass could be converted into an energy wood product such as chips or hog fuel (i.e., ground woody biomass). However, forest biomass is often underutilized because collection and transportation costs are often greater than the market value of the materials [2].

Bioenergy is the largest source of renewable energy in the United States, with over 11 gigawatts of installed capacity [3]. Beckert and Jakle (2008) noted that 20% of all biomass used for bioenergy comes from the forestry sector, but improvements in the supply of feedstock is necessary to meet the demands of today's renewable energy development. Available woody biomass in the forest is not often utilized because of high costs associated with harvesting and transportation [4]. Improved knowledge on new and innovative systems used to harvest and remove woody biomass would aid land managers in the planning and execution of cost-effective bioenergy operations.

Integrated harvesting is defined as a single pass harvesting operation so that an energy component is produced in conjunction with conventional sawlog assortments [5]. Research has shown that integrated harvesting systems can be effectively used to harvest and supply woody biomass

Figure 1: Tanoak dominated stand that was once a productive conifer stand, now managed through rehabilitation silviculture.

for energy from conventional forestry plantations [6]. Integration of biomass harvesting into an active logging operation could also reduce the cost of producing biomass by utilizing the equipment on site for multiple products and minimizing the amount of tree handling [7]. Since integrated harvesting removes biomass with sawlogs in a single pass, there is no need for a second operation to clean up harvesting residues. Integrated harvesting systems have been applied to fuel reduction thinning treatments to reduce the threat of forest fires. To reduce fuel loads in high density stands, whole trees are felled and removed to landings or roadsides where they are processed into sawlogs and biomass. This approach facilitates slash disposal without prescribed burning and increases opportunities for the utilization of biomass for energy production. Costs of integrated fuel reduction thinning operations have also been shown to be economically feasible at \$25.79/m^3 for sawlogs and \$34.94/BDT for biomass [8].

There are a variety of site conditions which favor integrated biomass harvesting operations. First, the sites to be harvested need to be readily accessible. Poor road surfacing, tight turns, and adverse grades should be improved prior to operations or avoided if possible. These conditions contribute to longer round-trip transportation times and higher transportation costs for vehicles with long lengths or low ground clearance (e.g., chip vans, log trucks hauling whole trees). Second, landing size at centralized processing sites should be sufficiently adequate for the flow of incoming material. If more than one harvest unit is storing material to a centralized processing site, several hectares may be required to store both biomass and sawlog products. Since there are multiple tasks happening with various schedules, centralized processing sites are often busy and need to safely accommodate multiple machines working on site. Addressing all of these conditions will aid in maximizing the production of biomass for bioenergy cost-effectively.

Delays are recognized as one of the major factors that limit chipping/grinding productivity in an integrated system and are an essential part of most time studies. Chipping utilization has been reported in a study relating to biomass harvesting operations at 73.8% [9]. Since utilization rates are correlated with production rates, lower utilization means lower daily production and higher unit production costs (\$/BDT). Ideally, one would aim to minimize chipping/grinding delays when planning an integrated harvesting operation, because it can be one of the most sensitive and expensive components of an operation.

This study evaluated the operational performance and cost of an integrated biomass harvesting system that harvested sawlogs and biomass (i.e., energy wood chips) in stand conversion clearcut operations. Specific objectives for this study were to determine the following.

(1) The hourly production rate for each stage of operation and the operation as a whole for both sawlog and biomass components.

(2) The unit production cost for each stage of operation and the operation as a whole for both products (\$/BDT).

(3) The major factors that affect the overall cost and productivity of the integrated biomass harvesting system.

2. Material and Methods

2.1. Study Sites. Three study units, with prescriptions for stand rehabilitation harvest, were located on private industrial forestlands in northern California. The composition of the three units ranged from 45 to 82% tanoak, 0 to 7% madrone (*Arbutus menziesii*), and 18 to 48% young growth Douglas-fir (*Pseudotsuga menziesii*), with slopes ranging from 0 to 45% (Table 1). The three stands ranged from six to nine hectares in area and were classified as understocked conifer stands (<11.49 m^2/ha basal area of conifer stocking), except for Unit 2 which averaged 40.18 m^2/ha basal area of conifer stocking. Study units were cruised prior to operations with a systematic sampling grid (31.7% of the total harvest area) of 0.08 ha per plot, with a minimum of two plots per hectare. Trees larger than 12.7 cm in diameter at breast height (DBH) were recorded at each plot and used to estimate the preharvest stand volumes and average tree size.

All three units were clearcut with a mechanized ground-based shovel logging system. The integrated system utilized one Timbco T445D feller-buncher to cut and bunch whole trees at the site. Two Komatsu PC300 log loaders (Komatsu 1 & Komatsu 2; Figure 2) were used to swing (i.e., shovel) bunches of whole trees to the roadside. Both loaders took turns loading roadside bunches of logs, whole trees, and tops onto two log trucks for transportation to a centralized processing site (Figure 2). The whole trees and residues delivered to the centralized processing site were immediately unloaded by another Komatsu log loader (Komatsu 3; Figure 2) which was equipped with a grapple saw, and worked with a remotely controlled pull-through delimber. The Komatsu log loader used for unloading was then also used to process sawlogs and sort nonsawlog (i.e., biomass) trees and residues for chipping.

All materials to be chipped were grappled by an adjacent Linkbelt 3400 swing loader and fed into a Morbark disk chipper. Chips were blown into a large pile on the ground, and then loaded by a Cat 962 G front-end loader into

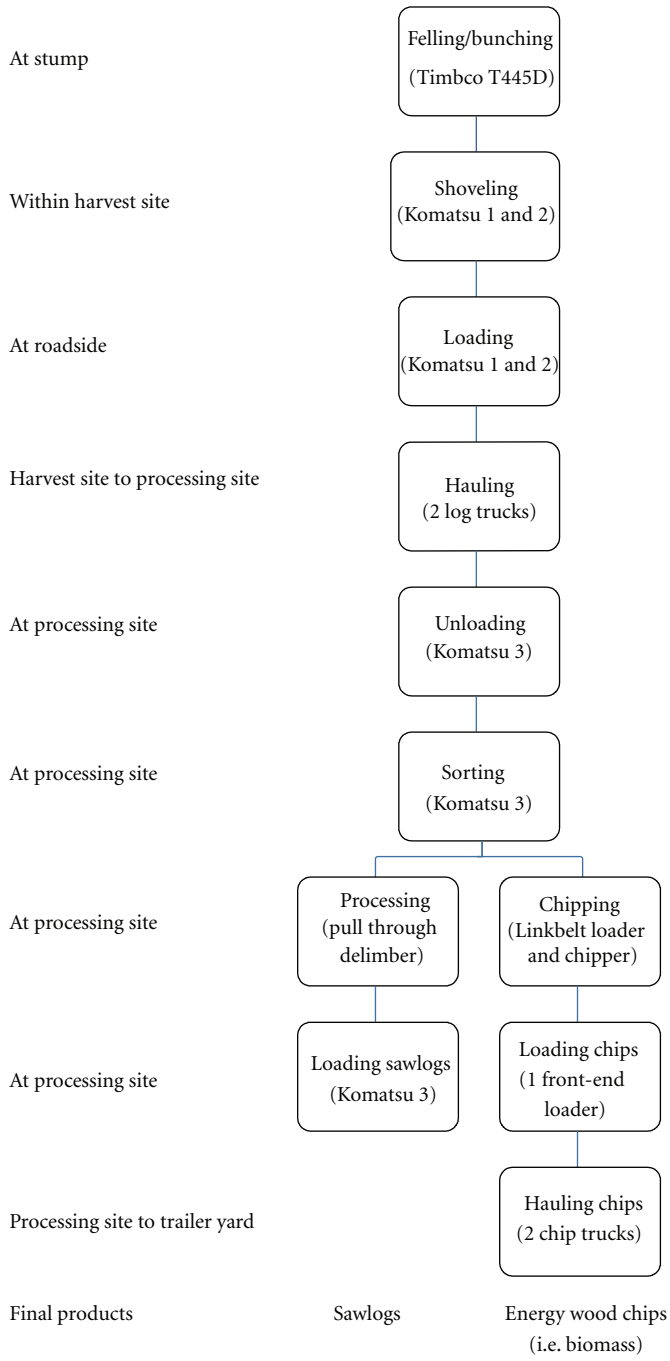

Figure 2: Integrated harvesting and processing system flow chart.

Table 1: Preharvest study unit descriptions.

		Tanoak				Douglas-fir				Pacific madrone				Total		
		Density		DBH		Density		DBH		Density		DBH		Density	DBH	
Harvest site	Area (ha)	(stems/ha)	%	Mean (centimeters)	S.D.[a]	(stems/ha)	%	Mean (centimeters)	S.D.[a]	(stem/ha)	%	Mean (centimeters)	S.D.[a]	(stems/ha)	Mean (centimeters)	S.D.[a]
Unit 1	9.30	84.81	82	25.68	10.97	18.65	18	29.92	11.13	0.35	0	15.24	0.00	103.81	25.50	11.10
Unit 2	6.07	51.08	45	28.47	16.51	54.14	48	27.53	13.46	7.54	7	30.96	23.04	112.76	28.17	15.37
Unit 3	6.88	136.92	74	23.83	7.11	48.79	26	33.05	13.36	0.22	0	78.74	0.00	185.93	27.10	10.13

[a] S.D.: standard deviation.

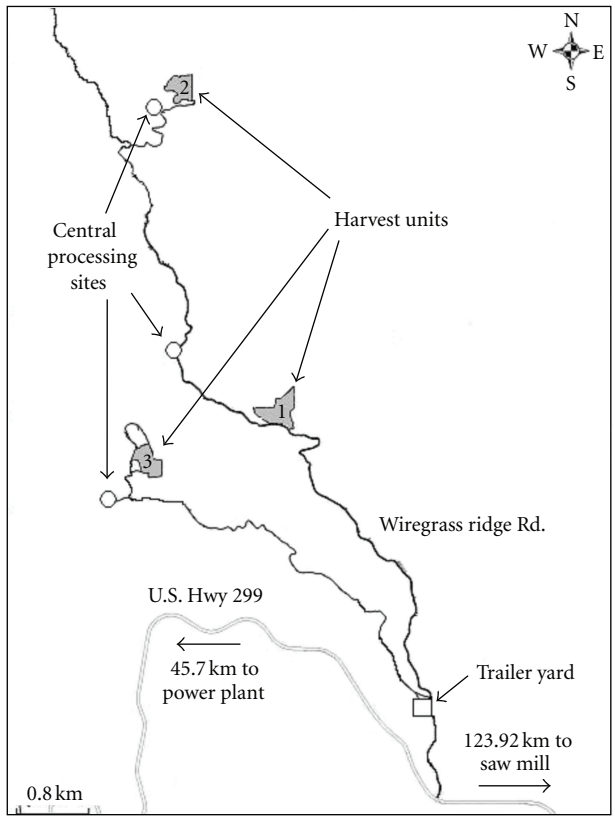

Figure 3: Operation layout map showing three harvest units with corresponding central processing sites. Whole trees and logs were hauled to the central processing sites to process and sort into biomass and sawlogs.

13.72 m long chip trailers. The trailers were transported by two wood chip trucks, and staged approximately 6.5 km away at a trailer yard near the highway where many trailers were stored for further transportation to an energy plant 45.7 km away (Figure 3). Loaded trailers were traded at the yard for empty trailers and returned to the central processing site immediately in order to keep the chipper busy. A trucking company was hired to deliver the trailers from the trailer yard to the power plant, which took nearly two hours for a round trip at 45.7 km one-way distance. The staging of chip trailers at the trailer yard was necessary due to the limited space available at central processing sites. Sawlogs that were sorted and processed by the loader were decked at the centralized processing site, which loaded onto log trucks and delivered directly to the sawmill from the centralized processing sites more than 124 km one-way distance.

2.2. Measurement Protocol. Hourly machine costs in dollars per scheduled machine hour ($/SMH) were calculated using standard machine rate calculation methods [10]. Delays were defined as all activities that do not directly contribute to the production of the operation. Purchase prices, salvage values, and all other necessary information for the standard machine rate calculation were obtained from the contractors who owned the equipment. Diesel fuel prices were determined from local market prices effective during the study period. All machinery was assumed to have a 10-year economic life and work 1800 scheduled machine hours (SMHs)/year, except for the chipper which had a five-year economic life due to its extensive use.

Costs of each stage of operation and the operation as a whole were determined using the joint products allocation method [11]. Under this method, all stages of operations that produced both biomass and sawlogs apportioned their costs based on the contribution of each product to the total production. Costs associated with operational stages that produced a single product in its final form, or that only handled one product type, were charged solely to that product (e.g., chipping, loading sawlogs).

Activity sampling at the central processing site was observed over four of the 26 days of operation, sampling at fixed intervals of time (i.e., every 15 seconds for one hour, three times a day), to determine whether machines were working or not. Activity sampling data were collected over a relatively short period and were used to provide a glance at how well the machines and processes were matched at one particular centralized processing site. Through activity sampling, a better understanding could be gained of appropriate system balance by calculating individual machine utilization rates (ratio of PMH to SMH). Working at the central processing site was the Komatsu loader (Komatsu 3) which unloaded whole trees, sorted and delimbed trees, and loaded log trucks with saw logs. An adjacent Link Belt loader was used to feed biomass trees into the chipper, and the resulting chips were loaded into chip trailers with a front-end bucket loader.

Elemental time-motion data were recorded by a stop watch for each machine's cycle used in the harvesting system [12]. Cycle data were recorded for 10 hours a day, alternating between harvesting activities for a total of 26 working days. Regression equations were developed using Minitab 15 Statistical Software [13], through ordinary least squares estimators. To predict a machine's delay-free cycle time, average observed values for independent variables in the time study were entered into the developed regression equations. The following describe cycle elements for each harvesting activity phase.

(i) *Felling/bunching* started when the machine rotated or traveled empty to a tree followed by the cutting of the tree, then the machine rotated while loaded, and placed the tree in an existing pile or bunch, ending the cycle.

(ii) *Shoveling (*i.e., *swinging logs and whole trees to roadsides)* started when the machine rotated or traveled empty to a pile/bunch of trees, grappled the trees, rotated loaded to a new pile/bunch or road side, and ended when the machine dropped the trees or compacted them into another pile/bunch.

(iii) *Loading (whole trees)* started when the machine rotated or traveled empty to a pile/bunch of trees, grappled the trees, rotated loaded to the log truck, and ended when the trees were compacted onto bunks of the log truck.

(iv) *Hauling (whole trees)* began when the truck traveled loaded along various roads to the central processing location, where it was unloaded, then traveled unloaded back to the harvest unit, and ended when the truck was finished being loaded with trees.

(v) *Unloading at the centralized processing site* started when the loader swung empty to the log truck, grappled the trees, rotated loaded to a pile/bunch of trees, and ended when the machine dropped the trees into a pile/bunch of trees.

(vi) *Sorting/processing* (*sawlogs*) started when the machine rotated empty toward the pile/bunch of trees, grappled the tree, followed by the tree being delimbed and or bucked/topped, rotated loaded to a pile of trees/logs, and ended when the tree/logs were placed on the pile.

(vii) *Chipping* started when the trees/tops were placed on the chipper's in-feed table and ended when the last chips dropped from the chipper's out-feed shoot.

(viii) *Loading (biomass)* started when the loader traveled empty to the pile of chips, followed by the chips being scooped into the loader's bucket, traveled loaded to the chip trailer, and ended when the last chips fell into the trailer from the loader's bucket.

(ix) *Loading (sawlogs)* started when the loader rotated empty to the deck of logs, grappled the logs, rotated back to the truck loaded, and ended when the loader placed the logs onto the truck's log bunks.

(x) *Hauling (biomass chips)* began when the truck traveled on in-woods roads to the trailer yard adjacent to the highway, unloaded the trailer, picked up an empty trailer, traveled back unloaded to the central processing site, and ended when the replacement trailer was filled with chips.

Average piece size for whole trees was calculated from preharvest stand cruise data, and scaled weights of chips (biomass) and sawlogs delivered to markets. The number of stems per hectare for each species at each harvest site was summed and divided by the scaled weights to calculate average tree weight. Samples of chipped material were collected in the morning, afternoon, and evening over four days of operation and dried in a laboratory oven to determine their moisture content, which was used to convert green tons to bone dry tons. The average tree weight was then converted to dry tons using moisture content data collected on site [14]. Moisture content was then used to predict the productivity in bone-dry tons (BDTs) for each process (felling, shoveling, loading, hauling to the central processing site, unloading/sorting, and chipping) of the operation that handled whole trees. The average volume and weight per tree removed was 0.66 m^3 or 0.35 BDT. Chipped biomass weight was tracked by scaling ticket books from the local energy plant for every load. Log truck volume was tracked by ticket books obtained from the sawmill for every load, and both were averaged throughout the study.

Production rates (BDT/PMH) for each process were calculated using the delay-free cycle equations that were developed using detailed time study data. Average delay-free cycle times were estimated by entering average values for independent variables associated with a given cycle element into delay-free cycle equations to determine the PMH per cycle. The average number of trees recorded during the detailed time study was converted to BDT. Then weight per cycle was divided by the delay-free cycle time (PMH) to yield a production rate (BDT/PMH).

3. Results and Discussion

3.1. Productivity of the Integrated Harvesting System. The integrated system was monitored for 260 SMH over 26 working days during the summer of 2008. Throughout the study period, the system delivered 1,316 BDT of Douglas-fir sawlogs and 5,416 BDT of wood chips, which had an average moisture content of 43.2%. The total system production rate was 35.26 BDT/PMH, determined by the individual process with the lowest production rate (i.e., hauling chips).

The hauling of chips from central processing sites to the trailer yard yielded the lowest production of all stages of operations. A hauling cycle for chips took 43.9 minutes per round trip (Table 2). Round-trip times were highly influenced by traveling speeds associated with different road types. The distance in meters of single-lane dirt and spur (temporary road with unimproved surface) roads within the harvest unit were the variables that had the greatest effect on cycle time. The productivity of hauling whole trees from the harvest areas to the centralized chipping location (36.51 BDT/PMH), and for hauling chips from the centralized chipping area to the trailer yard (35.26 BDT/PMH), was the lowest of all phases of operation. Low production rates for hauling were most likely due to the slow traveling speeds observed on narrow forest roads (11 to 32 km/hr), and the long round trip distance of 2.80 km and 13 km for whole trees and chips, respectively.

The highest rates of production were achieved through the unloading of whole trees at the centralized processing sites. An average unloading cycle took only 3.46 minutes per truck (Table 2). The average production rate for unloading trees at the centralized processing site was 171.36 BDT/PMH. The unloading of trees was most influenced by the number of grapples to lift the materials off the truck and the number of degrees that the machine rotated from the truck to the log deck. This rate was substantially different from the loading of trees (73.42 BDT/PMH) because it took less handling to remove a tree from the trucks than to carefully arrange them on the truck.

Activity sampling results indicated room for improvement in operational efficiency by balancing productivity between processes at one of the central processing sites. Again, this was based on only four days of sampling and may not be representative of the entire 26 days of operation. However, the sampled utilization rates are interesting to note as they show the potential changes in cost and production with relation to utilization rates. During activity sampling the chipper had an average utilization rate of 41%, but at times was as high as 100%. This translated to a low utilization

Table 2: Regression equations that describe predicted delay-free cycle times in minutes for the integrated harvesting system.

Process	Regression model for delay-free cycle time	Independent variables		R^2	n	Average delay-free cycle time (minutes)
		Mean	Range			
Felling/bunching	= 4.16			0.66	766	0.52/tree(s)
	+0.09 (no. trees)	1.10	1–3			
	+0.03 (DBH cm)	27	15–66			
	+0.22 (loaded swing degrees)	117	0–270			
	+0.04 (no. grapples)	0.30	0–10			
	+0.02 (travel distance m)	1.54	0–25			
Shoveling	= 3.81			0.69	363	0.62/tree(s)
	+0.18 (%slope)	20.29	5–50.			
	+0.37 (no. grapples)	1.90	1–10			
	+0.28 (loaded swing degrees)	126	0–360			
	+0.11 (no. trees)	2.93	1–10			
	+0.04 (no. compactions)	0.55	0–11			
	+0.02 (travel distance m)	2.27	0–51			
Loading (whole trees)	= 4.60			0.63	440	8.08/truck
	−0.13 (%slope)	10.19	5–35			
	+0.41 (no. grapples)	1.90	1–11			
	+0.32 (loaded swing degrees)	101	0–270			
	+0.05 (no. compactions)	0.98	0–7			
	+0.01 (travel dist m)	0.10	0–10			
Hauling (whole trees)	= 2592.8			0.18	70	32.50/trip
	+0.12 (loaded spur distance m)	488.89	27–982			
	−0.01 (loaded single land dirt road distance m)	13.41	0–117			
Unloading	= 4.00			0.65	258	3.46/truck
	+0.48 (no. grapples)	1.29	1–5			
	+0.28 (loaded swing degrees)	125	90–180			
	+0.10 (no. pieces)	3.42	1–12			
	+0.04 (no. compactions)	0.15	0–3			
	+0.01(travel distance m)	0.14	0–15			
Sorting/processing (sawlogs)	= 4.02			0.65	311	0.66/tree(s)
	+0.53 (no. grapples)	2.10	1–10			
	+0.20 (loaded swing degrees)	125	90–360			
	+0.14 (no. pieces)	2.26	1–15			
	+0.02 (no. compactions)	0.39	0–5			
	+0.01 (travel distance m)	0.55	0–15			
Chipping	= 2.32			0.22	117	0.44/tree(s)
	−0.42 (no. trees)	1.79	1–6			
	+1.83 (DBH cm)	28	15–76			
Loading (biomass)	= 1.83			0.47	375	5.84/truck
	+0.04 (no. scoops)	0.99	0–3			
	+ 0.20 (travel loaded distance m)	23	0–80			
Loading (sawlogs)	= 3.82			0.49	107	9.22/truck
	−1.06 (loaded swing degrees)	108	90–180			
	+1.12 (empty swing degrees)	110	90–180			
	+0.28 (no. grapples)	1.64	1–5			
	+0.03 (no. compactions)	0.76	0–6			

Table 2: Continued.

Process	Regression model for delay-free cycle time	Independent variables		R^2	n	Average delay-free cycle time (minutes)
		Mean	Range			
Hauling (biomass)	= 615.35			0.79	46	43.87/trip
	+0.05 (loaded primary dirt road distance m)	5,260	0–6,807			
	+0.06 (loaded secondary dirt road distance m)	1,129	0–5,071			

n: number of observed cycles.

rate of 49% for the loader (Linkbelt) which fed the chipper and 43% for the front-end loader which loaded the chips into trailers, because these machines were dependent upon one another. The Komatsu loader (Komatsu 3) had the greatest utilization rate (74%) at the processing site, because the machine had three tasks of unloading, sorting/processing, and loading sawlogs. Log trucks hauling whole trees were utilized to nearly their full potential (96%) which indicated the need for an additional log truck to keep the processing site busy. However, introducing another log truck into the system would require additional feller-bunchers and loaders at the harvest unit to keep up with trucking over the short round trip hauling distance of 2.80 km. Hauling of biomass chips had a relatively low utilization rate (69%) which was primarily a result of low productivity (BDT/PMH) of chipping. If chipping production was to increase, additional trucks would be needed for the long round-trip cycle (43.87 minutes) (Table 2) from the processing site to the trailer yard adjacent to the highway.

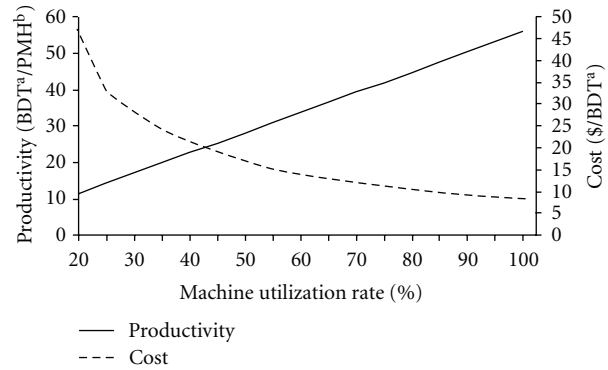

Figure 4: Cost and productivity of whole tree chipping with various utilization rates for associated machinery. ([a]BDT: bone dry metric tons; [b]PMH: productive machine hour; SMH: scheduled machine hour; Utilization = (PMH/SMH)∗100).

3.2. Costs for Harvesting Both Sawlogs and Biomass . Machine rates, production rates, and production costs for each stage of operation, and the operation as a whole, are summarized in Table 3. The total hourly system cost of running all the machines used in the integrated harvesting operation was $1,936.76/PMH, which included ownership, operating, and labor costs. When applying production rates for each harvesting process, the most expensive system process was found to be chipping ($9.94/BDT). This was due to the low production rate (47.18 BDT/PMH) in relation to the high machine rate ($468.78/PMH) for two machines: the chipper and the loader that feeds it. Using the joint products allocation method, the total unit production costs from the integrated system were $29.87/BDT for biomass and $4.26/BDT for sawlogs. These total system costs do not include the costs associated with supporting machinery (fuel, water, maintenance, and personnel trucks), profit margin, move-in, or transportation of products in their final form to markets.

Machines used throughout system processes were all assumed to have a utilization rate of 85% as suggested by Miyata (1980) [10]. Activity sampling at one central processing site was used to demonstrate how these utilization rates can change by site or when system balance is not ideal. For example, the observed utilization rate for chipping, as indicated through the four days of activity sampling, was 41%. The low observed utilization rate would translate to reduced production and higher costs than those calculated in Table 3. Figure 4 shows the possible production rates and costs of chipping if the machines involved were operating at utilization rates of less than 85%. The linear relationship between production and utilization rate should be noted. Increasing the utilization rate by only 10% can raise chipping production by 5.55 BDT/SMH. The relationship between cost and utilization rate, on the other hand, is quite different; chipping costs were as low as $9.94/BDT when utilization was 85% and as high as $20.60/BDT when utilization rates fell to 41%. In this sensitivity analysis, more than $1/BDT for every 5% increase in chipping utilization rate could be saved, until the rate reaches 70%. Thereafter, the savings would be less than $1/BDT. Having a high utilization rate is important since chipping is one of the most expensive stages of operation, and because production in any following stages of operation is often influenced by chipping. Having a high utilization rate will also increase productivity and reduce costs, saving money for the other stages of operation like collection and transportation. It is ideal to maximize utilization rates of all machines and processes involved in integrated systems. Potential savings could be as high as $32.05/BDT for biomass and $4.58/BDT for sawlogs, if all machines in the system operated at a balanced utilization rate of 85% compared to 41% observed during activity sampling (Figure 5).

Table 3: Harvesting system productivity and costs in the integrated harvesting system.

Process	Cycle time (minutes)	Production rate (BDT[a]/PMH[b])	Machine rate ($/PMH[b])[c]	Joint products cost ($/BDT[a])	
				(sawlogs)	(biomass)
Felling/bunching	0.52	44.69	188.24	0.84	3.37
Shoveling	0.62	99.13	176.47	0.36	1.42
Loading	8.08	73.42	176.47	0.48	1.92
Hauling	32.50	36.51	211.76	1.16	4.64
Unloading	3.46	171.36	130.62	0.15	0.61
Sorting	0.66	71.29	138.36	0.39	1.55
Chipping	0.44	47.18	468.78	0.00	9.94
Loading (biomass)	5.84	132.36	121.48	0.00	0.92
Loading (sawlogs)	9.22	147.67	130.62	0.88	0.00
Hauling (biomass)	43.87	35.26	193.96	0.00	5.50
		Total	1936.76	4.26	29.87

[a]BDT: bone dry metric ton.
[b]PMH: productive machine hours.
[c]$/PMH: machine rates were calculated using the assumptions of 33% fringe benefits, 10% interest, and 2% insurance.

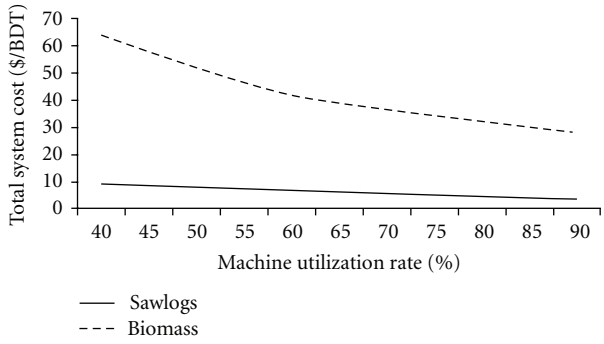

Figure 5: Total system cost for producing biomass in an integrated harvesting system based on varying machine utilization rates.

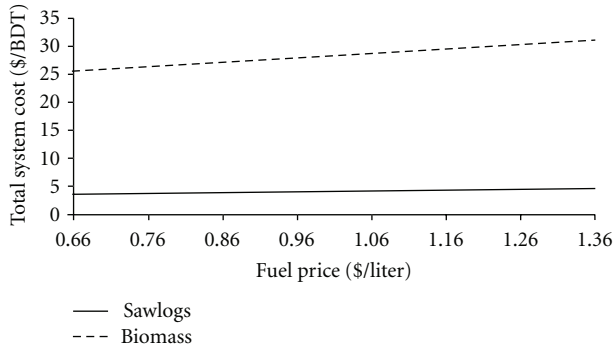

Figure 6: Total system production cost associated with various diesel fuel prices.

Transportation of whole trees on log trucks yielded one of the lowest productivities of all stages of operation that handled both products 36.51 BDT/PMH and was the most expensive stage of operation for the production of sawlogs ($1.16/BDT) (Table 3). This was due to low traveling speeds on forest roads (<12 km/hr) caused by poor road conditions, including rough road surface with no gravel, single lane road width, steep road grades, and sharp curves. In this study, the average round trip distance was only 2.80 km but took 32.5 minutes without delays.

There was a noticeable relationship between whole tree hauling costs and whole tree one-way hauling distances with relation to road type. Every 50 meter increase of spur road was proportional to a $0.08/BDT and $0.02/BDT increase in the cost of hauling for biomass and sawlogs, respectively. It should be noted how the increased use of mainline (two-lane gravel road) or one-and-a-half lane width improved dirt roads in proportion to spur roads can reduce total hauling costs. This relationship between reduction of cost with increased mainline road distance was due to the higher traveling speeds (26 km/hr) observed along higher quality road types.

Diesel fuel prices reached a peak at $1.21/liter in the region during the course of operations in the summer of 2008 and then steadily declined to $0.66/liter six months after commencement of operations. Fuel costs had a greater influence on cost per unit of product in an integrated harvesting operation, due to the high fuel consumption rate of machinery. The integrated harvesting operation in this study consisted of 11 machines, including the chipper which had the greatest fuel consumption rate of 113 liters per hour. Holding all other variables constant, every $0.10/liter increase in fuel price is equivalent to an increase of $0.78/BDT and $0.08/BDT in total system production cost for biomass and sawlogs, respectively (Figure 6).

4. Conclusion

During 26 days of operations, the integrated harvesting system produced and delivered 1,316 BDT of sawlogs and 5,416 BDT of chips, with an average wet-based moisture

content of 43.2%. The total cost for the integrated system was $1,936.76/PMH and produced Douglas-fir sawlogs at a cost of $4.26/BDT, while chipping nonmerchantable size material and species into energy wood chips at a cost of $29.87/BDT. Hauling chips to the trailer yard adjacent to the highway was the least productive stage of the entire operation at 35.26 BDT/PMH. The highest rates of production were achieved through the unloading of whole trees at the centralized processing sites. Round trip transportation distances averaged 2.80 km for hauling whole trees from the harvest units to the centralized processing sites, and 13.0 km for hauling biomass chips from the centralized processing sites to the trailer yard adjacent to the highway. Loaded trailers were traded at the trailer yard for empty trailers, which were then transported to a local energy plant approximately 45.7 km away by a contracted trucking service.

The results of activity sampling indicated some room for improvement in balancing productivity between components in the integrated harvesting system. There were four machines working simultaneously at the processing, but not all machines were working at the same production rate. The most expensive process of chipping ($468.78/PMH) was found to have a utilization rate of only 41% during activity sampling. Ideally, machines should be paired to adjacent operational phases and machinery with similar production rates in an attempt to maximize their individual utilization rates. This can increase potential productivity and decrease production costs.

Sensitivity analysis evaluated how machine utilization rates, road hauling distances, and diesel fuel costs can affect system costs. Raising the utilization rate of the chipper by only 10% is equivalent to a 5.55 BDT/PMH increase in production. Every 5% increase in utilization results in a cost savings of $1/BDT, until 70% utilization, where it decreases thereafter. Transportation costs were found to be the most expensive stage of operation, which is correlated with hauling distance and road quality. Ideally, the use of single-lane dirt spur roads should be minimized due to their slow associated travel speeds, with every 50 meters producing a $0.08/BDT and $0.02/BDT increase in hauling cost for biomass and sawlogs, respectively. Diesel fuel prices are often overlooked in harvesting operations but can have a substantial effect on total system production cost. This is especially true when using a chipper, which consumes more than 113 liters/hr. Each 10 cent increase in diesel fuel price per liter represents a $0.78/BDT or $0.08/BDT increase in total system production cost for sawlogs and biomass, respectively.

Careful planning of integrated harvesting systems, such as this one, should take into account conditions between harvest units and processing sites, and appropriate pairings and number of machines, in order to maximize production. System balance is essential in order to match production levels of different system processes, thereby minimizing congestion and improving efficiency. These concepts are typical of most operations but become especially important during integrated harvests, due the large amount of personnel and machinery in use, the dependency of operational phases, and the complexity of producing more than one product.

The integrated harvesting of biomass and sawlogs in stand conversion operations was cost-effective. Previously understocked conifer stands with large nonmerchantable hardwood components were removed and planted back to productive conifer stands. Forest residues were successfully removed without prescribed burning. Additionally, costs associated with the biomass harvesting operation were minimized by best utilizing machinery on site to produce both biomass and sawlog products. Finally, the most exciting outcome of the stand conversion operation and integrated harvesting system was the clean renewable energy produced. The nearby biomass power plant converted the wood chips into electricity, which supplied homes and businesses across the region.

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