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Potential production of bio-ethanol from woody biomass feedstocks

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Abstract

Forests are important dendro-energy sources of raw materials in the form of woody biomass feedstock (branches, tree tips, dead trees, saw-milling residues, and other industrial residues). The aim of this research was to exemplify the ligno-cellulosic quantification and its potential transformation into bio-ethanol with the goal of providing management alternatives for forest residues derived from forest management practices and the industrial transformation of timber. The example was conducted for the State of Durango, Mexico. For the period of 2001-2011, data analysis revealed industrial timber harvesting has a mean (± confidence interval) of 1.4 M m^3 (± 0.2 M m^3). Of this volume, tree tips, branches, industrial residues, and on site dead trees recorded an average of 0.286 (± 0.052) M m^3, 0.815 (± 0.051) M m^3, 0.285 (± 0.023) M m^3 and 0.132 (± 0.031) M m^3, respectively. These biomass feedstocks have the potential to yield a mean annual volume of 223 M L (± 18 M L) of bio-ethanol and a simple economic analysis showed its value outcompetes either the price of selling the timber as raw material or vending the industrial woody biomass residues for making particle boards. At the present, on-site dead trees represent a major untapped source of woody biomass feedstock for bio-ethanol production as well as for any other dendro-energy source in temperate forests elsewhere.

Keywords: Woody biomass feedstocks, timber harvesting residues; saw dust; taper functions; biomass equations.

INTRODUCTION

High world energy consumption, unstable and erratic fossil fuel reserves, and potential global climate change are contemporary issues leading the development of energy production alternatives (Coyle, 2007). The most common sustainable renewable fuel used today is bio-ethanol. Bio-ethanol can be produced from different kinds of raw biomass feedstocks, classified into three major kinds of agricultural products: simple sugars, starch and lignocelluloses. Of these, grain (starch) is the most common raw biomass source used to produce bio-ethanol. However, starch will not be sufficient to meet renewable energy demands in the near future. Consequently, large-scale production of ethanol will most certainly have to be based from lingo-cellulosic feedstocks.

Forest woody biomass is a renewable lingo-cellulosic raw material that is: (i) more evenly distributed in geographical grids than fossil fuel, (ii) minimize the potential conflict between land use for food and energy production than sugar or grain based products, (iii) generate low net greenhouse gas emissions, and (iv) might become a potential source of employment in rural areas (Coyle, 2007). Considerable amounts of fresh raw forest biomass residues are left on-site in the forest floor after logging operations as well as on-site in the industry after saw-milling logs. Fortunately, most of the forest residues can be collected at any time during the year (Pérez-Verdín et al., 2012). Field forest residues encompass tree tips, branches and foliage and they represent the main input of fresh litter atop the mineral soil after harvesting industrial logs (Morales-Alanis et al., 2000; Renteria-Animas et al., 2005). Industrial forest residues (sawdust & bark) result from saw-milling industrial logs. Other fresh biomass forest resources available in forests are on-site standing dead trees. In northern temperate forests of Mexico, on average of 100 000 m^3 per year are standing trees killed by senescence, pests and diseases (bark beetle outbreaks), forest fires, or a combination of these factors (SEMARNAT, 2012; Návar, 2015). In addition, severe drought episodes combined with unusual warm spells can kill over 1,000,000 m^3 per year in Durango, Mexico (Návar, 2015). Other forest disturbances such as strong cold winter winds can kill and overthrow trees that could become a major source of forest fuels for wildfires and pest and disease outbreaks (Engelmark and Hytteborn, 1999).

The evaluation of the volume or mass of on-site forest residues is not a simple task (White, 2010; Acuña, 2010). The planar intersection methodology of Brown (1974) has been widely recommended to estimate forest fuels in the US forests (Stephens et al., 2005), and this technique has been also used in northern temperate forests of Mexico as well (Morales-Alanis et al., 2000; Rentería-Animas et al., 2005). The quantification of standing dead trees that have lost an important mass portion is one of the missing components of the Brown's transect approach. Fortunately dead on-site standing trees are usually quantified in most commercial forest inventories.

Taper (stem profile) functions provide an alternate approach to merchantable volume estimation for the different portions of the tree bole (Návar et al., 2013), allowing the quantification of potential timber tips left on-site in the forest floor after logging commercial industrial timber. Then, the determination of the accumulated biomass for each fraction of the tree is important, as the size and quality of the portion will influence its end use and its half-life in the environment. Examples of the use of taper models to evaluate tree tips at the forest scale are missing elsewhere. Branch biomass can be approximated by applying biomass component equations. For northern temperate forests of Mexico, fortunately, Návar (2009) developed biomass equations for aboveground and belowground biomass components. The industrial residues by saw-milling logs are conventionally evaluated by multiplying the timber volume entering the saw mill times a saw-milling coefficient. The saw-milling coefficient is derived from the veneer volume over the log volume that is usually derived for each single saw mill (Zavala and Hernández, 2000).

Bioconversion of lingo-cellulosics to bio-ethanol presents at this time important challenges due to: (1) the resistant nature of lingo-cellulosic biomass to breakdown, (2) the variety of sugars released when the hemicellulose and cellulose polymers are broken, and the need to find or genetically engineer organisms to efficiently ferment these sugars, and (3) costs associated to the supply chain. Processing of lingo-cellulosics for bio-ethanol consists of four major unit operations: (1) pretreatment, (2) hydrolysis, (3) fermentation, and (4) product separation/distillation. Soto-Alvarez et al. (2013) transformed in the laboratory forest residues (timber tips and branches) of northwestern temperate tree species of Mexico and reported the yield efficiency of dry forest biomass.

The abundance of woody raw forest feedstocks and their transformation into bio-ethanol are issues that should be addressed in forest management operations to guide or set appropriate policies for the long-term management of conventional timber harvesting for multiple goods and services. Hence, the aim of this research was to propose techniques for the evaluation of forest residues and their potential transformation into bio-ethanol as an alternative to other conventional uses including waste disposal. The application of this methodology serves as an example for the quantification of woody forest residues and its transformation into bio-ethanol elsewhere.

MATERIALS AND METHODS

Location of the study area. The State of Durango spans the north-central portion of Mexico and covers an area of approximately 12.3 M ha (Figure 1). It is located within 22º35' NL and 104º50' WL; 24º44' NL and 22º58' WL; 26º83' NL and 104º27' WL, and 23º52' NL and 107º21' WL. Four main physiographic regions feature the State; a) the western Plains of the Pacific Ocean, b) the Sierra Madre Occidental mountain range, SMW, c) the central valleys of Durango and Chihuahua, and d) the Chihuahuan Desert.

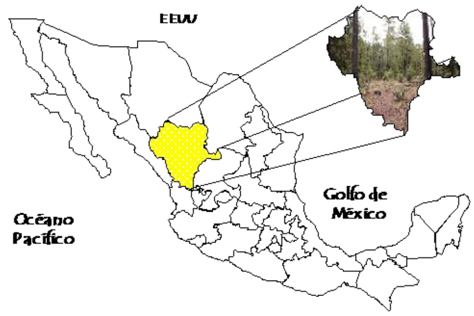

Figure 1. Location of the State of Durango in México.
Source: Author

Northern Pine-oak forests of Mexico. The northern Sierra Madre Occidental mountain range, SMW, of Mexico boasts extensive areas of pine-oak forests that contain more than two thirds of the standing timber volume in Mexico. The SMW mountain range holds a temperate climate, with mild summer temperatures. Typical timber pine and oak species distributed in this mountain range are: *P. cooperi* O., *P. engelmannii*, *P. durangensis*, *P. oocarpa*, *P. herrerae*, *Pinus arizonica*, *Q. gambelii*, *Q. rugosa*, *Q. sideroxyla*.

Methods. The methodology consisted of collecting harvested timber data of the two major forested regions of the State of Durango; El Salto, Pueblo Nuevo and Santiago Papasquiaro. The former region is found at the southwestern portion of the SMW, featured by a temperate-cold climate, with mean annual temperature and precipitation of 11.7ºC and 1000 mm, respectively (INEGI, 2002). The region has a long forestry tradition dating back to late 1900's. The region of Santiago Papasquiaro is found in the northwestern tip of the State of Durango. Climate is temperate-cold, with mean annual temperature and precipitation of 12°C and 900 mm, respectively (INEGI, 2002). The region was primarily managed for mining since the early 1600's and forestry activities started during the early 1900's with the opening of the railroad system.

Evaluation of Forest Residues. Forest residues were classified as timber tips and branches left on-site after logging trees and harvesting main logs; and saw dust and timber bark that result from the log-transformation into veneer at the sawmills.

Timber tips. Timber tips are the distal portions of logs that do not meet the size for its transformation into veneer. They are sometimes collected for the transformation of secondary forest products. Mathematical functions used to predict the stem profile were previously developed by Newnham (1990; 1992) and tested for northern temperate tree species of Mexico (Návar et al., 2013). The equation of Newnham (1990) is depicted by eq. [1] with reported parameters for local pines and oaks (Table 1) by Návar et al. (2013) predicted total, merchantable, and tip volume.

$$\left[\frac{d}{D}\right] = b_1 \cdot \left(\frac{H-hi}{H-1.3}\right)^{b_2} \qquad [1]$$

Where: H = top height (m); hi = relative height (m); D = diameter at breast height (cm); d = relative diameter (cm)

Table 1. Coefficients of the Newnham (1990) taper model and their standard errors for tree species of northern Mexico.

		Parameters	
Species	Statistic	b_1	b_2
Quercus spp	Mean	0.010400	0.916300
	SE	0.000036	0.011100
Pinus spp	Mean	0.010300	0.595400
	SE	0.000017	0.003200

Source: Návar et al., (2013).

The difference between total, Vt, and merchantable timber volume, Vc, evaluated the timber tip volume, Vtt, as explained mathematically by eq. [2], as follows:

$$Vtt = Vt - Vc \therefore Vt = 0.7854 di^2 H$$

$$Vtt = 0.7854 \cdot \left[\int_{hi=0}^{hi=H} D \cdot b_1 \cdot \left(\frac{H-hi}{H-1.3}\right)^{b_2} \partial hi\right]^2 - 0.7854 \cdot \left[\int_{hi=0}^{hi \therefore di=20cm} D \cdot b_1 \cdot \left(\frac{H-hi}{H-1.3}\right)^{b_2} \partial hi\right]^2 \qquad [2]$$

Equation [2] cannot be analytically integrated, hence numerical analysis was conducted using $\Delta hi=1$ cm. Merchantable timber was evaluated from the base to the length of stem where diameter is > 20 cm. Logs with $D \leq 20$ cm are classified as tips. Tip biomass was estimated by multiplying the tip volume times its wood specific gravity.

Branch biomass. Branch biomass of harvested timber was evaluated using the allometric equations reported by Návar (2009) for northwestern temperate pine, Bbp, and oak, Bbq, tree species of Mexico. These equations are:

$$Bbp = 0.0565 D^{2.2729}$$
$$Bbq = 0.0202 D^{2.6480} \qquad [3]$$

Where: dry biomass is in kg; D = diameter at breast height (cm).

Dead on-site trees. The SEMARNAT (2012) reports the total annual volume of harvested dead trees. However, the total volume of dead on-site trees is approximated with the forest inventory and this volume can be sometimes twice as large as the total official harvested timber volume for the State of Durango, Mexico. For example, Návar (2015) reported two important episodes (1998-2001 and 2012-2012) that killed on-site large volumes of trees by a combination of drought-related disturbances such as heat waves, frosts, wildfires and bark beetle outbreaks. Official reports recorded an area of nearly 200,000 ha affected by these disturbances in each of these two dry spells that may have accounted for a standing volume of approximately 2 M m^3.

Industrial residues. Saw milling is the main forest industry in Durango, Mexico. The transformation of logs into lumber has end residues (sawdust, capotes & bark). An average saw milling coefficient was employed to evaluate industrial residues. The saw milling coefficient is usually calculated as the ratio of lumber volume over log volume, giving the industrial residues as 100%-the ratio. Several authors have reported saw milling coefficients for several mills (Flores et al., 2007; Zavala and Hernández, 2000) and an average value was multiplied by the total timber harvested for the State.

Bio-ethanol transformation factor. The bio-ethanol productions was calculated using optimal yields of available sugars (Holocelulosics) and a fermentation yield of 100, using Eq. [4].

$$\mathbf{BE\,(L) = ((M(g) * Sh * 0.51)/(789.00\,(g/L)\,)) * .9990} \qquad [4]$$

Where: M = total dry biomass available for bio-ethanol production (g); Sh = total sugar (holocelullosic).

RESULTS

Diameter structures of harvested trees. Diameter structures of harvested trees for the State of Durango, Mexico are depicted in Figure 2.

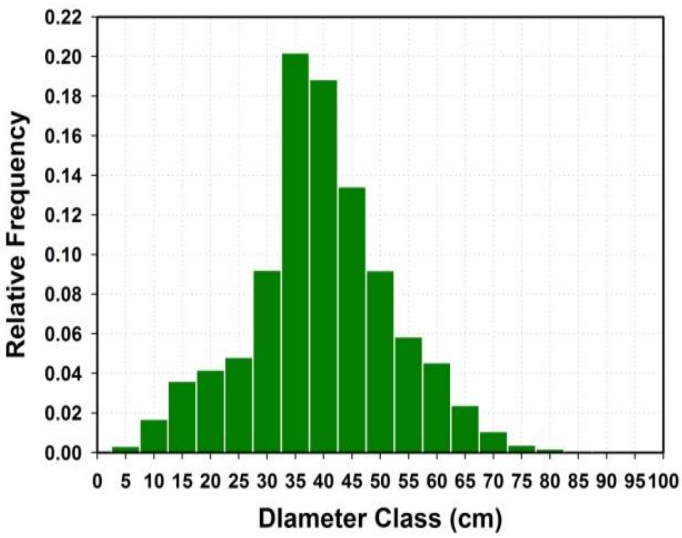

Figure 2. Diameter structures of harvested trees for the State of Durango, Mexico during the period of 2001-2011. **Source:** Authors

Taper functions and evaluated volume of forest residues. A tabular form of the application of the taper function fitted to timber harvested is depicted in Table 1. Using $D \geq 20$ cm, timber can be logged to yield a sleeper with conventional size.

Table 1. Derivation of forest products or the saw mill industry with taper functions with local coefficients.

D (m)	H(m)	V(m^3)	Vt20 (m^3)	M Prop
0.05	6.98	0.01	.	.
0.10	10.21	0.05	.	.
0.15	12.76	0.13	.	.
0.20	14.94	0.26	0.07	0.28
0.25	16.89	0.45	0.30	0.67
0.30	18.67	0.70	0.58	0.83
0.35	20.32	1.01	0.91	0.90
0.40	21.87	1.40	1.31	0.94
0.45	23.33	1.87	1.79	0.96
0.50	24.72	2.41	2.34	0.97
0.55	26.05	3.04	2.98	0.98
0.60	27.32	3.75	3.70	0.98
0.65	28.55	4.56	4.51	0.99
0.70	29.74	5.46	5.41	0.99
0.75	30.89	6.45	6.41	0.99
0.80	32.00	7.55	7.51	0.99
0.85	33.08	8.75	8.71	1.00
0.90	34.14	10.05	10.01	1.00
0.95	35.17	11.46	11.42	1.00
1.00	36.17	12.98	12.94	1.00

D= Diameter (cm); H= Height (m); V=Timber volume (m^3); Vt20= Timber volume available for sawmilling (m^3); Mprop = Merchantable timber (%). **Source:** Authors

Forest residues. For the study period (2001-2011), for both regions the preferred harvested tree genera is *Pinus* from which most residues are obtained. Figure 3 depicts El Salto provides with the largest (≈ 3.1 M Mg) and Santiago Papasquiaro produced the smallest mass of branches and tips (≈1.6 M Mg) (Fig. 3).

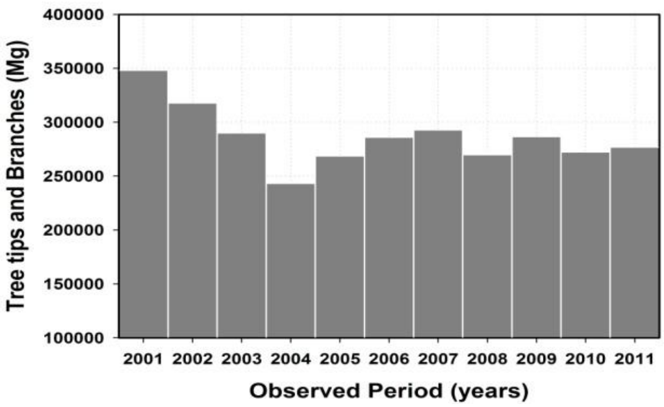

Figure 3. Annual forest residue biomass composed of branches and tips generated by logging in Durango, Mexico. **Source:** Authors

Dead standing on-site trees. The annual volume of standing on-site dead trees for the study period shows a mean concentration of 460,214 Mg and 122,590 Mg (Fig. 4) for the regions of Santiago Papasquiaro and of El Salto, respectively.

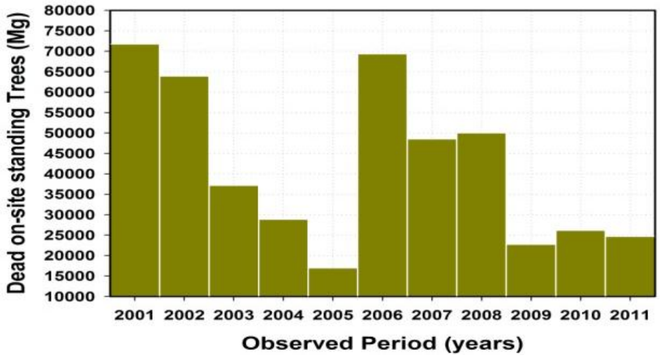

Figure 4. Tonnage of standing on-site dead trees in Durango, Mexico. **Source:** Authors

Drought spells (1997-1998; 2010-2012) combined with unusual hot heaves, as well as unusual frosts (1997; 2011) weakened forests dampening large masses of fresh dry-foliage fueling intense wildfires (1998; 2011) in the region. Official harvesting permits of dead standing trees set on-record statistics, with a volume of approximately 700,00 m^3, in an area of 78,830 ha (SEMARNAT, 2012).

Industrial residues. industrial residues recorded an annual average of 1,253,910 Mg. These residues were produced by 1,190 saw mills distributed across the State of Durango.

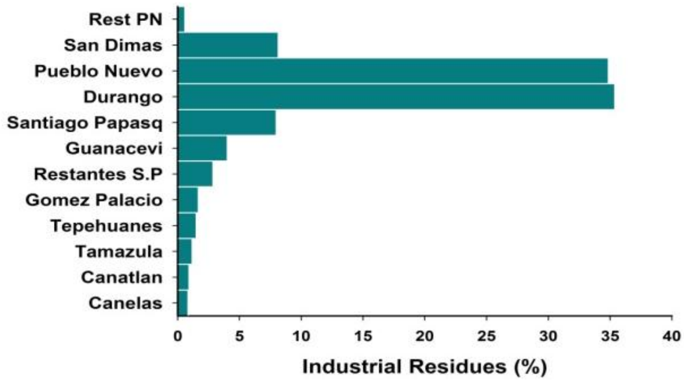

Figure 6. Forest residues resulting from log transformation in saw mills distributed across the State of Durango, Mexico, for the period of 2001-2011. **Source:** Authors

The sum of these residues yield a total tonnage of 6,684,256 Mg. Branches and tips accounted for by 75.52%; industrial residues accounted for by 18.75% and standing on-site dead trees accounted for by 8.71 %.

The polymere concentration in biomass was considered in the production of bio-ethanol. Soto-Alvarez (2013) reported the holocelulose concentration in soft and hard woods has an average of 64% and 62%, respectively. Using this data, in addition to equation [4], the State of Durango could have produced a total annual average of 2,450 M L (Millions of liters), during the study period (Figure 7).

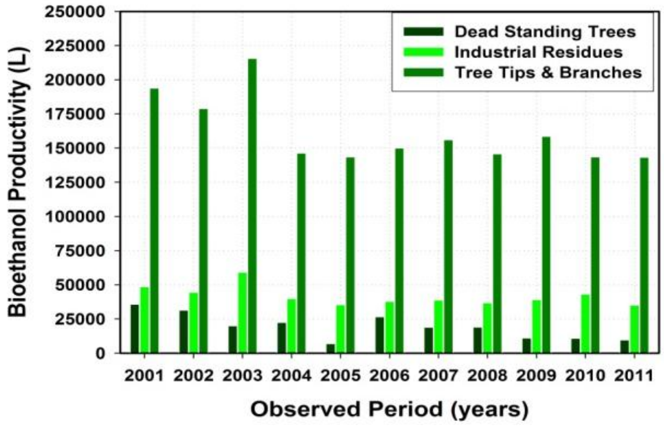

Figure 7. Bio-ethanol production for the period of 2001-2011 in the State of Durango, Mexico. **Source:** Authors

Evaluating potential productivity of bio-ethanol. Table 2 depicts a summary of evaluated total and annual woody biomass feedstocks as well as the potential productivity of bio-ethanol.

Table 2. Evaluating forest residues and potential production of bio-ethanol in the State of Durango, Mexico.

Residues	2001-2011					
	Biomass (Million Mg)			Bio-ethanol (Millons liters)		
	Total	Mean	C.I (±)	Total	Media	C.I (±)
Harvested Biomass	6,2	0,561	82			
For Residues	4,8	0,440	32	1,78	162	12
Ind Residues	1,3	0,113	9	0,46	42	3
Stand trees	0.6	0,052	12	0,21	19	5
T/M Res	6,4	0,607	49	2,45	223	18

Source: Authors

DISCUSSION

Evaluated volume and woody biomass of forest residues as well as its transformation into bio-ethanol provide compelling evidence the State of Durango could become a potential producer of bio-ethanol, without having any major impacts on the saw milling industry. However, future scenarios must help to set the appropriate policies that eventually lead to major changes in forest management to comply with the production of alternate renewable energy projects.

Woody biomass feedstocks. Forest residues left on site could provide an average (confidence interval) of 440,686 (± 32,808) Mg. However, this woody biomass feedstock presents at this time several challenges to make it available for bio-ethanol production or for any other form of renewable energy. Dead on-site trees could become an important raw source of woody biomass feedstocks for its transformation into bio-ethanol due to the large number of killed trees by a series of forest perturbations, which could worsen in the near future. Climate variability and/or change appear to control the core of these perturbations and play key roles in weakening trees. However, tree dieback by unusual warm spots associated with drought spells are difficult to predict as they are at this time considered stochastic processes in nature. The raw data made of a matrix of dead on-site trees over time usually includes only a couple of time periods making this short data source difficult to model over time. The large number of dead on-site trees over the last two major drought episodes is not accounted for in the historic annual average (52,982 ± 12,600 Mg per year). Associated perturbations such as bark beetle population eruptions and intense wildfires also yield important woody biomass residues. A very preliminarily information for the state of Durango showed tree dieback reached nearly 2 M m^3 during the last two major dry episodes. This biomass represents an untapped source of woody biomass feedstock for bio-ethanol transformation.

Technical and economical challenges. The technical limitations that present the woody biomass supply chain made of harvesting, collection, pre-processing, storage and transportation costs in contrast to the conventional costs industrial residues represent for the the saw mil had been worked out in recent investigations (Smith et al., 2003). A very preliminarily economic analysis points the end value of produced bio-ethanol outcompetes either the price of vending the industrial timber or the price of selling woody biomass feedstocks as a raw material for producing particle boards. However, the woody biomass supply chain was unaccounted for in this analysis.

In the woody biomass supply chain, harvesting and transportation stage can generally contribute 60% ~ 80% to the final delivered cost (Saunders et al., 2012). To better determine the economic viability of bio-ethanol production, cost analysis models such as BioSum 3.0, Auburn Harvest Analyzer (AHA) and FRCS-North are recommended prior to embarking on these kinds of projects. Once costs are quantified, models can be used to set several scenarios. In this way, linear programming models and GIS-based forest biomass data had been used to minimize transportation costs in Canada and in European Countries (Ranta, 2005; Panichelli and Gnansounou, 2008).

Woody biomass feedstock quality can deteriorate during storage, as inappropriate storage methods will result in dry matter loss, high moisture level and low recoverable bio-ethanol volume. These issues can significantly reduce the value of the woody biomass, and decrease the transportation and energy conversion efficiency (Rentizelas *et al.,* 2009; Casal et al., 2010). To ensure the quality control, many studies have been conducted to monitor and to illustrate the most influential factors during woody biomass storage (Ramstedt, 2008; Afzal et al., 2010; Lin and Pan, 2015).

Improved forest biomass production systems can be developed using the models described above, as well. For example, a forest biomass production system was developed using linear programming to achieve a minimal total cost of biomass pre-processing, storage, and transportation (Lin et al., 2015). The system showed to effectively lower the supply chain logistics costs, improve the feedstock quality and concurrently meet the end-user's energy demand. Using woody biomass with higher fuel quality can improve the energy conversion efficiency and reduce the use of green biomass. These authors accounted the green biomass reduction achieved in the improved biomass supply chain model. In addition, the improved system increased profit by selling higher quality biomass, which partially offset the increased transportation costs, increasing the feedstock supply radius for the end-user.

Grinding woody residues to optimal size reduce costs, facilitate and reduce the transportation, among others. Ramstedt (2008) recommended storing forest residues near forest roads for as long as the material reaches minimum moisture content to facilitate conversion and to reduce transportation costs. Forest residues are then incorporated to an in-situ extraction-grinding procedure using specialized machinery (e.g., Cane Harvester de Ausoft y Class Jaguar 980) storing in containers to facilitate handling. Grinded particle size plays key roles in defining transportation and transformation costs (Rentizelas *et al.,* 2009), and this variable must be investigated more precisely. Ileleji et al. (2010) using models, recommended the transportation distance of the ligno-cellulosic particles can be transported in trucks when the distance is <100 km and in trains when the distance to the transformation centers is > 100 km.

Forest management operations. To minimize costs of the woody biomass supply chain model, silvicultural prescriptions must aim to program the harvesting schedules in blocks of forests to facilitate harvesting, collection, pre-processing, storage and transportation. This implies the modification of the silvicultural selection system conventionally used in the region. Siniestered trees must also be harvested in forest blocks whenever is possible. When dead on-site trees are isolated they must be left on-site to meet several ecological requirements.

Environmental concerns. Harvesting forest woody biomass residues and dead-on site trees may affect in the long run the cycle of forest nutrients. This concerns ecologists and debate at this time centers on the residues left on site. Litterfall and forest residues make up the major input of nutrients to the forest soil. The concern rises because timber harvesting operations leaves on site an approximate 50% of the total harvested biomass. Should these woody biomass feedstocks be harvested for bio-ethanol production, only 5% of the timber harvested would be left on site in the form of foliage biomass. Then, it is highly likely forest productivity would decline in the short run. An appropriate fertilizing program schedule would eventually improve forest productivity. This is a matter of further research.

CONCLUSIONS

The evaluation of woody biomass feedstocks and its potential transformation into bio-ethanol provides compelling evidence The Sate of Durango, Mexico could become an important producer of bio-ethanol if the legal, technical and economic challenges are met. Durango has a mean annual potential woody biomass feedstock and bio-ethanol production of 607,660 (± 49,563 Mg) of lignocelulosic derived from residual biomass sources; and 223 (± 18) M Liters, respectively. Although delivered costs and quality of the biomass supply chain may deter the current progression of this kind of dendro-energy programs, new forest management operations associated with better collection, transportation and transformation practices would help foresters to tap on this potential new clean and sustainable form of renewable energy and a new source of income in the near future as conventional energy reserves and production decline.

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