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SHORT COMMUNICATION

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Analysis of forest wood supply chains for round-wood production restricted by technical constraints

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Abstract

Aim of the study: Integrated information tools models are fundamental for analyzing supply chains as regards pattern of consumption and production. These models are very useful for availability estimations of natural resources when social and environmental uncertainties need to be addressed, as it is the case for forest wood supply chains. This work presents an analysis of a forest wood supply chain focusing on forest operations to estimate the availability of round-wood volume restricted by technical constraints using a local case study in Mexico. The theoretical and technical potentials of woody biomass availability were reviewed considering an assessment of forest operations for round-wood production.

Area of the study: municipality of Santa Maria del Rio S.L.P. inside the forested land of San Antonio in Mexico.

Material and methods: Geographical, historical and socioeconomic data and field work were used to develop technical constraints as extraction limits. Felling and extraction operations were analyzed resulting in a production rate of 2.48 m^3 per productive machine hour.

Main results: The theoretically produced standing timber accounted to 21,132 m^3. After simulating technical constraints, the technically feasible supply of round-wood accounted to 2,113 m^3. Furthermore, a biomass flow chart for tracing biomass along the system boundaries was developed.

Research highlights: With the given results, it is possible to give recommendations and conclusions for the improvement of wood supply chains supported by time studies values, technical constraints on terrain slope, harvesting intensity and mechanization level.

Additional keywords: Mexico; modeling; forest operations; sustainable forest management.

Authors´ contributions: UF conceived and designed the experiments, collected field work data, performed the experiments, analyzed the data and wrote the paper.

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Introduction

The creation of forest wood supply chains, which are based on sustainability criteria, opens a range of opportunities to develop bio-economies supported by forest biomass markets. This is certainly the case of Mexico, a country with a challenging scenario regarding round-wood supply with a considerable demand of forest products. According to the National Forestry Council (Comisión Nacional Forestal), Mexico has a vegetation surface of approximate 138 million hectares, which represents 70.4% of the national territory. This includes 41% of xeric shrublands, 24% of temperate forest, 23% of tropical forests and 12% of other forest vegetation (CONAFOR, 2012). In addition to the fact that only 15% of the forested areas are under management, during the last decade, timber production constantly decreased: From 7 million m^3 in 2007 the production declined to 6.7 million m^3 in 2016 (SEMARNAT, 2017). This reduction was mainly due to issues regarding management, sector profitability, harvesting systems and quality of available technical services. If *status quo* is assumed for the short-term, it is expected that the decrease of production will continue during the following years (Flores Hernandez *et al.*, 2018). The reduction of harvested areas could be explained by forest fragmentation and land use change, a continued trend within the forest sector at a national level. Furthermore, an increase in national timber demand affects the commercial and industrial balance. All over the country, only few forest enterprises have developed good practices for efficient forest wood supply chains. The poor technological development on operations, low support for improved transportations systems and restricted infrastructure on forest roads, among others, hinder possibilities of a profitable industry. In addition, most of the forest activities only offer short term employment performed by low qualified personnel. The challenging situation demands analyses of forest woody biomass supply regarding harvesting operations, silvicultural practices, forest logistics and business models. In Mexico there are studies considering the evaluation of wood supply chains based on forest operations at a local level. These studies involved the estimation of productivities according to work cycles and functional elements of felling, clearing, debranching and chopping among others (Flores *et al.*, 2014; Zárate, 2012; Luna & Sánchez, 2008). Unlike these studies, the presented methodology includes an assessment of technical constraints involving terrain conditions, harvesting intensity and mechanization level to calculate a technically available round-wood production. Time studies of harvesting and extraction forest operations were reviewed to give recommendations to upgrade wood supply chains using a modeling approach.

The aim of this study is to identify significant parameters and model scenarios to improve round-wood production given domestic conditions This work considers the low performance along the forest wood supply chain focusing in critical parameters of forest utilization to give recommendations based on a local case study in Mexico.

Materials and Methods

In order to analyze the forest wood supply chain in Mexico, an assessment of the theoretical and technical potential of round-wood supply focusing in three technical constraints was developed. The modeling of the wood supply chain potential was supported by data and information from the local forest management plan, together with data collection from field work. Forest parameters were selected to define technical and operational restrictions which limit biomass availability for round-wood production. They also covered sustainability criteria in terms of environmental impact of forest utilization:

1. Terrain slope: Using GIS spatial analysis supported by digital elevation models (DEM), an analysis of the terrain slope at a local level was carried out. Five slope classes were defined. In addition, terrain slope data was collected in a sample of 35 plots in a forested area of 145 ha. The size of each plot was 1,000 m^2 with a radius of 17.84 m compensated according to the slope class. Standing timber availability was constrained by only considering utilization in forested areas up to 35% slope.

2. Harvesting intensity: It was defined as the percentage of the available harvesting standing timber volume, in order to have a sustainable productivity without degrading the forested area (SEMARNAT, 2008). This was calculated based on Eq. 1:

$$HI = \left[1 - \frac{1}{(1 \times p)^{cc}}\right] \times 100 \quad (1)$$

Where *HI* is the harvesting intensity (%), *p* is the percentage of current increase (%) and *cc* is the cutting cycle (years). Based on data from the local forest management plan, *p* has a value of 1.0307, while the value for *cc* was 14.25 years.

3. Mechanization level: The extraction limits based on the level of mechanization were developed through an analysis of current forest operations techniques on felling and extraction, using productivity as the analyzed parameter. Productivity was analyzed to estimate a reference point for the effects of the mechanization level on the supply of round-wood. Moreover, equipment, slope percentage at felling site and diameter at breast height (DBH) of the stand to be felled were considered as input for the simulation. The cycle include felling, delimbing and extracting. A time study to account for amount of cubic meters per productive machine hour (PMH) was conducted.

The analysis of the wood supply chain considered activities from felling at stand to the releasing of round-wood volume at landing. The local case study corresponded to a natural pine-oak forested land, where the forest wood supply chain has not been fully analyzed. Obsolete and poor equipment, low know-how regarding harvesting techniques and deficient forest roads were the weakest points along the supply chain. The study was conducted in “San Antonio” a forested area located in the municipality of Santa María del Río in the state of San Luis Potosí, Mexico. The analyzed species were *Pinus michoacana, Pinus teocote* and *Quercus spp*. in a private forest with an area of 145 hectares. Time studies involved 30 cycles for felling and 31 cycles for extraction. The observed terrain slope from sampled trees varied from 12% to 31% with an average slope percentage of 28%. Regarding workforce, the felling operation had a crew of two operators, a feller and an assistant while the extraction was conducted by a tractor operator and an assistant for the choking. Time studies were based on an element level approach, where the measurements consisted of dividing the work cycle into steps and then collecting time consumption separately for each element (Ackerman *et al.*, 2014). Since the model outputs were based on yearly production, a production schedule of 7 months with 5 days per week and 8 hours per day was assumed. In order to estimate productivities (m^3/h) delays were not included in the calculations. Furthermore, each log was measured in three diameters (cm) (at base, half and full lengths) and height. Volumes were calculated and related with times to estimate production rates based in cubic meter per productive machine hour (m^3/PMH). Using this output, the resulting productivity was set as base line productivity (BL). Then, the required productivity to harvest the technically standing timber volume constrained by terrain slope and harvesting intensity per year was compared with the BL productivity that accounted for extraction limits. The comparison between this required productivity and the given productivity (BL) resulted in the extraction limits per species. Values were calculated for each species to set extraction limits according to the mechanization level. These extraction limits assumed that *Pinus michoacana* and *Pinus teocote* had a priority in the harvesting planning. Furthermore, in order to trace biomass production as round-wood volume from the analyzed species, a biomass flow chart was developed (Rosillo-Calle & Woods, 2012). For the local case study, residues left on site due to harvesting activities were also accounted for. Thus, coefficients of harvesting residues of 0.18 for pine and 0.35 for oak were used (INIFAP, 2012). Basic densities of 0.487 t/m^3 and 0.740 t/m^3 for pine and oak were used to account for biomass production values in ton (World Agroforestry Centre, 2018). After applying the technical constraints and modeling felling and extraction productivities of the analyzed supply chain, outputs in terms of theoretically available standing timber volume and technically available round-wood volume were estimated.

Results and discussion

A total of 5,794 m^3, 523 m^3 and 14,815 m^3 for *Pinus michoacana, Pinus teocote* and *Quercus spp.* respectively were calculated as theoretically available standing timber volume. Then, based on terrain slope analysis supported by field data collection and geographical information systems (GIS) analyses, slope constraints were applied to the theoretical availability of standing timber volume. When only areas with a slope up to 35% are considered, the technical availability of standing timber volume amounted to 6,038 m^3. The simulation outputs for standing timber volume restricted by terrain slope presented a high potential for timber volume above 35% slopes, resulting in a total potential of 10,582 m^3. Furthermore, using equation (1) to estimate the harvesting intensity based on existing standing timber volume, current increase (%) and cutting cycle (years), a harvesting intensity of 35% was calculated. When applying the harvesting intensity restriction to the technically available standing timber volume restricted by terrain slope, the total technically available standing timber volume resulted in 2,113 m^3. For the available potential of round-wood volume restricted by mechanization level, a time study considering the activities of felling and extraction was

Table 1. General statistics parameters of time study for each analyzed operation and cycle element.

	N	Min	Max	Range	Mean	Standard deviation
Felling net time (min)	30	8.10	25.60	17.50	16.50	4.12
Change position	30	0.00	6.25	6.25	1.47	1.36
Consideration	30	0.18	4.03	3.85	0.98	0.97
Clear site	30	0.00	0.37	0.37	0.03	0.11
Felling	30	0.87	4.00	3.13	1.82	0.82
Delimbing and cross cutting	30	5.18	21.53	16.35	12.18	3.46
Extraction net time (min)	31	6.52	17.87	11.36	12.03	3.00
Travel	31	0.05	1.75	1.70	0.62	0.49
Reaching log	31	2.73	7.57	4.83	4.74	1.51
Choking log	31	0.17	3.18	3.02	1.29	0.82
De-choking log	31	2.12	8.32	6.20	5.38	1.41
Total net time (min)	30	18.97	35.67	16.70	28.37	4.71
Winching distance (m)	30	14.94	261.00	246.06	61.69	58.82

developed. A production rate of 2.48 m^3/PMH was estimated based on the data and statistical parameters collected in field work (Table 1). Afterwards, using this value as base line (BL) production rate, a restriction of the technically available round-wood volume was applied, amounting to 2,113 m^3 (Table 2). That is to say, according to the local conditions and restriction used in the model, a production rate of 2.48 m^3/PMH is estimated to be enough to harvest all the technically available standing timber volume constrained by terrain slope and harvesting intensity. Moreover, the calculated BL production rate amounted to a surplus of 664 m^3.

According to the time study, a total mean net time of 28.27 min for the operations of felling and extraction was calculated, with the element delimbing and cross cutting as bottleneck for the felling cycle. For the extraction, the bottleneck was identified in the activity de-choking log. Each analyzed cycle, felling and extraction, had a total mean consumption time of 16.50 min and 12.03 min respectively. Winching distances, as critical factor for estimating production rates, were also taken in field with a range between 14.94 m and 261 m (Table 1). Once the three technical constraints were applied, technically available round-wood volume comprising the systems boundaries from harvesting to landing was calculated (Table 2). Afterwards, a biomass flow chart was developed to graphically represent biomass production to end use within the system boundaries. With it, tracing biomass production can be represented graphically to identify improvements along the supply chain in terms of production, utilization rate and technical constraints (Figure 1) (adapted from Rosillo-Calle & Woods, 2012). Results pointed out a low utilization rate of available standing timber volume, where non-utilized standing timber volume above 35% terrain slope accounted for 71% of available standing timber volume for potential production. Based on the biomass flow chart, the 21,132 m^3 corresponding to the theoretical available standing timber volume reduced to 6,038 m^3 because terrain slope and 2,113 m^3 when the three technical constraints were applied. This means a reduction of 5,214 m^3, 471 m^3 and 13,334 m^3 for *Pinus michoacana, Pinus teocote* and *Quercus ssp.* respectively. Using the biomass flow chart (figure 1), it is possible to follow biomass production within the boundaries of the analyzed system.

Based on results, there was a technical potential of 2,113 m^3 which corresponds to 10% of the total theoretical biomass production as standing timber volume. It is important to notice that for this local case study, round-wood production constrained by mechanization level is equal to round-wood volume constrained by harvesting intensity. The time study output resulted in an optimal production rate in which the technical available round-wood constrained by harvesting intensity was not restricted. Thus, these two values were equal. Moreover, a total of 19,010 m^3 resulted when slopes above 35% and harvesting intensities higher than 35% were considered. Given these results, recommendations are shown supported by time studies values, technical constraints on terrain slope, harvesting intensity and mechanization level. The forested land in San Antonio in the municipality of Santa María del Río in the state of San Luis Potosí, Mexico, is representative of a small private forest wood supply chain where current round-wood production has potential for improvement. Forest operations were carried out with poor equipment and best practices of forest utilization were not fully considered. The operators had low training and low capacity development, affecting productivities. Moreover, the 145 forested hectares corresponded to a hilly terrain with more than 60% of total surface with slopes above 35%. Thus, the introduction of advance techniques of forest operations in San Antonio could make the standing timber volume on slopes above 35% available. When cable yarding systems are considered, for instances, the mechanization level in San Antonio is positively affected, allowing harvesting standing timber volume on slope above 35%. Modeling the introduction of such systems for this case study would result in an extra potential of 6,038 m^3 for

Table 2. Theoretical and technical availability of round-wood volume constrained by terrain slope, harvesting intensity and mechanization level (m^3).

	Theoretically available standing timber volume	Technical constraints		
		Terrain slope	Harvesting intensity	Mechanization Level
Pinus michoacana	5,794	1,655	579	579
Pinus teocote	523	149	52	52
Quercus ssp.	14,815	4,233	1,482	1,482
Total	21,132	6,038	2,113	2,113

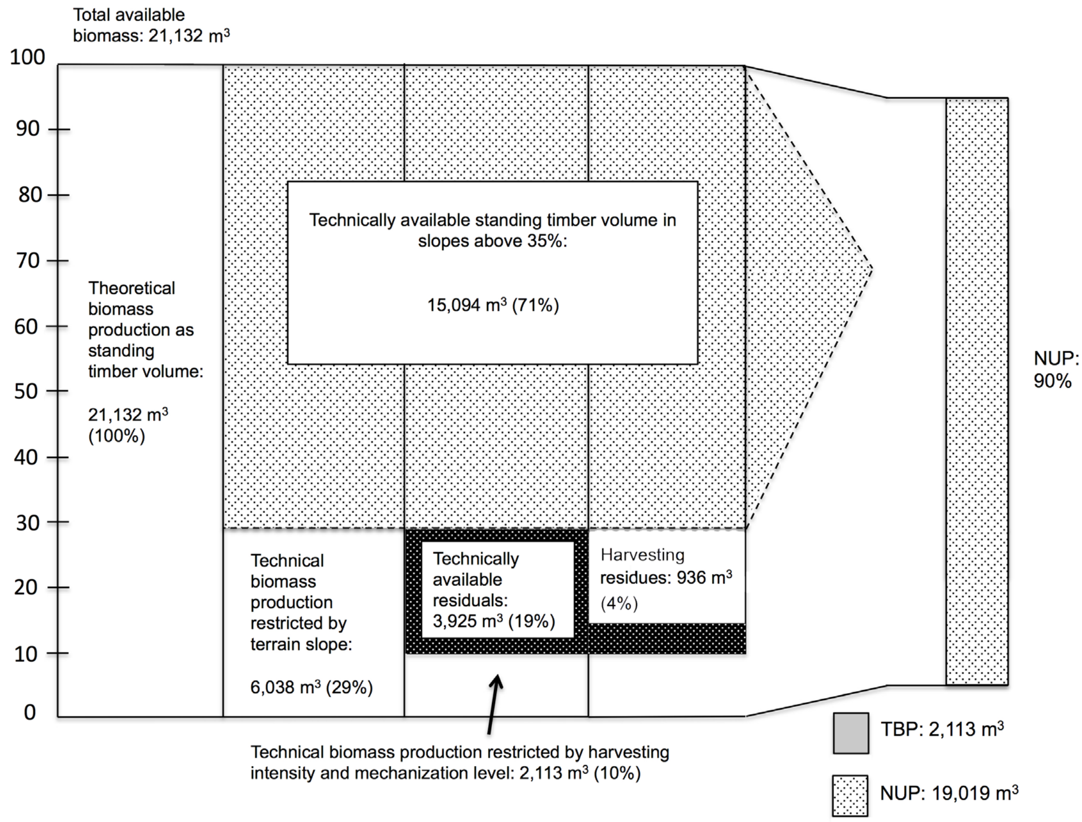

Figure 1. Biomass flow chart for tracing biomass along the analyzed forest wood supply chain. NUP: non-utilized biomass potential as standing timber volume; TBP: total biomass potential as round-wood volume.

round-wood production. Given local conditions and based on national best forest management practices, the harvesting intensity for the forested land in San Antonio was calculated. Harvesting intensity is an important parameter as it initially determines round-wood volume output for the supply chain. It is also a key indicator to assess sustainable forest management at the European scale. In order to achieve a sustainable forest management, a 35% of harvesting intensity was used to model round-wood supply in San Antonio. This implied that, in the long-term, forest harvesting should not get close to or even exceed the annual increment of analyzed species. However, intensity rates at levels well below increment can have strong negative environmental impacts. The resulting harvesting intensity for San Antonio can be slightly increased while maintaining sustainable practices. This technical constraint is depending on management practices which can be improved by applying innovative silvicultural systems and therefore allowing for an extra potential up to 3.925 m^3.

Recommendations are given for improving round-wood volume as main output of the forest wood supply chain in San Antonio: Within the felling net time, the functional element delimbing and cross cutting accounted for the highest mean value of time consumption with 12.18 minutes followed by the element felling with 1.82 minutes. For instance, accounting for a reduction of 3.04 min from the functional element delimbing and cross cutting, which corresponds to 25% of total time consumption, the total felling time is reduced by 18%. A reduction of these two elements would be possible with capacity building and training in regard to felling standards. For the extraction net time, the functional element de-choking log resulted in 5.38 minutes which represented 45% of the total cycle. Reducing time consumption of this bottle neck based on alternative forest operations would result in improved productivities. In addition, the introduction of cable yarding systems would positively affect round-wood supply as it enables standing timber volume above 35% terrain slope, while also improving extraction production rate. Recollection of data regarding harvest frequency, size of production units, tree species selection, harvesting systems and frequency of thinning and tending is recommended to estimate accurate harvesting intensities, thus efficiently utilizing the technical potential of round-wood availability.

This research considered implications regarding the development and application of modeling methodologies based on the simulation of technical parameters which are critical for forest utilization. It also implied the design of forest management plans for decision-making processes considering, for instance, the identification of bottlenecks along the supply chain. Further research concerning forest logistics, silvicultural practices and business models are fundamental to assess forest value chains. Data collection about species, terrain conditions, machinery cost, management plans and productivities according to region are required to boost the performance of forest wood supply chains in Mexico. The outputs and approaches considered in this work suggest opportunities for the development of innovative models to analyze forest wood supply chains.

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