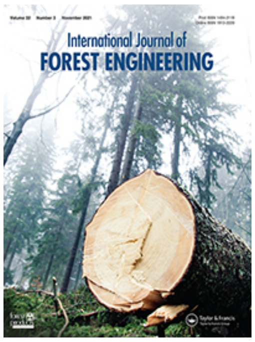

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Worldwide trends in methods for harvesting and extracting industrial roundwood

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ABSTRACT

Globally, almost 2 billion cubic meters of industrial roundwood are harvested yearly. Two of the most common methods of harvest and extraction are cut-to-length (CTL) and full-tree or tree-length (FT/TL). The aim of this study was to compile data on annual volumes of industrial roundwood harvested by the main methods in forestry countries. To quantify the effect of potential explanatory variables, the data were subjected to linear regression analysis, using shares of roundwood volumes harvested by fully mechanized CTL and/or FT/TL as response variables. Generally, high diesel price and Gross Domestic Product appear to favor CTL, while high shares of steep terrain (>20°) in forest land decrease the leve l of both mechanization and CTL, and low Social Security Rate (SSR) favor FT/TL. Two models were created for CTL, one with an R^2 of 0.64 and another more complex with an R^2 of 0.75. A separate model for mechanization (CTL and FT/TL together) showed an R^2 0.57. The CTL models could potentially be used to predict shares of roundwood volumes harvested by CTL in countries not included in this study. Predictions for countries with large harvested volumes, e.g. China and India, are presented here, but they require validation, as does the model's applicability for countries with small harvested volumes. Countries with less than 10% of steep slope forests are almost exclusively mechanized according to the model. For FT/TL, the proposed model is probably not sufficiently robust for prediction, but it highlights SSR as one important explanatory variable.

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Harvesting method; harvesting system; mechanized; CTL; full tree; tree length; international; slope

Introduction

Globally, 1.9 billion solid cubic meters under bark (m^3) of industrial roundwood is harvested annually (FAO 2016), and 1 billion m^3 is harvested in the five largest producers: the USA, Russia, China, Canada, and Brazil. Another 250 million m^3 is produced by Sweden, Indonesia, Finland, and India, while about 200 countries account for the rest, each producing less than 50 million m^3 per year (FAO 2016). The wood is harvested and extracted in various ways (c.f. Heinimann 2004; Heinrich and Arzberger 2004; Arets et al. 2011; Hiesl 2013; Moskalik et al. 2017), but no analysis of the global variations in harvesting methods has been previously presented and there is no clear consensus even regarding some of the key terms. However, it is known that diverse ecological, legal, social, and economic factors form frameworks for commercial activities such as harvesting roundwood that affect choices of harvesting methods and systems (Nordfjell et al. 2004; Ghaffariyan 2014). For example, Nordfjell et al. (2004) suggest the following six important factors: "1) terrain conditions, 2) tree sizes, 3) silvicultural strategy, 4) density in the remaining stand, 5) labor cost and 6) object volume (the total harvested volume in a stand)". Although factors such as *density in the remaining stand* and *object volume* indicate that choices may be stand-specific, they can also be treated as averages for regions or countries.

Definitions

The terms "harvesting method" and "harvesting system" are commonly used in the forest operations literature, but definitions and conceptions of the terms vary. For example, Sundberg (1988) and Robert et al. (2017) use the terms interchangeably. In contrast, Gerasimov and Sokolov (2014) and Lindroos et al. (2017) clearly distinguish between *harvesting methods*, defined according to the state of harvested material at roadsides, and *harvesting systems*, defined according to the combinations of machinery, workforce, and tools used. However, in contexts where stands on steep terrain are frequently harvested, there is also a need to distinguish ground-based harvesting from cable-based and air-based harvesting (cf. Visser et al. 2014). Furthermore, the level of mechanization adds another dimension that may affect the terms used. Therefore, there is a need for a globally applicable framework to systematically classify and exemplify the key terms. Use of the framework presented in Figure 1 is proposed here.

In the proposed framework, all kinds of harvesting are first classed in terms of the "*harvesting approach*," depending on whether the operations are all ground-based or some of the operations involve use of cables or aerial systems (designated "ground-based," "cable-based," and "air-based," respectively). They are then further classified in term of *harvesting method*, depending on the state of harvested wood at landings, for example salable logs and full stems in the cut-to-length and full tree (tree-length) methods, respectively. Finally, the concept *harvesting system* refers to the specific combination of machinery, workforce and tools used, i.e. what Lindroos et al. (2017) and others also refer to as the harvesting system. The comprehensiveness of the examples in Figure 1 is high at the top of the figure and low at the bottom, i.e. there are many

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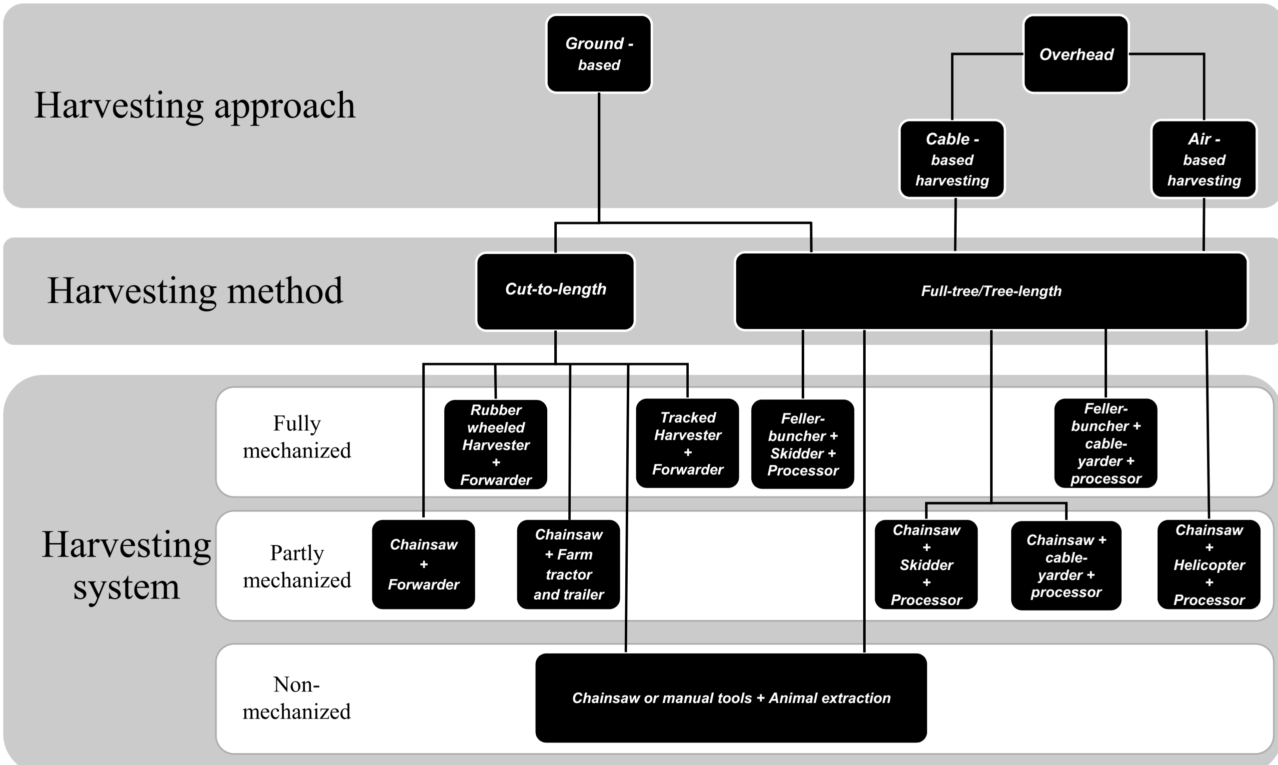

Figure 1. Framework including examples of the most common harvesting operations classified according to the concepts "Harvesting approach," "Harvesting method," and "Harvesting system." The examples of harvesting systems are biased toward the most mechanized harvesting systems; a wide range of partly mechanized harvesting systems are not included here.

more harvesting systems than those included in the figure, a few more harvesting methods, and perhaps only one more imaginable harvesting approach (water-based).

The choice of harvesting method

Theoretically, the variation in harvesting trees among countries could be considered in terms of any of the three concepts in the proposed framework (Figure 1). However, in many countries only ground-based harvesting approaches are used, so global comparison of harvesting approaches would not be very informative, and harvesting systems are too diverse for international-level generalizations (if a single machine or tool is changed the harvesting system also changes, by definition). Thus, the harvesting method is the most convenient and potentially informative conceptual level for comparison.

Regarding factors that influence the choice of harvesting method listed by Nordfjell et al. (2004), acquiring or analytically applying national-level information on tree sizes, silvicultural strategies, density in remaining stands, and object volumes (total harvested volumes in stands) may be difficult. However, two terrain-related factors that most clearly affect the harvesting of roundwood generally on the national level are the shares of steep terrain and soil with low bearing capacity in the total forest land area. For the harvesting method specifically, the share of steep terrain is probably most important, and this variable can be assessed relatively conveniently (Lundbäck et al. 2020a). The financial factor labor cost can also be assessed at a national level, and high labor costs would generally be expected to favor harvesting methods often performed by harvesting systems with low labor intensiveness, such as mechanized CTL (Asikainen et al. 2011). Although labor costs play an important role in choices of harvesting methods according to Nordfjell et al. (2004), there are also other harvesting costs, regardless of whether forest owners themselves, small contractors or large forest companies do the harvesting. One is the cost of diesel, as nearly all harvesting operations around the world involve use of diesel engines, and there is a clear difference in diesel consumption between most full tree harvesting methods and most CTL harvesting methods. This is because CTL harvesting generally involves use of fewer and smaller machines, resulting in around 40% less diesel consumption per unit harvested roundwood (Zhang et al. 2016). Effects of these, as well as several other economic variables, and countries' amounts of forestland, relative to their total areas, were tested in this study.

Aims of the study

The aims of this study were to compile data on annual volumes of industrial roundwood harvested by the main harvesting methods in the major roundwood-producing countries, and assess the effects of possible explanatory variables on level of mechanization and choices of methods. Since the focus was on harvesting roundwood for industrial use, methods for harvesting and extracting material from forests for use as firewood or other applications throughout the world were not mapped or analyzed.

Materials and Methods

This section first describes the collection of data on industrial roundwood volumes harvested by each of the harvesting methods considered and then the methods used to analyze effects of potential explanatory variables on the volumes.

Collection of data on harvested roundwood volumes

All countries that produced at least 5 million m^3 of industrial roundwood per year for which data on volumes harvested by the considered methods could be obtained were included in the study. It was not possible to obtain estimates of volumes harvested by these methods for a number of countries with an annual harvest over 5 million m^3, most importantly China and India (Table 1), so they were excluded from the modeling. However, some countries that produced less than this threshold were also included because they are well suited for the intended analyses of harvesting methods in terms of available data and frequency of inclusion in studies of forestry operations. The included countries are listed in Table 4.

We estimated each of the countries' volumes of roundwood harvested annually by the following three pre-defined categories of methods, reflecting the main differences between cut-to-length and full-tree/tree-length operations, as well as the level of mechanization:

Fully mechanized CTL – Ground-based cut-to-length operations in which all steps are mechanized, known in Canada as "CTL at stump".

Fully mechanized FT/TL – Ground-based full-tree or tree-length operations in which all steps are mechanized, defined by bucking no earlier than at landings.

Other – All other operations, such as cable- or air-based harvesting approaches, partly mechanized harvesting systems and harvesting systems with simple equipment.

Four sources of material were used to obtain the harvested volumes and their distributions in the three categories. First, official global statistics on harvested volumes from the Food and Agriculture Organization (FAO) of the United Nations. Second, peer-reviewed papers and reports from research institutes and universities. Third, manufacturers' estimates of the distributions. Fourth, corresponding estimates by forestry experts.

Official statistics of annual roundwood production were obtained from the *FAO Yearbook of Forest Products 2016 (FAO 2016)*.

Literature was systematically searched to find published material concerning harvesting methods in the studied countries. The same relevant keywords were applied in Web of Science and Google Scholar searches for all studied countries. In addition to articles found through this search, some articles found in their reference lists and search engines' recommendations, such as "related articles," were included in the review. All included literature is listed in the supplementary material.

Estimates of total demand for various types of forest machines and volumes harvested by associated categories of methods in the countries included were mainly provided by Komatsu Forest in Umeå, Sweden. As the head office for a worldwide organization of forest machine retailers, they have access to information that enables them to present highly educated estimates on this matter. To improve and validate the estimated distributions of harvesting methods further, researchers engaged in forest operations research in various parts of the world helped to fill blanks and refine some of the estimates. Substantial contributions have been made by experts and researchers from Australia, New Zealand, and Canada. In addition, researchers from the USA, Scandinavian countries, South Africa, and Eastern European countries have helped efforts to validate the estimates. The most significant contributors are listed in the supplementary material.

To create data for Table 4, the different sources of information have been weighted together in a way that give the most certain figures for a specific country a higher weight than other weaker figures. When the different sources of information were weighted together, more emphasis is put on more recent literature and experts with country-specific knowledge.

Explanatory variables for mechanization and choices of harvesting methods

The shares of fully mechanized CTL and fully mechanized FT/TL as well as the combination of the two were chosen as response variables for ordinary least squares (OLS) linear regression analyses. For this, open source statistical software R (versions 3.5.1 and 4.0.2) was used.

Potential explanatory variables were chosen (Table 2) for which cause-effect relationships could be theoretically explained and/or relevant data were available for all the studied

Table 1. Countries with annual harvests over 5 million m^3 (FAO 2016), but lacking estimates of volumes harvested by thecategories of harvesting methods considered in the study.

Country	Annual harvest of industrial roundwood (M m^3 under bark)
China	164.4
Indonesia	74.0
India	49.5
Japan	21.3
Thailand	14.6
Argentina	11.8
Portugal	11.0
Nigeria	10.0
Vietnam	6.7
Myanmar	6.0
Mexico	5.4

Table 2. Variables tested in the regression analysis.

Variable	Source	Description
Diesel price (US$/L)	https://www.globalpetrolprices.com/diesel_prices/	Accessed 1 November 2018
Fossil energy consumption (%)	ourworldindata.org	Share of a country's energy consumption from fossil fuel
Human Development Index (HDI) (index between 0 and 1)	ourworldindata.org	A combined index of life expectancy, level of education and Gross Domestic Product
GDP (US$/capita)	ourworldindata.org	Gross Domestic Product for each country
Gross value from forestry (1000 US$)	(FAO 2015)	Gross value from forestry for each country
Publicly owned land (%)	(FAO 2015)	Share of the forest land that is publicly owned
Slope (%)	(Lundbäck et al. 2020a) and the online database: (Lundbäck et al. 2020b)	Shares of forest land in selected slope classes. Lundbäck et al. (2020a) used four: < 15°, 15°-20°, 20°-30° and >30°. Here, the classes were also combined to form new classes, so in total seven slope variables were tested.
Forest land/Total land (%)	(FAO 2015)	Forest land as a share of total land area
Interest rate (%)	https://tradingeconomics.com/country-list/interest-rate	The steering interest rate in January 2019 set by respective central banks
Social security rate (SSR) (%)	https://tradingeconomics.com/country-list/social-security-rate	Total Social Security Rate per country
PPP index (number of LCU units)	https://data.worldbank.org/indicator/PA.NUS.PPP	Global index of the number of units of local currency (LCU) corresponding to the same amount of goods or services as 1 US$ in the USA in 2011

countries. Data for all variables included in the models were collected from different sources and compiled to enable further analyses (Table 3).

To refine each model, correlation matrices between new candidate variables and residuals of the existing model were generated to see how much (if at all) they improved the model. A high correlation between residuals of the existing model and a potential new variable was used as an indicator for its inclusion, as residuals of a model represent the unexplained part of the variation. Residual plots were examined to check that residuals met requirements of approximation to a normal distribution, homoscedasticity, etc., for the regression analysis.

The final models are trade-offs between high R^2 values at a 5% significance level, low numbers of variables, interpretability and relevance to the aims of the study. Fivefold cross-validation with three repetitions was applied at the end of the process to validate the models as good as possible with available data. This is an internal validation approach that is suitable when there are relatively few observations since it does not rely on splitting the gathered data into training and control sets before the start of the analysis. Instead, the dataset is split into five subsets (hence fivefold) after the regression model has been constructed, which are subsequently used as control datasets. This whole process is then repeated, in this case three times. The results are displayed, in terms of root mean square error of cross–validation (RMSECV) values, in Tables 5–8.

The CTL models were applied to the countries in Table 1 after completion of their construction. This application was not validated since there are no true observations for comparison of the predictions, but rather an application of the models that requires evaluation in future research.

Results

The total annual harvested volume of industrial roundwood in the countries included in this study amounted to 1.38 billion m^3, 74% of the total global harvest, in 2016. The results indicate that over two thirds of this volume was harvested by fully mechanized methods (Table 4).

Factors affecting the level of mechanization

A model was constructed with the level of mechanization (expressed as fully mechanized CTL and fully mechanized FT/TL combined) as response variable. R^2 = 0.57 (Table 5). High GDP per capita is associated with a high level of mechanization while a high share of steep terrain (slope >20°), and publicly owned forest land is associated with a low level of mechanization (Table 5, Equation 1, and Figure 2).

$$\begin{aligned} &\textit{Level of mechanization}(\%) = 64.7493503 + 0.0010198* \\ &\textit{GDP per capita}(US\$) - 0.9135723 * \textit{Slope} > 20^{\circ} \\ &\textit{in forest land}(\%) - 0.4186511 * \textit{Share of forest land} \\ &\textit{puplicly owned}\,(\%) \end{aligned} \tag{1}$$

Factors affecting use of the CTL harvesting method

Two models were constructed with fully mechanized CTL (CTL hereafter) as the response variable. The first model is simpler, with R^2 0.64 (Equation 2) while the other is slightly more complex due to inclusion of an interaction variable, R^2 0.75 (Equation 3). According to Model 1, high diesel price and high Gross Domestic Product (GDP) are associated with a high share of CTL, while a large share of steep terrain (slope, >20°) is associated with a low share of CTL (Table 6 and Equation 2, and Figure 3). Table 6

$$\begin{aligned} &\text{Share of fully mechanized CTL}(\%) = -27.37 + 49.76* \\ &\text{Diesel price}(\text{US\$/Litre}) - 0.9282*\text{Slope } 20^{\circ} \text{ in forest land}(\%) \\ &+0.0006317 * \text{GDP per capita}(\text{US\$}) \end{aligned} \tag{2}$$

$$\begin{aligned} &\text{Share of fully mechanized CTL}(\%) = -64.8047 + 59.0055* \\ &\text{Diesel price}(\text{US\$/Litre}) + 0.7721*\text{Slope} < 15^{\circ}\text{in forest land}(\%) \\ &- 0.407*\text{Dieselprice}(\text{US\$/Litre})*\text{Share of forest land} \\ &\text{publically owned}(\%) \end{aligned} \tag{3}$$

Table 3. Variable data used in the models.

Country	Diesel price ($/L)[a]	GDP/capita (1000 $)[b]	Share of forest land with slope >20° (%)[c]	Share of forest land with slope <15° (%)[c]	Share of forest land publicly owned (%)[d]	Diesel price × Share of forest land publicly owned[e]	Social Security Rate, SSR (%)[f]
Australia	1.14	45	6	90	73	83.2	11.5
Austria	1.51	45	53	35	19	28.7	39.6
Belarus	0.69	19	0	100	100	69.0	35.0
Brazil	0.97	13	2	95	62	60.1	39.8
Bulgaria	1.32	18	32	50	88	116.2	32.4
Eastern Canada	1.01	43	3	94	91	91.9	13.8
Western Canada	1.01	43	26	67	91	91.9	13.8
Chile	0.96	21	50	39	25	24.0	24.6
Czech Republic	1.48	31	8	82	77	114.0	45.0
Estonia	1.60	26	0	100	41	65.6	35.4
Finland	1.70	38	1	98	30	51.0	32.5
France	1.79	39	16	77	25	44.8	59.2
Germany	1.52	47	10	82	52	79.0	40.2
Italy	1.77	35	49	37	34	60.2	39.4
Ireland	1.82	56	4	93	53	96.5	14.8
Latvia	1.42	23	0	100	52	73.8	35.1
Lithuania	1.27	26	0	100	61	77.5	41.9
Malaysia	0.52	23	15	70	95	49.4	20.0
New Zealand	1.16	34	44	41	60	69.6	11.0
Norway	1.98	76	39	50	12	23.8	22.3
Poland	1.37	26	4	93	82	112.3	36.1
Romania	1.48	19	34	48	67	99.2	37.3
Russia	0.67	23	10	84	99	66.3	30.0
Slovakia	1.49	27	33	49	50	74.5	48.6
South Africa	1.19	12	31	59	60	71.4	2.0
Spain	1.48	32	35	51	29	42.9	36.3
Sweden	1.88	44	2	95	25	47.0	38.4
Turkey	1.08	19	51	33	100	108.0	37.5
United Kingdom	1.77	39	8	86	28	49.6	25.8
Ukraine	1.12	10	10	85	100	112.0	22.0
United States	0.87	53	13	80	42	36.5	15.3
Uruguay	1.23	20	0	99	1	1.2	35.8

[a]https://www.globalpetrolprices.com/diesel_prices/(Accessed November 2018).
[b]https://ourworldindata.org (Accessed January 2019).
[c](Lundbäck et al. 2020a).
[d](FAO 2015).
[e](FAO 2015) The interaction between diesel price and share of forest land publicly owned has no unit, and it is not interpretable as numbers as such but rather describes the behavior of Model 2.
[f]https://tradingeconomics.com/country-list/social-security-rate (Accessed January 2019).

According to Model 2, high diesel price and high share of forest land with slopes <20° are associated with a high share of CTL. The model shows that the third variable "Share of forest land that is publicly owned" also helps to explain the share of CTL, but its effect depends on the diesel price. At a given diesel price, an increase in publicly owned land has a negative effect on the share of CTL (Table 7 and Equation 3, and Figure 4).

Factors affecting use of the FT/TL harvesting method

The data acquired in this study cannot explain variations in the share of fully mechanized FT/TL as good as variations in the share of CTL with the applied modeling technique. The best linear function found only included the variable Social Security Rate (SSR), a low SSR indicating a high share of FT/TL. The R^2 value of this model is 0.36 (Table 8, Equation 4, and Figure 5).

$$\begin{aligned}\text{Share of fully mechanized FT/TL}(\%) \\ = 48.0224 - 1.0805 * \text{SSR}(\%)\end{aligned} \tag{4}$$

Model visualization

The relations between the level of mechanization and three explanatory variables included in the model are visualized in Figure 2. The share of forest land with slope >20° is put on the x-axis and show a clear effect of slope on the level of mechanization. Also, a change between the extreme values of the variables GDP/capita and share of forest land publicly owned show a big difference in the level of mechanization (Figure 2). Countries with less than 10% of steep slope forests (>20°) are almost exclusively mechanized according to the model (Figure 2)

The relationship between the share of CTL and three explanatory variables included in Model 1 are visualized in Figure 3.

Table 4. Annual volumes of industrial roundwood harvested[a] in included countries and the shares harvested by the categories of methods described in this paper.

Country	Annual harvest (M m^3 solid under bark)[a]	Fully mechanized CTL (%)[b]	Fully mechanized FT/TL (%)[c]	Other (%)[d]
Austria	12.2	35	<1	65
Belarus	11.3	10	10	80
Bulgaria	3.5	<5	<5	95
Czech Republic	14.1	30	10	60
Estonia	6.6	80	5	15
Finland	54.3	95	<1	<5
France	25.1	55	10	35
Germany	42.8	65	10	25
Ireland	2.7	98	0	2
Italy	2.1	60	<1	40
Latvia	11.4	70	5	25
Lithuania	4.7	50	5	45
Norway	10.3	95	<1	<5
Poland	36.8	20	10	70
Romania	11.0	5	5	90
Slovakia	8.8	<5	<5	95
Spain	13.3	60	<1	40
Sweden	67.2	95	<1	<5
Turkey	20.4	2	6	92
UK	8.7	90	0	10
Ukraine	8.2	<5	<5	95
Europe	*375.5*	*59*	*5*	*36*
Eastern Canada	57.9	75	20	5
Western Canada	99.9	5	80	15
USA	356.6	15	70	15
North America	*514.4*	*20*	*66*	*14*
Brazil	145.1	45	25	30
Chile	44.6	25	25	50
Uruguay	11.3	75	<1	25
South America	*201.0*	*42*	*24*	*34*
Russia	198.2	35	10	55
Malaysia	13.9	<1	<1	>95
Australia	30.1	45	50	5
New Zealand	28.7	10	55	35
South Africa	14.4	30	60	10
Weighted totals[e]	1,376	37%	33%	30%

[a]Based on data compiled in the *FAO Yearbook of Forest Products 2016* (FAO 2016).
[b]Fully mechanized CTL – Ground-based cut-to-length operations in which all steps are mechanized, called "CTL at stump" in Canada (see Figure 1).
[c]Fully mechanized FT/TL – Ground-based full-tree or tree-length operations in which all steps are mechanized, and stems are bucked no earlier than at landings (see Figure 1).
[d]Other – All other types of operations, such as cable- or air-based harvesting approaches, partly mechanized harvesting systems and harvesting systems with simple equipment (see Figure 1).
[e]The average shares for all countries were weighted with harvested volume.

Table 5. Summary statistics for the model on level of mechanization.

Variable[a]	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	57.4	19.63	20.67
Intercept	64.7493503	15.88	<.001	-	-	-	
GDP per capita	0.0010198	0.0002834	.0012	1.21	-	-	
Slope >20°	−0.9135723	0.2423362	<.001	1.04	-	-	
Publicly owned land	−0.4186511	0.1439266	.007	1.25	-	-	

[a]See Table 2 for definitions.

The figure shows (*inter alia*) that changing the diesel price from the lowest to highest value completely shifts the scale of the response variable, regardless of GDP and share of land with >20° slope. Model 2 also indicates the same pattern, but the slope variable is expressed in the opposite direction, a high share of terrain with slope <15° increases the share of CTL (Figure 4). Furthermore, the interaction variable adds another dimension to the interpretation. The FT/TL model solely shows the relationship between SSR and the share of FT/TL (Figure 5), a high SSR being associated with a low share of FT/TL.

When the predicted level of mechanization and shares of CTL and FT/TL are plotted against the recorded data (Figure 6 to Figure 9), it is visible that some countries have a good alignment between predicted and recorded values while other countries are more far off. The difference between the two CTL models in terms of R^2 is also graphically expressed in this way (Figure 7 and Figure 8).

Application of models

Data for countries that were not included in the regression analysis (Table 1) are shown in Table 9 along with the predictions made by the CTL models.

Discussion

This study provides the first comparisons of estimated volumes of industrial roundwood by the harvesting methods considered in

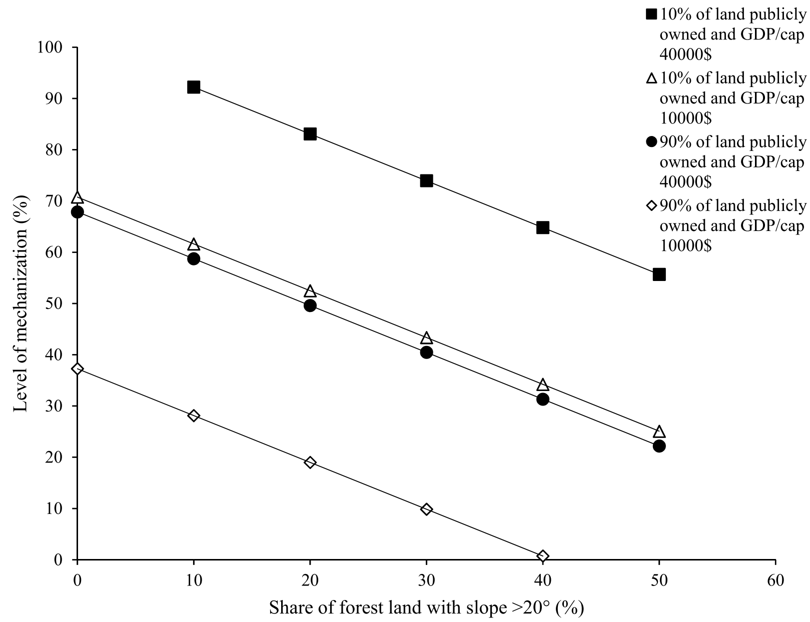

Figure 2. Shares of volume of industrial roundwood harvested fully mechanized at indicated shares of slope >20° according to the model. The four lines reflect shares with indicated combinations of extremes of the variables Gross Domestic Product per capita and forest land publicly owned. For example, the line with quadratic points indicates shares when 10% of the forest land is publicly owned and the GDP is 40,000$ per capita.

Table 6. Summary statistics for fully mechanized CTL model 1 (with no interaction variable).

Variable[a]	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	63.9	18.52	21.20
Intercept	−27.37	13.37	.050	-	-	-	
Diesel price	49.76	10.91	<.001	1.31	-	-	
Slope >20°	−0.9282	0.226	<.001	1.01	-	-	
GDP per capita	0.0006317	0.0002774	.031	1.31	-	-	

[a]See Table 2 for definitions.

countries from all over the world. Overall, the estimates of distributions between CTL and FT/TL in this study, as well as the level of mechanization, are similar to results presented by the North European Regional Office of the European Forest Institute (EFINORD) (Jonsson et al. 2013) for the European countries represented in both studies. However, there are differences in definitions and categorization of the data between the two studies.

Implications of definitions and boundaries

The definitions of CTL and FT/TL

The categories of harvesting methods in this study are limited by the inclusion criteria that the cut-to-length and full-tree methods must be *fully mechanized* to qualify for categorization as CTL and FT/TL, respectively. The non-mechanized harvesting systems that are widely used in some countries will include

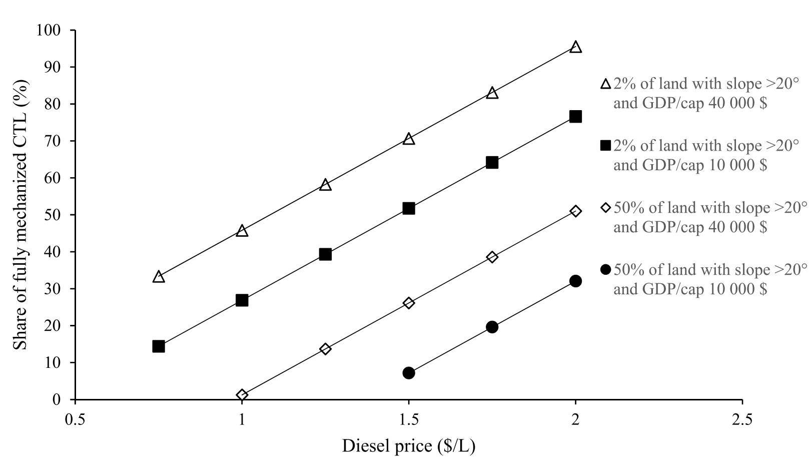

Figure 3. Shares of volume of industrial roundwood harvested by fully mechanized CTL at indicated diesel prices according to Model 1. The four lines reflect shares with indicated combinations of extremes of the variables Gross Domestic Product per capita and forest land with slope >20°. For example, the line with triangular points indicates shares when 2% of the forest land has slopes more than 20° and the GDP is 40,000$ per capita.

Table 7. Summary statistics for fully mechanized CTL model 2 (with an interaction variable).

Variable[a]	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	75.0	15.43	17.51
Intercept	−64.8047	17.53	<.001	-	-	-	
Diesel price	59.0055	8.00	<.001	1.02	-	-	
Slope <15°	0.7721	0.14	<.001	1.02	-	-	
Diesel price * Publicly owned land (Interaction)	−0.407	0.10	<.001	1.01	-	-	

[a]See Table 2 for definitions.

elements of both CTL and FT/TL harvesting methods, but by definition they will be included in the ”other” category. Also, volumes harvested with partly mechanized systems were categorized as “other,” creating an underestimation of the level of mechanization. The underestimation is likely to be small in countries with high level of mechanization and bigger in countries that are less mechanized.

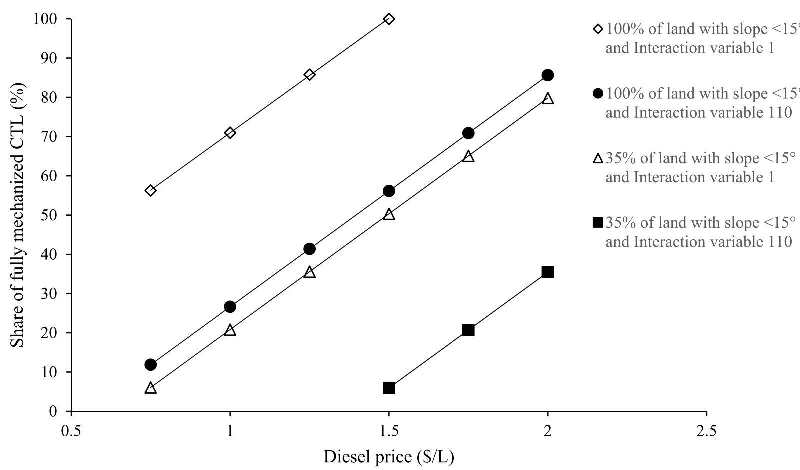

Figure 4. Shares of volume of industrial roundwood harvested by fully mechanized CTL at indicated diesel prices according to Model 2. The four lines reflect shares with indicated combinations of extremes of the interaction and share of forest land <15°.

Table 8. Summary statistics for the FT/TL model.

Variable	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	36.0	17.32	17.84
Intercept	48.0224	8.27	<.001	-	-	-	
SSR[a]	−1.0805	0.252	<.001	-	-	-	

[a]See Table 2 for definition.

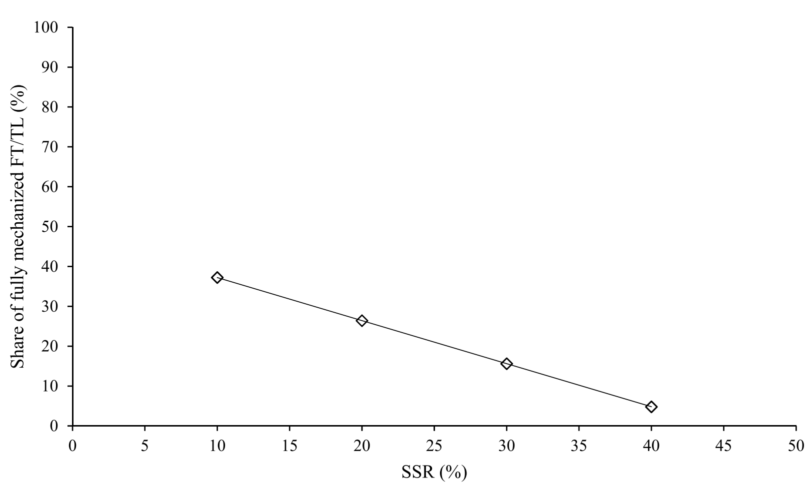

Figure 5. Shares of volume of industrial roundwood harvested by fully mechanized FT/TL at indicated levels of social security rate according to the model.

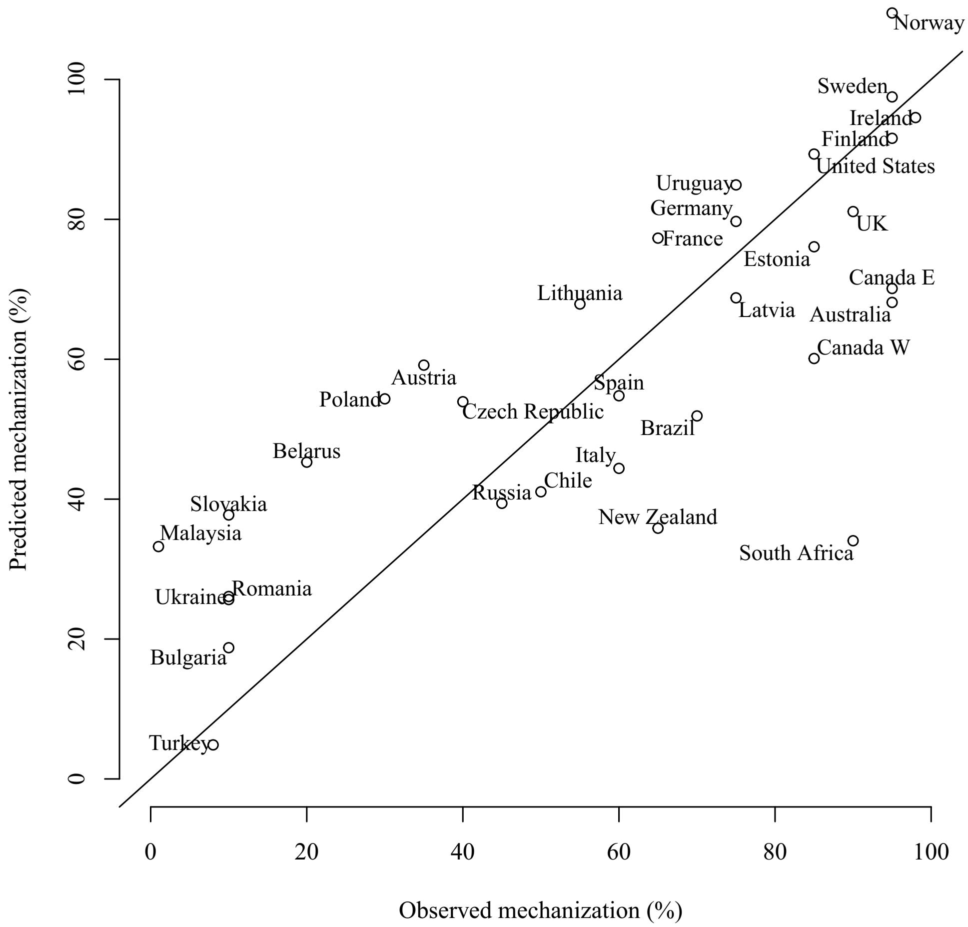

Figure 6. Shares of volume of industrial roundwood harvested fully mechanized in indicated countries according to the model versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

Global CTL vs FT/TL

The results imply that roughly equal volumes of roundwood are harvested by fully mechanized CTL and FT/TL, 37% and 33% of the total volumes, respectively (Table 4). This conflicts somewhat with the general notion that the FT/TL method is the dominant harvesting method or *group of harvesting systems* in the world (c.f. Drushka and Konttinen 1997). Much of the discrepancy is probably due to the comparison here being based on harvested volumes rather than numbers of machines sold (frequently applied metrics), as more machines are usually used per harvested m^3 in FT/TL harvesting systems. Another contributory factor is that FT/TL's dominance may have declined in recent years, and the CTL method may have gained ground during mechanization in previously less mechanized countries, the timespan between sources of information on this matter is large. A third factor is that the exclusion of all partly mechanized systems from these categories may have affected the distribution between CTL and FT/TL. Accordingly, observations in the literature (Demir 2010; Moskalik et al. 2017) and common knowledge of the authors suggest that harvesting systems in countries with a substantial share of the ”other” category (Table 4) probably involve more FT/TL than CTL. In some countries, e.g. Austria, Italy, and New Zealand, a large share of steep terrain is probably a major factor (Lundbäck et al. 2020a), due to the frequent requirement for cable-based harvesting systems, many of which involve manual/motor-manual work elements. In other countries, e.g. in eastern Europe, FT/TL methods were probably favored by the equipment available after World War II, but during further mechanization CTL is increasingly favored. This can be seen in Table 4 in the tendencies for shares of CTL to be higher in the more mechanized Baltic countries than in Eastern European countries and, according to Moskalik et al. (2017), shares of FT/TL to be higher in the less mechanized countries closer to Russia. Hence, CTL may also be favored during mechanization in other parts of the world. However, FT/TL methods still dominate in some countries, or parts of countries, that are important producers and have high levels of mechanization generally, including the USA and western Canada.

What decides the choice of harvesting method and harvesting system?

Explanatory variables, both those included in the models and potentially others, can be roughly placed in one of three groups representing physical, economic, and social/traditional dimensions of the framework affecting commercial activities such as harvesting roundwood (c.f. Nordfjell et al. 2004). All of these dimensions are, to a certain degree, represented in CTL models 1 and 2 and in the mechanization model (consisting of CTL and FT/TL), which is probably the reason for their quite good R^2 values (the physical, economic and social dimensions by the

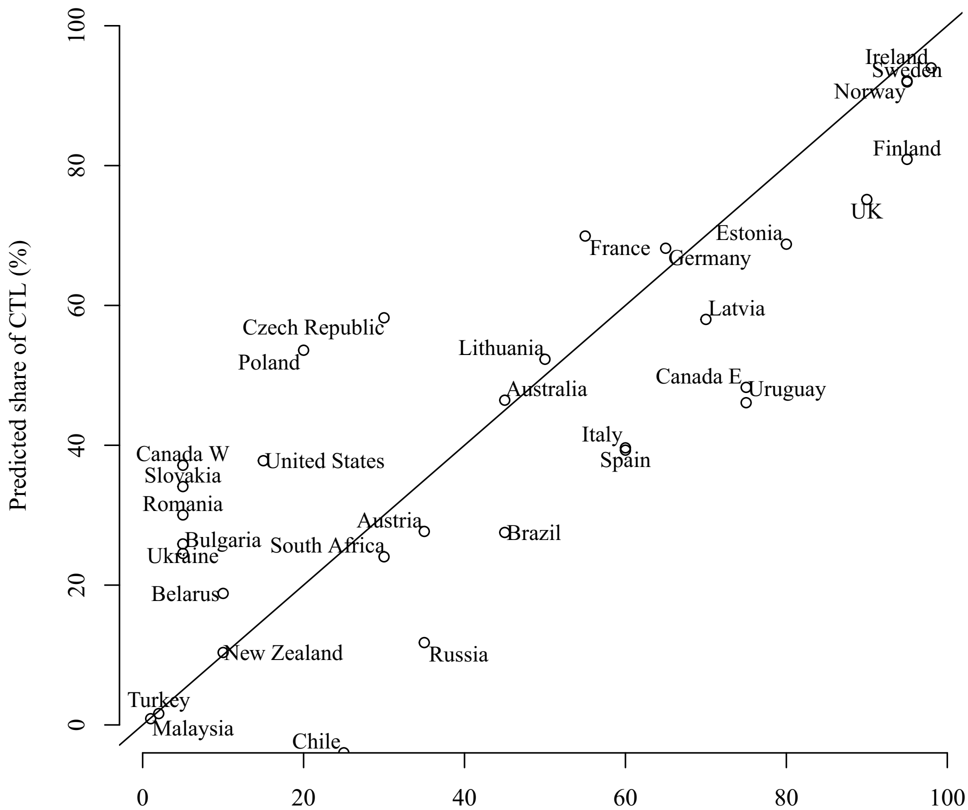

Figure 7. Shares of volume of industrial roundwood harvested by CTL in indicated countries according to Model 1 versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

slope-variables, diesel price, and GDP in Model 1, and these factors plus the share of publicly owned land in Model 2). None of these variables capture the full explanatory power of the respective dimensions, and some (e.g. GDP and share of publicly owned land) may encompass parts of both economic and social dimensions, but they proved to be useful to combine for these models.

Diesel price vs share of publicly owned land

One factor that apparently influences the share of CTL in a country is the amount of privately owned forest land, as a proportion of the total. More strictly, we found negative correlations between the share of publicly owned land and level of mechanization as well as share of CTL which are probably more than coincidental, but the causality is difficult to explain. A somewhat far-fetched hypothesis is that owners in countries with a large share of private forest owners are dependent on frequent income from their forests and thus more likely to perform thinnings. This may favor the CTL method since a forwarder with short logs can more easily move around in a remaining stand than a skidder with full-length stems.

Actually, the share of publicly owned land was the most strongly correlated variable with the share of CTL. However, diesel price was chosen as the first variable in the model since the cause-effect relationship is easier to explain and it was almost as strongly correlated with CTL. One main difference between most FT/TL and most CTL operations is that FT/TL operations generally involve more (and larger diesel engines). Thus, we hypothesized that CTL harvesting is likelier to be favored in countries with high diesel prices. This seem to hold also because the effect of diesel price was not significant for level of mechanization, implying that diesel price distinguishes between harvesting methods rather than levels of mechanization.

Share of steep terrain in forest land

The share of steep terrain in forest land is an important variable of the physical environment that must be considered when planning harvest operations (Nordfjell et al. 2004). The slope of the terrain together with its roughness, ground-bearing capacity and sizes of the trees often determine the harvesting systems that can be applied in a specific area or region. Terrain slope was considered the easiest of these factors to quantify on a global level according to Lundbäck et al. (2020a), and proved to explain a substantial part of the variation in level of mechanization and the share of CTL. Since all non- or partly mechanized systems as well as all cable-based systems were categorized as "others," quite a lot of steep terrain harvesting will fit in that category. That leaves much of the flat terrain in the fully mechanized categories and is a reason for the usefulness of share of steep slope as an explanatory variable. Regardless, effects of the other mentioned physical variables warrant attention in future research.

Gross domestic product and social security rate

Shares of harvesting methods and probably even more level of mechanization in a country are also influenced by demographic factors, partly because CTL and FT/TL harvesting

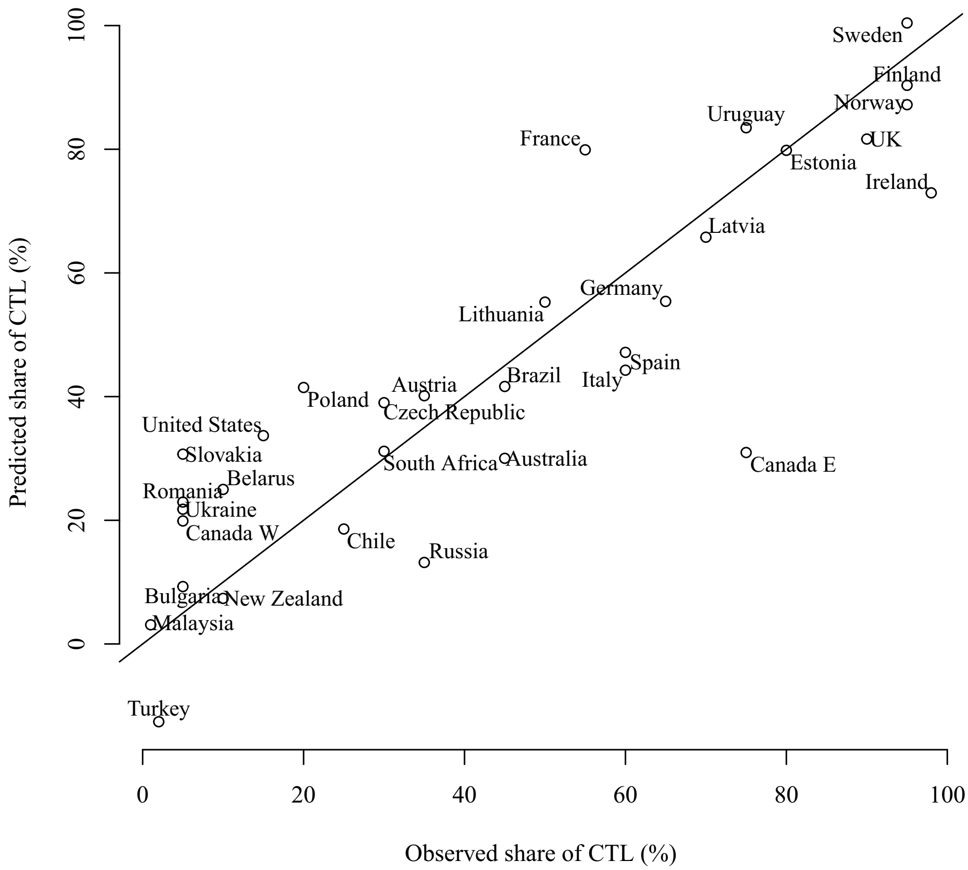

Figure 8. Shares of volume of industrial roundwood harvested by CTL in indicated countries according to Model 2 versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

methods differ in complexity of the machines and equipment typically used. It takes more training and education to effectively operate harvesters and forwarders than fellers, skidders, and processors because more decisions are made by the same person and the machines used in CTL operations are more technically complex. Further down on that scale is manual and motor-manual work which usually is less paid and traditionally takes less training/education. Together with the higher prices for CTL machines this results in workers being hired for longer terms and receiving higher salaries in CTL operations than in FT/TL operations (under otherwise similar conditions). We hypothesized that this effect would be demonstrable using some kind of economic national statistics. GDP per capita is a common measure of a country's economic output and general economic strength, but it provides no information specifically about the forest sector. Nevertheless, it improved Model 1's goodness. The finding that Social Security Rate (SSR) is an explanatory variable for FT/TL can probably be partly explained along the same lines.

Other variables

The Human Development Index (HDI) incorporates GDP, life expectancy, and level of education, so it embraces much more than GDP alone, but it did not improve the fit of the regression models. Like many available statistics for countries tested in this analysis (Table 2), it is probably too general and unable to distinguish differences specifically in the forestry sector between countries.

The variable fossil energy consumption did not improve the fit of the models either, probably because it is correlated to a certain degree with diesel price and partly explains the same variations. However, diesel price is much more helpful for explaining the share of fully mechanized CTL.

Many variables in official global statistics are available to test, but there also probably many concerning forestry that would be interesting to use, but no globally comparable data are available. One example is the size of harvested trees, as small equipment cannot handle trees larger than a certain size and large equipment cannot cost-effectively handle trees smaller than a certain size. Thus, a tree size variable would probably improve models. Another potentially useful variable may be some index linked to a country´s history of timber transportation by river, or lack of it. At least in parts of Scandinavia, the manual handling of logs and size of creeks in forests historically set some limits for both the length and weight of logs. Similar observations may also be informative for practices and harvesting methods in other countries.

Model 1 vs model 2 for CTL

The CTL regression analysis resulted in two models, because we sought both a simple model with high level of interpretability and (as in all regression analysis) as high as possible goodness of fit. Model 1 includes three variables, all of which affect the share of CTL in an intuitive way:

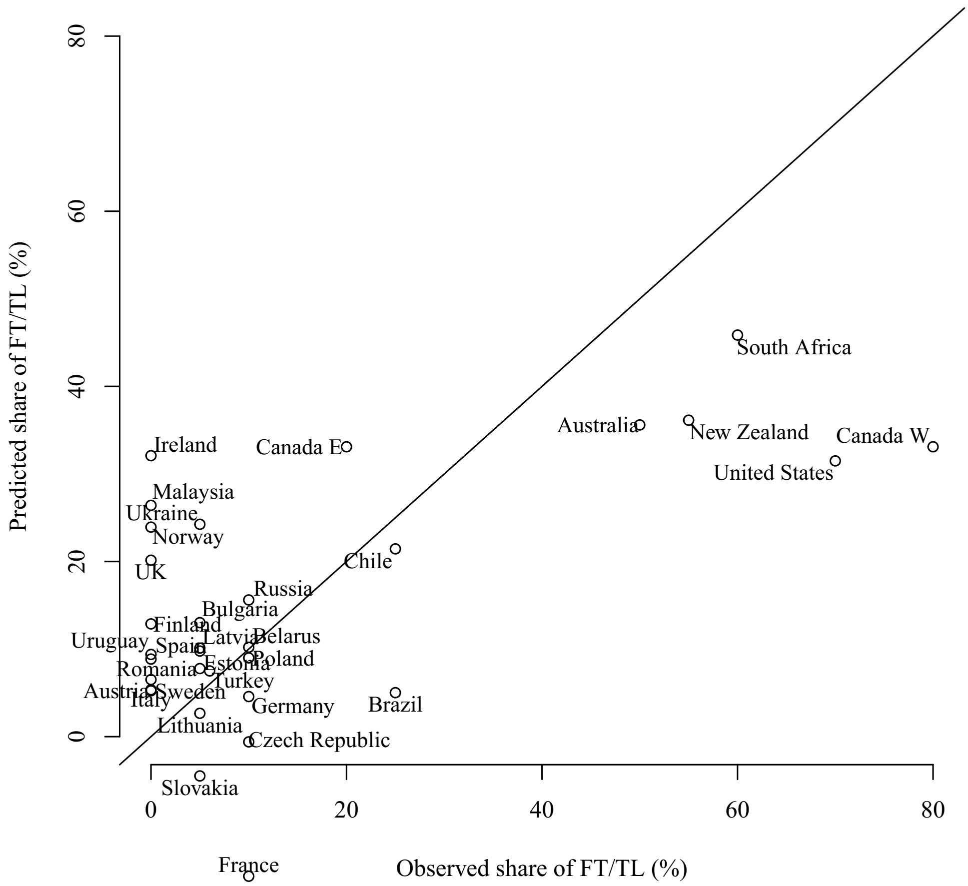

Figure 9. Shares of volume of industrial roundwood harvested by FT/TL in indicated countries according to the model versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

Table 9. Data and predicted shares of fully mechanized CTL for countries that were not included in the modeling but produce more than 5 million m^3 of industrial roundwood.

Country	Share of fully mechanized CTL Model 1 (%)	Share of fully mechanized CTL Model 2 (%)	Diesel price ($/L)	Share of slope >20° (%)	Share of slope <15° (%)	Share of forest land publicly owned (%)	Diesel price × Share of forest land publicly owned
Argentina	24.9	36.9	0.93	6.3	91.0	62	57.66
China	0.0	4.5	1.02	40.5	42.4	57	58.14
India	0.0	2.7	1.03	33.1	55.4	86	88.58
Indonesia	6.5	21.1	0.79	13.0	87.1	87	68.73
Japan	19.3	19.5	1.17	37.2	45.0	41	47.97
Mexico	13.6	47.3	1.08	24.5	63.2	1	1.08
Myanmar	0.0	0.0	0.67	28.7	55.8	100	67.00
Nigeria	0.6	17.4	0.57	4.1	93.0	100	57.00
Portugal	60.8	88.3	1.66	12.9	74.1	3	4.98
Thailand	10.3	3.1	0.91	18.0	66.4	100	91.00
Vietnam	0.0	0.0	0.8	33	49.7	68	54.4

diesel price and GDP per capita positively and share of forest land with slope >20° negatively. Model 2 is more elaborate since apart from another measure of steep slope it also considers the interaction between diesel price and share of forest land that is publicly owned. Model 2 is less straightforward to interpret; the share of publicly owned forest land affects the share of CTL but how much depends on the diesel price.

As discussed above, the share of forest land that is publicly owned is an indirect measure of part of the multi-dimensional framework that sets the choice of harvesting method in a given country. It probably incorporates elements of political history, economic development, forest politics, and both social and cultural aspects. Clearly, apart from being correlated to the share of CTL it is also correlated to GDP per capita and many of the other tested variables, which thus lack the orthogonality required for a parsimonious regression model. In model 2, it seems that GDP per capita is replaced by share of publicly owned forestland through the interaction variable.

Model performance

It is easy to compare recorded (Table 4) and predicted (Figure 7 and Figure 8) shares of CTL. However, the input data in the models clearly do not cover real situations of some countries well. For example, results for Canada are divided into eastern and western parts because CTL harvesting is much more dominant in the eastern parts. Our analysis is that the difference in share of CTL is largely due to the western parts of the country having a larger share of trees which are too big to handle with regular CTL harvesting equipment. In contrast, in eastern Canada there are large areas with relatively small trees, which are suitable for forwarders and thinning operations, both characteristics of the CTL category. However, tree size was not available as input to the models. Only national-level data for both diesel price and GDP per capita were available as input, so eastern and western Canada differ only in the slope variable in these regression models. Clearly, the difference in terrain slope between east and west (Table 3) does not provide reliable results of the share of CTL, as the predicted share of CTL is basically the same for eastern and western Canada.

The Scandinavian countries have very similar culture and traditions in harvesting wood and they all have a very large share of CTL. However, Model 1 differentiates Finland from the other two slightly but clearly, due to Finland's lower diesel price and GDP/capita (Table 3), although there are no real differences among them in share of CTL harvesting methods. This illustrates a weakness of all regression models: they are limited to the included variables and may therefore indicate erroneous differences or similarities in the response variable. Both models ignore effects of tradition, collaboration and so on, which are much stronger than effects of differences in diesel price and GDP per capita in the Scandinavian countries. Model 2 differentiates Norway most strongly from the other Scandinavian countries, corroborating the conclusion that the models exaggerate minor variation, and indicating that they may show the major patterns, but probably cannot be used to spot small differences between countries. In the case of Norway, their higher share of steep slope in forest land does not result in a lower share of CTL than the other Scandinavian countries simply because Norway harvests less of their total forest area annually; therefore, it is possible to find harvest areas with less slope.

The FT/TL models' performance is much poorer, in terms of R^2, than that of the other models. In large part because the small number of countries with a high share of fully mechanized FT/TL (only three observations exceeding 50%) makes it harder to fit a good regression model. An approach to use the difference between the models for level of mechanization and CTL was also attempted but did not result in an improved model.

Application in new countries

The application of the final Models 1 and 2 to the countries in Table 1 does not validate the models as there are no estimates of the shares of CTL for those countries. However, if these countries have a large share of motor-manual work today, the estimates indicate a likely path during a mechanization process.

Some predicted values are negative numbers, which is of course nonsensical for percentages. Therefore, all negative predictions were interpreted as a zero share of CTL, and corresponding countries are unlikely to have a substantial share of fully mechanized CTL according to the models. Of course other factors could favor CTL harvesting methods, but these countries are less likely to have high shares of CTL than other countries.

As a final remark regarding the usability of the models, they were constructed for countries with at least 5 million m^3 of annual harvest of industrial roundwood. Therefore, the models cannot be expected to perform well on new countries with smaller annual harvests, as they are beyond the model boundaries. Likewise, the models are not applicable for prediction of level of mechanization or shares of harvesting methods for non-industrial roundwood.

Future studies

Since the CTL models developed in this study explain 64% and 75%, respectively, of the variation in the share of fully mechanized CTL recorded in Table 4 there is still room for improvement. A variable that is highly likely to improve the models is, as discussed above, the average size of harvested trees in each country. Perhaps also the proportion of hardwood vs softwood and/or the proportion of intensive plantation forests in different countries would bring valuable information. Other variables, such as terrain roughness and more forestry-specific economic measures would probably also improve the CTL models. Suitable data on terrain roughness could potentially be obtained using a large-scale GIS approach and available fine-grained elevation models. The resolution would probably have to be much finer than for slope data (Lundbäck et al. 2020a), so there would be very high computing power requirements. However, it should not be neglected as an interesting topic for future research.

The lower R^2 of 36% for the FT/TL model shows it has even more scope for future improvement. Efforts could be made to improve explanation of either the *fully mechanized* share of FT/TL, as in this study, or the overall division between CTL and FT/TL, regardless of the level of mechanization. However, the last option poses new challenges in gathering sufficient data for the response variables. Machine manufacturers probably know less about the proportion of overall FT/TL than about the fully mechanized FT/TL in a country since the non- or partly mechanized volumes are handled with their specific machines to a lesser extent.

Conclusions

The general conclusion of this study is that it is possible to explain parts of the variation between countries in the level of mechanization and harvesting methods. The main explanatory variables identified are: diesel price, share of steep terrain in forest land, GDP per capita, the share of forest land that is publicly owned, SSR and the interaction between diesel price and the share of forest land that is publicly owned.

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