GREENHOUSE GAS EMISSIONS IN TYPICAL FOREST BIOFUEL SUPPLY CHAINS IN STATE FORESTS

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Abstract. Latvia is one of the leaders in production and use of forest biofuel in Europe. The rapid increase of forest biofuel market raises questions about sustainability of the supply chains and contribution of the forest biofuel produced in Latvia to the climate change mitigation. Sustainability of forest biofuel is addressed in multiple recent international political initiatives; particularly, the European 2030 climate and energy package and the nature restoration regulation. Climate change mitigation potential of forest biofuel is surrounded by multiple speculations, which have to be addressed by comprehensive evaluation of greenhouse gas (GHG) emissions due to production and delivery of forest biofuel. According to the study results, average GHG emissions due to delivery of harvesting residues from the state forests correspond to 1.4 kg CO_2 eq GJ^{-1}, including forwarding, comminution and delivery to a 68 km distance. This is significantly less than the default values provided in the regulation (EC) 2018/2001, particularly during the delivery of forest biofuel. GHG emissions due to delivery of forest biofuel from removal of vegetation in abandoned farmlands are 1.9 kg CO_2 eq GJ^{-1}, from forest drainage ditches – 1.7 kg CO_2 eq GJ^{-1}, from pre-commercial thinning – 2.1 kg CO_2 eq GJ^{-1}. Estimation of the GHG emissions is complicated by limited information on some of the sources and productivity. Building of the system for collection of activity data is a crucial task for transparent demonstration of GHG emissions and the effect of applied mitigation measures.

Keywords: forest biofuel production, greenhouse gas emissions, sustainability.

Introduction

Biomass is identified as an important component of the future renewable energy of Latvia according to the National energy and climate plan for Latvia in 2021-2030 highlighting the significant contribution that forest resources to the total indigenous biomass supply [1]. Forest resources are comprised of residues from harvesting operations in commercial forests and from sawmills. In total, this could yield up to 128411 TJ of primary energy under the current harvest rate [2]. Residues consist of small and damaged roundwood, branches, stem tips, undergrowth trees and stumps, while sawmills produce sawdust and slab wood. It is anticipated that the timber-using industries will make use of the readily available resources, such as small roundwood and sawdust, with the remainder being accessible to new biomass-based energy projects. Significant part of this remaining biomass is left in forest during felling operations due to abundant availability of other resources, e.g., sawmill residues and firewood [3]. However, the situation is rapidly changing due to aggression of Russia in Ukraine and forest biofuel prices increased three times during 2022 following to termination of import of biomass from Russia and Belarus [4]. Currently production of nearly any type of forest biofuel becomes feasible and importance of environmental aspects of biofuel production, particularly, conformity to the sustainability criteria increases as set in the regulation 2018/2001 [5].

One of the sustainability criteria is GHG emissions due to forest biofuel production and delivery. The regulation 2018/2001 provides default values for calculation of emissions; however, they are not verified in Latvia and may significantly overestimate the production related emissions, e.g., due to delivery of forest biofuel, because the regulation provides the emission factors for delivery distances starting from 500 km, while in Latvia delivery distances of forest biofuel are significantly smaller [2].

Assessment of the climate change impact of forest biofuel production and delivery is a complex process requiring multiple activity data and assumptions, where complexity of calculation is determined by the need to harmonize productivity and materials' consumption during different stages of production of forest biofuel. The aim of the study is to estimate GHG emissions due to forest biofuel production and delivery from state forests, based on the actual productivity figures provided by the Joint stock company "Latvia's state forests" (JSC) and literature reviews and forestry companies-based information on fuel consumption, oil, grease and refrigeration related material consumption. The most common forest biofuel supply chains are covered by the study including delivery of harvesting residues from regenerative fellings, whole tree harvesting on abandoned farmlands and forest drainage ditches, as well as from pre-commercial thinning. Typical setup of forest machines (harvesters, forwarders, chippers and chip trucks) is used in the assessment. The study is part of broader assessment of GHG emissions in forest operations.

Materials and methods

The main assumptions in the calculation are fuel and lubricant consumption per working hour and productivity, summing up various work elements and work conditions, e.g., delivery distance. A questionnaire was elaborated to gather the necessary data (Table 1). It was partially provided by the JSC summarizing production statistics collected by the company. Missing information was acquired in scientific materials.

Table 1

Production indicators included in the survey

Group	No.	Title	Comment
Fuel and electricity consumption	1	average L per engine hour	fuel consumption during operation or average fuel consumption if more precise data is not available
	2	L 100 km^{-1} (outside the city with and without load)	average fuel consumption
	3	L 100 km^{-1} (in city with and without load)	average fuel consumption, in addition, the proportion of the distance travelled in city is used
	4	regardless of the type of felling, L LV m^{-3}	average fuel consumption (chipper, loader) per loose volume (LV) of forest biofuel
	5	regardless of the type of felling, kWh LV m^{-3}	electricity consumption (chipper)
Consumption of lubricants and oil, filling of conditioners	6	lubricants, transmission and hydraulic oil, g per engine hour	average consumption of lubricants for the lubrication of the manipulator and other moving parts excluding bio-oils
	7	engine oil, g per hour/km^{-1}	average engine oil consumption during regular maintenance is converted to engine hours; for a chainsaw – oil that is mixed with fuel
	8	air conditioner agent, g per engine hour	average consumption during breakdowns and regular maintenance
	9	chain oil, g m^{-3}/m^{-3}	consumption of chain oil for the production of logs and firewood, excluding bio-oils
Seasonality	10	monthly distribution of work time	percentage distribution of load when producing forest biofuel, LV m^3, working hours or km per month
Relocation of equipment and transport distances	11	distance of relocation of equipment, km	average distance of moving machinery with a trailer in one direction depending on the machine and felling type
	12	forwarding distance, m	average off-road transport distance depending on the felling and machine type
	13	moving equipment (times per year)	number of trips per year related to the relocation of equipment
	14	chip transport distance, km	chip delivery distance in one direction
	15	firewood transportation distance, km	firewood delivery distance in one direction
	16	chip truck loading time, min.	loading and unloading time

Table 2 (continued)

Group	No.	Title	Comment
Productivity	17	logging residues, LV m^3 h^{-1}	average productivity, harvesters and chainsaws (only if the production of logging residues increases fuel consumption)
	18	firewood, m^3 h^{-1}	average productivity depending on the felling type
	19	wood chips, LV m^3 h^{-1}	average productivity for chipping and chip handling
	20	whole tree harvesting, LV m^3 h^{-1}	average productivity depending on the felling type
Load size	21	off-road transport of harvesting residues and whole trees, LV m^3	average load size depending on the felling type
	22	off-road transport of roundwood logs, m^3	average load size depending on the felling type
	23	chip truck, LV m^3	average load size
	24	log truck, m^3	average load size

Fuel emission factors taken from the Intergovernmental Panel on Climate Change (IPCC) guidelines [6], separating road and off-road transport. The emission factors for diesel and various oils are taken from Latvia's national GHG inventory report [7]. The values applied in the calculations are summarized in Table 3.

Table 3

Characteristics and emission factors of fuels and lubricants

Fuel	Net heat value		Density, kg L^{-1}	CO_2, tons t^{-1}	CO_2, tons TJ^{-1}	CH_4, kg TJ^{-1}	N_2O, kg TJ^{-1}
	MJ L^{-1}	MJ kg^{-1}					
Diesel fuel in off-road transport	36.0	42.6	0.8	-	74.7	5.5	28.0
Diesel fuel in road transport	36.0	42.6	0.8	-	74.8	2.8	2.8
Lubricants	-	41.9	-	0.6	-	-	-
Transmission and hydraulic oil	-	39.5	1.0	0.6	-	-	-
Engine and chain oil	39.2	39.5	1.0	0.6	-	-	-

The rest of the assumptions are summarized in Table 4. The proportion of bio-additive in the summer months is assumed to be 6%. This indicator can be scaled up to estimate the impact of partial or complete substitution of fossil fuels with biofuels on GHG emissions. The density of wood chips, as well as the calorific value of wood chips and firewood, are taken from regulations of the Cabinet of Ministers No. 42 [8]. Average relative density of wood, carbon content in wood, as well as methane (CH_4) and nitrous oxide (N_2O) global warming potentials are taken from Latvia's national GHG inventory report 2022 referring to the IPCC Fourth Assessment Report [7].

To characterize the consumption of fuel, lubricants and other materials in the forest operations average productivity figures provided by JSC and cost calculation calculator developed by Ackerman etc. (2014) was applied. The following forest biofuel supply chains are evaluated: (1) extraction of harvesting residues in regenerative felling with mid-class forwarder; (2) harvesting of woody vegetation in abandoned farmlands with compact-class harvester and forwarder; (3) extraction of woody vegetation from ditch-sides with mid-class harvester and forwarder; (4) extraction of undergrowth trees from pre-commercial thinning (average tree height 9-12 m) with compact-class harvester and forwarder; as well as firewood production in (5) regenerative felling and (6) thinning with large and mid-class harvesters and forwarders, accordingly. These supply chains contribute to more than 90% of the forest biofuel deliveries at JSC. In all cases, except firewood production, it is assumed that hipping is done at a roadside and road transport is done to 68 km distance using a two container (70 m^3) chip truck (average transport distance 68 km, average forwarding distance 480 m). Chipping is done at roadside.

Table 4

Coefficients and conversion factors

No.	Indicator and unit of measure	Numerical value
1	Proportion of bio-additives in fuel in the summer months (expert judgment)	6%
2	Lowest calorific value of chips (GJ LV m^{-3}) [8]	3.3
3	Net calorific value of firewood at 40% relative humidity (GJ LV m^{-3}) [8]	10.0
4	Average wood density (tonnes m^{-3}) [9]	0.42
5	Average carbon content in biomass [9]	50%
6	CH_4 global warming potential [9]	25.0
7	N_2O global warming potential [9]	298.0
8	HFC134-A (refrigeration agent) GHG equivalent [10]	1430.0

Research data were used to acquire missing data for the involved machinery as summarized in following outline:

- compact class harvester [12-15], mid-class harvester [16-18] and large harvester [17; 19-21];
- compact class forwarder [22-24], middle class [25-29] and large forwarder [17; 30; 31];
- self-propelled chipper relocated by tractor [32], [33];
- trailer for relocation of forwarders and harvesters [34-36];
- timber truck [29; 37] and chip truck with two containers [27; 29; 35].

The calculation model elaborated for the study is published in the ResearchGate.net portal [38]. GHG emissions during the production are calculated as the emissions per produced units, per ton of CO_2 in forest biofuel and per net heat value of the forest biofuel. The same assumptions are used for chipping and biomass delivery.

Results and discussion

The GHG emissions generated by the forwarding, chipping and delivery of harvesting residues from regenerative felling to a 68 km distance correspond to 1.4 kg of CO_2 eq. GJ^{-1} (Table 5). By increasing the delivery distance to 152 km, the GHG total emissions would increase to 1.7 kg CO_2 eq GJ^{-1}.

Table 5

GHG emissions due to production and delivery of biofuel from logging residues in clear felling

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Mid-class forwarder	1.5	4.9	0.4
Chipper	1.6	5.1	0.5
Chip truck	1.6	5.1	0.5
Total	4.7	15.2	1.4

The GHG emissions due to delivery of forest biofuel from harvests in abandoned farmlands is calculated according to productivity of Vimek forwarder and harvester, based on the study data. In production conditions the productivity would likely be higher, as the study investigated the limits of the use of machinery. The GHG emissions due to the biofuel delivery in this supply chain is 1.9 kg CO_2 eq GJ^{-1} (Table 6).

Table 6

GHG emissions due production and delivery of biofuels from abandoned farmlands

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Compact class harvester	1.4	4.5	0.4
Compact class forwarder	1.5	4.9	0.5
Chipper and chip truck	3.2	10.2	1.0
Total	6.1	19.7	1.9

The calculation of GHG emissions due to extraction of biomass from forest ditches is calculated according to the research results. It should be considered that the threshold values of productivity were evaluated in the study in extreme conditions; therefore, in production conditions the productivity would increase. The total GHG emissions for production and delivery of wood chips correspond to 2.1 kg CO_2 eq GJ^{-1} (Table 7).

Table 7

GHG emissions due to biofuel extraction in ditch cleaning operations

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Mid-class harvester	1.7	5.7	0.6
Mid-class forwarder	0.6	2.1	0.5
Chipper and chip truck	3.2	10.2	1.0
Total	5.5	18.0	2.1

Pre-commercial thinning is a growing supply chain of forest biofuel in Latvia. Average GHG emissions due to biofuel production in pre-commercial thinning is 2.2 kg CO_2 eq GJ^{-1} (Table 8).

Table 8

GHG emissions due to production and delivery of forest biofuel from pre-commercial thinning

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Compact class harvester	2.3	7.5	0.7
Compact class forwarder	1.5	4.9	0.5
Chipper and chip truck	3.2	10.2	1.0
Total	7.0	22.7	2.2

Firewood is the dominating source of primary biofuel in state forests. Average GHG emissions due to firewood production in clear-felling are 0.6 kg CO_2 eq GJ^{-1} (Table 9). In commercial thinning GHG emissions increase to 1.0 kg CO_2 eq GJ^{-1} due to significantly bigger emissions in forwarding while using a mid-class forwarder.

Table 9

GHG emissions due to production and delivery of firewood from clear-felling

Equipment	kg CO_2 eq m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Large harvester	1.6	2.1	0.2
Large forwarder	1.5	1.9	0.1
Log truck	3.4	4.4	0.3
Total	6.5	8.4	0.6

The regulation (EU) 2018/2001 contains default values for certain types of forest biofuel including harvesting residues (1.6 g CO_2 eq MJ^{-1} for production and 3.0 g CO_2 eq MJ^{-1} for delivery) and roundwood biomass (0.3 g CO_2 eq MJ^{-1} for production and 3.0 g CO_2 eq MJ^{-1} for delivery) [5]. Our study demonstrates that the GHG emissions due to extraction of harvesting residues are significantly smaller, while the emissions due to production of firewood are like the default values in the regulation, while the delivery related emissions in our study are up to 9 times (for firewood) smaller. This is partially associated with different delivery distances (the regulation starts with 500 km, while in our conditions 68 km is an average). Recent study in Finland [39] demonstrates similar rate of GHG emissions in roundwood production – 3.64 kg CO_2 eq m^{-3} and (in our study) 3.1 kg CO_2 eq m^{-3} in clear felling, and 6.23 kg CO_2 eq m^{-3} and (in our study) 6.8 kg CO_2 eq m^{-3} in thinning.

Conclusions

1. Despite abundance of different data on the harvesting productivity, there are significant knowledge gaps in the data necessary for calculation of GHG emissions; therefore, the calculation of GHG emissions in the study is largely based on research data, which may not characterize typical

production conditions. There is homework for industry to collect and to systematize the data on resource consumption during the production and delivery of forest biofuel.

2. The estimated emissions are significantly smaller than the default values provided in the Regulation (EU) 2018/2001, while they conform to other research results. The biggest difference, comparing the default values given in the Regulation (EU) 2018/2001 and the data obtained in the study, was found in the biofuel delivery operation, therefore this process should be substantiated in more detail than others to be able to justify the significantly smaller emissions.
3. The threshold productivity and resource consumption values should be identified to describe the reason for the worst cases and to evaluate the improvement potential, as in the best examples, to reduce the GHG emissions. The study also demonstrates that use of the research results to substitute actual production figures may lead to over- or under-estimation of emissions, since the research may not represent typical production conditions.

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Author contributions

Conceptualization, A.L.; methodology, A.L. and K.M.; software, A.Z.; investigation, A.Z., S.K. and K.M.; data curation, A.L.; writing – original draft preparation, K.M.; writing – review and editing, A.L.; project administration, A.L. All authors have read and agreed to the published version of the manuscript.

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