PROMOCIJAS DARBA KOPSAVILKUMS
Zinātniskā doktora grāda
zinātnes doktors (Ph.D.) Lauksaimniecības un
zivsaimniecības zinātnēs, mežzinātnē iegūšana

MAŠINIZĒTAS ENERĢĒTISKĀS KOKSNES SAGATAVOŠANAS TEHNOLOĢISKIE UN EKONOMISKIE RISINĀJUMI STARPCIRTĒ

Santa Kalēja

TECHNOLOGICAL AND ECONOMIC SOLUTIONS OF MECHANISED FOREST BIOFUEL PRODUCTION IN THINNING

SUMMARY OF THE DOCTORAL THESIS
for the doctoral degree
Doctor of Science (Ph.D.)
in Agriculture, Forestry and Fisheries

LATVIJAS VALSTS MEŽZINĀTNES INSTITŪTS “SILAVA”
LATVIAN STATE FOREST RESEARCH INSTITUTE “SILAVA”

LATVIJAS LAUKSAIMNIECĪBAS UNIVERSITĀTE
LATVIA UNIVERSITY OF LIFE SCIENCES AND TECHNOLOGIES

Mg.silv. **SANTA KALĒJA**

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Promocijas darba zinātniskie vadītāji / *Supervisors*:
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Promocijas darbs izstrādāts Latvijas Valsts mežzinātnes institūtā "Silava", doktorantūras studijas – Latvijas Lauksaimniecības universitātes Meža fakultātē laikā no 2012. līdz 2017. gadam. Promocijas darbs izstrādāts saskaņā ar LVMI Silava un AS "Latvijas valsts meži" 2011. gada 11. oktobra memorandu "Par sadarbību zinātniskajā izpētē", īstenotā pētījuma "Meža darbu mašinizācijas un biokurināmā pētījumu programma" ietvaros.

The doctoral thesis is designed at the Latvian Sate Forest Research Institite "Silava" and Latvia University of Life Sciences and Technologies, Forest Faculty in period from 2012 to 2017. The doctoral thesis has been elaborated within the scope of the study "Research program on mechanization of forest operations and forest bioenergy" of the memorandum between LSFRI Silava and JSC "Latvia's State Forests" on "Collaboration in scientific research" from 11 October 2011.

Oficiālie recenzenti / *Official reviewers:*
1. Dr.silv. Jurģis JANSONS, Latvijas Valsts mežzinātnes institūts "Silava" / *Latvian State Forest Research Institute "Silava";*
2. Dr.silv. Linards SISENIS, Latvijas Lauksaimniecības universitāte / *Latvia University of Life Sciences and Technologies;*
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ANOTĀCIJA

Promocijas darba mērķis ir izpētīt enerģētiskās koksnes sagatavošanas ražīgumu un ražošanas izmaksas ietekmējošos faktorus, kā arī novērtēt koksnes resursus mežaudzēs, kurās nav savlaicīgi veikta jaunaudžu kopšanas cirte.

Promocijas darbā izvirzīta sekojoša hipotēze: mežaudzēs, kurās nav savlaicīgi veikta jaunaudžu kopšanas cirte, mašinizēta starpcirte, gatavojot enerģētisko koksni, var būt rentabla.

Promocijas darbā izvirzītā mērķa sasniegšanai un izvirzītās hipotēzes pārbaudei noteikti sekojoši pētnieciskie uzdevumi:

1) noskaidrot savlaicīgi neizkoptās jaunaudzēs pieejamos koksnes resursus un tehnoloģiski pieejamos enerģētiskās koksnes resursus Latvijā;
2) izpētīt faktorus, kas ietekmē meža darbu ražīgumu un enerģētiskās koksnes ražošanas pašizmaksu mašinizēti un ar rokas motorinstrumentiem izstrādātās starpcirtes cirsmās;
3) novērtēt dažādu starpcirtes mašinizācijas risinājumu ietekmi uz enerģētiskās koksnes sagatavošanas rentabilitāti.

Saskaņā ar MSI 3. cikla (2014–2019) datiem mežaudzes, kurās valdaudzes koku augstums ir 9–12 m, aizņem 7% no kopējās meža platības Latvijā. Šim resursu veidam ir neliela saimnieciskā nozīme, taču mašinizēta starpcirte laikus neizkoptās meža platībās, gatavojot enerģētisko koksni, var sekmēt mežaudžu vērtības pieaugumu nākotnē. Mašinizētā starpcirtē vislabākie ražīguma rādītāji sasniegti, izmantojot visizplatītāko mežistrādes risinājumu kopšanas cirtēs Latvijā – vidējas klases mežizstrādes mašīnu, kas aprīkota ar standarta darba galvu (John Deere 1070 E ar H 754 darba galvu). Vidējās enerģētiskās koksnes sagatavošanas izmaksas vidējas klases mežizstrādes mašīnai, pateicoties labākiem ražīguma rādītājiem, ir par 15% mazākas nekā mazas klases (Rottne H8 ar EGS 405 darba galvu) mežistrādes mašīnai. Mežizstrādes mašīnu noslodze gadā būtiski ietekmē efektīvās darba stundas vidējās izmaksas. Standarta tehnikas izmantošana ļauj palielināt tās izmantošanas efektivitāti un samazināt tehnikas pārvietošanas izmaksas, veicot mežizstrādi arī starpcirtēs un galvenajā cirtē nelielu dimensiju koku audzēs. Tā kā enerģētiskās koksnes gatavošanā izmanto galvenokārt mazu dimensiju kokus, lai mežizstrādes tehnoloģisko procesu padarītu efektīvāku, ekonomiski pamatotāks ir šķeldu piegādes scenārijs.

ABSTRACT

The aim of the thesis is to investigate, which factors have impact on productivity and costs of biofuel production, to evaluate wood resources in forest stands, where thinning has been delayed, and to elaborate proposals for mechanization of thinnings.

The following research tasks of the doctoral thesis were set:

1) To examine the available wood resources of young stands, where thinning has been delayed, and the technologically available wood biofuel resources in Latvia.
2) To investigate, which factors affect productivity of forest operations and prime cost of wood biofuel production in thinning implemented either mechanically or using a hand-held chainsaw.
3) To evaluate the impact of different mechanization solutions on the profitability of wood biofuel production.

The following research hypothesis has been proposed in the doctoral thesis: in forest stands, where thinning of young stands has been delayed, mechanized biofuel production is feasible.

According to the data of the 3rd cycle of the National Forest Inventory (2014–2019), forest stands with an average tree height of 9–12 m occupy 7% of the total forest area in Latvia. This type of resource has little economic importance, but mechanized thinning in poorly managed forest stands can contribute to the increase of the value of forest stands in the future. In mechanized thinning, the highest productivity can be achieved by using the most common logging solution in thinning in Latvia – medium-sized harvester equipped with a standard felling head (John Deere 1070 E with H 754 felling head). Due to better productivity the average energy wood preparation cost for a medium-sized harvester is 15% lower than for a small-sized (Rottne H8 with EGS 405 felling head). The annual work load of harvester significantly affects the average cost of a productive hour. The use of standard equipment allows to increase the efficiency of the harvesters' use, reduce the costs of relocation of machines and increase diversity of economic activities. Wood biofuel is mainly supplied to the final consumer using a wood chips supply scenario, which has been recognized in the study as an economically viable solution in wood biofuel targeted thinning.

SATURS / *CONTENTS*

1. DARBA VISPĀRĪGS RAKSTUROJUMS

1.1. Tēmas aktualitāte

Jau vēsturiski īpašnieki apsaimniekojuši mežu tā, lai nodrošinātu ilgtspējīgu resursu pieejamību un iegūtu saimnieciski nozīmīgākos meža produktus – apaļos kokmateriālus. Augošais pieprasījums pēc koksnes produktiem liek meklēt aizvien jaunus, zinātniski un praktiski pamatotus risinājumus mežsaimniecības prakses pilnveidošanai un koksnes piegāžu uzlabošanai. Enerģētiskā koksne ir viens no atjaunojamo energoresursu (AER) veidiem Latvijā, kam joprojām ir vislielākais izmantošanas pieauguma potenciāls. Izmaiņas koksnes izmantošanas pieejā varētu sekmēt Latvijas enerģētikas attīstību, sasniedzot Latvijas ilgtspējīgas attīstības stratēģijā līdz 2030. gadam izvirzītos mērķus, kas saistīti ar enerģijas, kas saražota, izmantojot AER, īpatsvara palielinājumu līdz 40% no bruto enerģijas galapatēriņa. Līdzšinējie pētījumi parāda, ka vislielākie starpcirtēs teorētiski iegūstamie neizmantotie enerģētiskās koksnes krājumi atrodami audzēs, kuru vecums ir no 21 līdz 30 gadiem. Tā kā šo resursu izmantošanā iespējami dažādi tehniskie un tehnoloģiskie risinājumi, pirms ražošanas uzsākšanas svarīgi izvērtēt ne vien teorētisko, bet arī tehnoloģisko un ekonomisko resursu pieejamību. Starpciršu, kas saistīta galvenokārt ar enerģētiskās koksnes ieguvi, mašinizāciju kavē ekonomiskie faktori. Līdzšinējie pētījumi Ziemeļvalstīs pierādījuši, ka līdzīga izmēra un jaudas mežizstrādes mašīnu ražīguma rādītāji, kas sasniegti, strādājot līdzīgos apstākļos, būtiski neatšķiras, kas ļauj domāt, ka mašinizētās starpcirtēs enerģētiskās koksnes ražošanā iespējams izmantot vidējās klases mežizstrādes mašīnas, ko Latvijā šobrīd plaši izmanto galvenās cirtes cirsmu izstrādē. Pētījuma aktualitāti nosaka tas, ka joprojām ir neatbildēts jautājums par piemērotāko tehnisko un tehnoloģisko risinājumu enerģētiskās koksnes ieguvē mašinizētā starpcirtē, izvērtējot mašīnu ražīgumu ietekmējošos faktorus, kā arī vērtējot mašinizētu starpciršu ekonomisko izdevīgumu.

1.2. Promocijas darba mērķis, uzdevumi un tēze

Promocijas darba mērķis ir izpētīt enerģētiskās koksnes sagatavošanas ražīgumu un ražošanas izmaksas ietekmējošos faktorus, kā arī novērtēt koksnes resursus mežaudzēs, kurās nav savlaicīgi veikta jaunaudžu kopšanas cirte.

Promocijas darbā izvirzītā mērķa sasniegšanai un izvirzītās tēzes pārbaudei noteikti sekojoši pētnieciskie uzdevumi:

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1.3. Darba zinātniskā novitāte un praktiskā nozīme

Kaut arī enerģētiskā koksne, kas iegūstama, veicot mašinizētas starpcirtes, ir viens no atjaunojamo energoresursu veidiem Latvijā, kura izmantošanai joprojām ir potenciāls, ražošanas izmaksas ir salīdzinoši lielas un kavē resursa izmantošanu. Lai efektīvi apgūtu resursu, nepieciešams rast piemērotāko tehnoloģisko un ekonomiski pamatotāko risinājumu. Latvijā šobrīd cirsmu darbu izmaksu kalkulācijā netiek izmantots vienots izmaksu aprēķinu modelis. Parasti ražošanas izmaksu aprēķinus veic katrs pakalpojumu sniedzējs katrai mežizstrādes tehnoloģiskā procesa fāzei.

Pētījumā iegūtie rezultāti sniedz ieskatu mašinizētu starpciršu tehnoloģiskajos risinājumos un darba metodēs meža platībās, kurās galvenokārt iegūst tikai enerģētisko koksni. Izmaksu aprēķina modelis, kas pētījuma ietvaros papildināts un pielāgots izmaksu aprēķināšanai cirsmu darbos, sniedz iespēju veikt enerģētiskās koksnes ražošanas ekonomisko izvērtējumu, kā arī ļauj aprēķināt mežizstrādes tehnoloģiskā procesa kopējās izmaksas.

Pētījumi šajā virzienā sniedz plašāku priekšstatu par to, kādi faktori jāizvērtē rūpīgāk un kam jāpievērš lielāka uzmanība, lai enerģētiskās koksnes ieguvi mašinizētā starpcirtē padarītu vēl efektīvāku gan no mežsaimnieciskā, gan ekonomiskā viedokļa. Izmantojot promocijas darbā iekļauto ražošanas izmaksu aprēķina modeli, aprēķinātie lielumi ir salīdzināmi un vērtējami katrā izmaksu pozīcijā, kas sniedz iespēju identificēt pozīcijas, kuras, mainot vai pielāgojot tehnoloģiju, būtu iespējams samazināt.

1.4. Zinātniskā darba aprobācija

Pētījuma rezultāti apkopoti sešās publikācijās starptautiskos un vietējos zinātnisko rakstu krājumos.

1. **Kaleja, S.**, Lazdins, A., Zimelis, A. (2019). Comparison of costs in pre-commercial thinning using medium-sized and small-sized harvesters. Proceedings of the 9th International Scientific Conference “Rural Development 2019”, 253–259. 10.15544/RD.2019.055
2. **Kalēja, S.**, Lazdiņš, A., Zimelis, A., Spalva, G. (2017). Model for cost calculation and sensitivity analysis of forest operations. Agronomy Research, 16(5), 2068–2078. 10.15159/AR.18.207
3. Prindulis, U., **Kaleja, S.,** Lazdins, A. (2016). Soil compaction in young stands during mechanized logging of biofuel and roundwood assortments. Research for Rural Development. International Scientific Conference Proceedings, 2, 69–76. Pieejams:

http://www2.llu.lv/research_conf/proceedings2016_vol_2/docs/LatviaResRuralDev_22nd_vol2-69-76.pdf

4. **Kaleja, S.,** Lazdins, A., Zimelis, A. (2014). Impact of assortments structure on harvesting productivity and costs of pre-commercial thinning. Research for Rural Development. International Scientific Conference Proceedings, 2, 83–89. Pieejams: http://www2.llu.lv/research_conf/Proceedings/20th_volume2.pdf
5. **Kalēja, S**., Grīnfelds, A., Lazdiņš, A. (2013). Economic value of wood chips prepared from young stand tending. Research for Rural Development. Annual 19th International Scientific Conference Proceedings, 2, 66–72. Pieejams: http://www2.llu.lv/research_conf/Proceedings/19th_volume2.pdf
6. Lazdiņš, A., **Kalēja, S.**, Gruduls, K., Bārdulis, A. (2013). Theoretical evaluation of wood for bioenergy resources in pre-commercial thinning in Latvia. Research for Rural Development. Annual 19th International Scientific Conference Proceedings, 2. 42–48. Pieejams: http://www2.llu.lv/research_conf/Proceedings/19th_volume2.pdf

Pētījuma rezultāti prezentēti septiņās starptautiskās un vietējās nozīmes zinātniskajās konferencēs.

1. 9th International Scientific Conference “Rural Development 2019: Research and Innovation for Bioeconomy”, 26.–28.09.2019., Kauņa, Lietuva. Prezentācija – **Kalēja, S.**, Lazdiņš, A., Zimelis, A. Comparison of costs in pre-commercial thinning using medium-sized and small-sized harvesters.
2. Biosystems Engineering 2018, 09.–11.05.2018., Tartu, Igaunija. Stenda referāts – **Kalēja, S.**, Lazdiņš, A., Zimelis, A., Spalva, G. The model for calculation of forest operations cost and sensitivity analysis.
3. Annual 24th International Scientific Conference “Research for Rural Development 2018”, 16.–18.05.2018., Jelgava, Latvija. Prezentācija – Zimelis, A., **Kalēja, S.**, Luguza, S. Factors affecting productivity of machined logging in thinning small sized forest machine.
4. Nordic Baltic Conference OSCAR14, 25.–27.06.2014., Knivsta, Zviedrija. Prezentācija – **Kalēja, S.**, Lazdiņš, A. Assessment of used work methods and environmental impact to young stand tending with timber harvarder.
5. Nordic Baltic Conference OSCAR14, 25.–27.06.2014., Knivsta, Zviedrija. Prezentācija – Lazdiņš, A., **Kalēja, S.**, Zimelis, A. Results of evaluation of Bracke C16.b working methods in coniferous and mixed stands.
6. Annual 20th International Scientific Conference “Research for Rural Development 2014”, 21.–23.05.2014., Jelgava, Latvija. Prezentācija – **Kalēja, S.**, Lazdiņš, A., Zimelis, A. Impact of assortments structure on harvesting productivity and costs of pre-commercial thinning.
7. Annual 19th International Scientific Conference “Research for Rural Development 2013”, 15.–17.05.2013., Jelgava, Latvija. Prezentācija – **Kalēja, S.**, Grīnfelds, A., Lazdiņš, A. Economic value of wood chips prepared from young stand tending.

1.5. Promocijas darba struktūra un apjoms

Promocijas darba struktūra veidota saskaņā ar darbā izvirzītajiem pētnieciskajiem uzdevumiem. Darbu veido trīs nodaļas, no kurām pirmajā – atspoguļots problēmas izzinātības apraksts citu autoru veiktajos pētījumos un gūtās atziņas; sniegts ieskats enerģētiskās koksnes resursu pieejamībā Latvijā un iespējām šos resursus izmantot; apskatīta mežizstrādes darbu organizācijas un izmantoto tehnoloģiju vēsture, kā arī mašinizētas mežizstrādes iespējas mūsdienās; raksturoti līdzšinējie sasniegumi, veicot mašinizētas starpcirtes, kā arī apzināti mašinizētas mežizstrādes ražīgumu ietekmējošie faktori; apskatīta enerģētiskās koksnes loma atjaunojamo energoresursu kontekstā un šī resursa nozīme tautsaimniecībā. Otrajā nodaļā aprakstīta enerģētiskās koksnes teorētiski, tehniski un tehnoloģiski pieejamo resursu noteikšanas metodika; raksturoti pētījuma objekti, kā arī parauglaukumu ierīkošana un datu ievākšanas metodika tajos; sniegts mašinizētā starpcirtē izmantoto mežizstrādes mašīnu apraksts, izvēlēto darba metožu un apstākļu raksturojums, kā arī izmēģinājumu laikā iegūto datu apkopošanas un analīzes metodes; raksturots enerģētiskās koksnes ražošanas izmaksu aprēķinu modelis, kas pētījuma ietvaros pielāgots mežizstrādes tehnoloģiskajiem procesiem Latvijā. Trešajā nodaļā veikts enerģētiskās koksnes resursu novērtējums; izvērtēti ražīguma rādītāji, kas iegūti mašinizētā starpcirtē, un apzināti faktori, kas to būtiski ietekmē; veikts enerģētiskās koksnes ražošanas izmaksu izvērtējums.

Promocijas darba apjoms ir 72 lappuses; informācija apkopota 23 tabulās un 24 attēlos, izmantoti 95 literatūras avoti, darba noslēgumā formulēti 7 secinājumi un pievienoti 9 pielikumi.

2. MATERIĀLS UN METODES

2.1. Enerģētiskās koksnes resursu pieejamības noteikšana

Resursu teorētiskās, tehniskās un tehnoloģiskās pieejamības izvērtējumā izmantoti Meža statistiskās inventarizācijas (MSI) 3. cikla (2014–2019) dati, kas iegūti meža platībās ar 9–12 m augstiem kokiem. Apstrādei un aprēķiniem atlasīti rādītāji, kas iegūti meža zemēs un ar mežu klātās lauksaimniecības zemēs izvietotos parauglaukumos.

Šajā pētījumā ar teorētiski pieejamajiem enerģētiskās koksnes resursiem saprot resursus, kas pieejami mežaudzēs, kurās koku skaits vai šķērslaukums pēc plānoto tehnoloģisko koridoru ierīkošanas nesamazinās zem minimālā koku skaita vai šķērslaukuma. Teorētiski resursi pieejami arī aizsargājamās dabas teritorijās.

No teorētiski pieejamajiem resursiem aprēķinot tehniski pieejamos resursus, tālākos aprēķinos nav iekļautas mežu platības, kurās, vadoties pēc meža tipa, resursu iegūšana starpcirtē nav ieteicama: sils (*Cladinoso-callunosa*), viršu kūdrenis (*Callunosa turf. mel.*) un viršu ārenis (*Callunosa mel.*), kā arī koksnes ieguvi parasti neveic vai arī enerģētiskās koksnes savākšanu no koksnes ieguves tehnoloģiskā viedokļa grūti realizēt: purvaiņi, grīnis (*Cladinoso-sphagnosa*), slapjais mētrājs (*Vaccinioso-sphagnosa*). Tāpat no aprēķina izslēgtas aizsargājamas dabas teritorijas (Lazdiņš et al., 2012).

Tehnoloģiski pieejamo resursu aprēķinā izmantoti tehniski pieejamie resursi, atņemot ražošanas zudumus (30% ciršanas atliekām un 5% malkai; Adamovičs et al., 2009), kā arī atsevišķi izdalīti resursi, kas iegūstami ziemas periodā (Lazdiņš et al., 2012).

2.2. Pētījuma objektu apraksts

Saskaņā ar pētījuma mērķi un izvirzītajiem darba uzdevumiem, empīriskā materiāla ievākšanai izvēlētas 10 mežaudzes valsts mežos ar kopējo platību 27.8 ha. Izmēģinājuma objekti koncentrēti Latvijas centrālajā daļā (Vidusdaugavas reģionā). Par audžu atlases kritērijiem noteikti valdaudzes vidējā koka augstums (9–12 m) un audzes biezums (koku skaits ≥2000 gab. ha^{-1}). Izmēģinājumiem par piemērotām atlasītas 3 lapkoku audzes – kārpainais bērzs (*Betula pendula* Roth) – un 7 skujkoku audzes – parastā egle (*Picea abies* (L.) H. Karst.) un parastā priede (*Pinus sylvestris* L.).

Empīriskais materiāls pētījuma veikšanai ievākts no 2013. līdz 2014. gadam.

Visas atlasītās audzes izzāģētas līdz minimālajam koku skaitam vai šķērslaukumam, veicot “apakšējo kopšanu”, kas paredz sākotnēji nozāģēt mazāko dimensiju un neperspektīvos kokus.

Tehnoloģiskie koridori ierīkoti 15, 18, 20 vai 30 m attālumā viens no otra. Atkarībā no mežizstrādes mašīnas gabarītiem un izlices snieguma, atsevišķās audzēs izzāģētas 1 vai 2 “slēptās brauktuves”, kas paredzētas, lai mežizstrādes mašīna pārvietotos pa neizstrādāto joslas daļu starp tehnoloģiskajiem koridoriem.

2.3. Pētījumā izmantotās meža tehnikas apraksts

Pētījuma ietvaros mašinizētas starpcirtes veiktas, izmantojot 3 dažādas mežizstrādes mašīnas, kuru darba galvas papildus aprīkotas ar stumbru uzkrāšanas mehānismiem.

Ar vidējās klases mežizstrādes mašīnu John Deere 1070 E (pašmasa 15.5 t, dzinēja jauda 136 kW pie 1900 apgriezieniem min.$^{-1}$), kas aprīkota ar H 754 darba galvu (masa 820 kg, maksimālais apstrādājamā stumbra caurmērs 55 cm, griezējmehānisms – ķēdes tipa zāģis, 5 kustīgie naži, 1 fiksētais nazis, 4 padeves veltņi, maksimālā strēles izlice 10 m), pētījuma ietvaros iegūti darba laika uzskaites dati par 127 darba stundām.

Ar vidējās klases mežizstrādes mašīnu John Deere 1070 D (pašmasa 14.1 t, dzinēja jauda 136 kW pie 1900 apgriezieniem min.$^{-1}$), kas aprīkota ar Bracke C16.b darba galvu (masa 570 kg, maksimālais apstrādājamā stumbra caurmērs 26 cm, griezējmehānisms – uz diska montēta zāģa ķēde, maksimālā strēles izlice 10 m), pētījuma ietvaros iegūti darba laika uzskaites dati par 66 darba stundām.

Ar mazās klases mežizstrādes mašīnu Rottne H8 (pašmasa 10.2 t, dzinēja jauda 125 kW pie 2000 apgriezieniem min.$^{-1}$), kas aprīkota ar EGS 406 darba galvu (masa 480 kg, maksimālais apstrādājamā stumbra caurmērs 33 cm, griezējmehānisms – ķēdes tipa zāģis, 2 kustīgie naži, 2 padeves veltņi, maksimālā strēles izlice 7 m), pētījuma ietvaros iegūti darba laika uzskaites dati par 262 darba stundām.

2.4. Pētījumā izmantoto darba metožu apraksts

Izmēģinājumos izmantotas 2 darba metodes. Abas metodes paredz atstāt pameža kokus, ja vien tie netraucē mežizstrādes procesu. Tāpat, neatkarīgi no izvēlētās metodes, zāģējot kokus, kas nav paredzēti standarta apaļo kokmateriālu gatavošanai, maksimāli izmanto stumbru uzkrāšanas ierīci. Ar jēdzienu “daļēji atzarota sīkkoksne” saprot enerģētisko koksni (ne garāku par 6 m), kas gatavota no neatzarotām galotnēm, mežizstrādes atliekām un pameža kokiem, kuru krūšaugstuma caurmērs ($D_{1.3}$) < 6 cm.

Pirmā no izmantotajām darba metodēm paredz gatavot visus apaļos kokmateriālus atbilstoši AS “Latvijas valsts meži” produktu grupām, kā arī daļēji atzarotas sīkkoksnes sortimentu (garums 2.5–3 m, minimālais tievgaļa caurmērs 3 cm).

Otrā darba metode paredz no visiem nozāģētajiem kokiem, izņemot pameža kokus, kuru $D_{1.3}$ < 4 cm, gatavot daļēji atzarotu enerģētisko koksni.

2.5. Mašinizētas starpcirtes darba laika uzskaite un ražīguma rādītāju aprēķināšana

Starpcirtes darba laika izlietojuma izpētei izmantota hronometrāžas metode, kas ir tiešā laika izlietojuma fiksēšanas metode un paredzēta darba procesa pamatelementu ilguma un secības fiksācijai pie to cikliskas atkārtošanās. Darba elementu ilguma noteikšanai veikta nepārtraukta hronometrāža, kas piemērota darba operācijas elementu, kuru ilgums nav mazāks par 10 sekundēm, izpētei (Bludiņš & Rudze, 1979). Hronometrāžas laikā mežizstrādes mašīnu darba laiks pielāgots motorstundu uzskaitei, dzinēja noslāpēšanas brīdī apturot hronometrāžu un atsākot to, tiklīdz dzinējs atkal iedarbināts.

Darba laika patēriņš noteikts katram darba ciklam atsevišķi, fiksējot cikla numuru. Veicot darba laika uzskaiti, papildus lauka datorā aizpildīti informatīvie lauki, kas sniedz ziņas par nozāģētā koka vidējo caurmēru zāģējuma vietā (D_0), izmantojot Rottne H8, vai krūšaugstuma caurmēru ($D_{1.3}$), izmantojot John Deere mežizstrādes mašīnu. Tāpat aizpildīti informatīvie lauki par vienā darba ciklā apstrādāto koku skaitu, veiktas atzīmes par pārtraukumiem darbā, mašīnas veiktajiem pārbraucieniem uz citu tehnoloģisko koridoru, kā arī identificēts operators, kurš veicis mežizstrādi.

Ražīguma rādītāji aprēķināti no darba laika uzskaites datiem iedalījumā pa cirsmām, tehnikas vienībām, darba metodēm un operatoriem.

Mežizstrādes mašīnu darba dienas (maiņas) laika izlietojums jeb kopējais darba laiks ietver visu pētījuma ietvaros uzskaitīto darba laiku, kad mašīnas dzinējs darbojies. Efektīvais darba laiks veidojas, no kopējā darba laika atņemot neefektīvo darba laiku, ko attiecīgi veido remontam (pie nosacījuma, ka darba laika uzskaites brīdī mežizstrādes mašīnas dzinējs turpina darboties) un ar tiešo darbu nesaistītām darbībām patērētais laiks.

2.6. Enerģētiskās koksnes ražošanas izmaksu aprēķināšana

Izmaksu aprēķināšanai izmantots COST projekta FP0902 aktivitātes ietvaros (Ackerman et al., 2014) izstrādāts modelis, kas šī pētījuma ietvaros papildināts ar standarta ekonomiskajām metodēm un pielāgots izmaksu aprēķināšanai cirsmu darbos, kā arī sagatavoto materiālu izvešanai, aptverot visu mežizstrādes tehnoloģisko procesu (Kalēja et al., 2018a).

Kalkulācijas modelī izmaksas sadalītas pa to veidiem jeb izmaksu posteņiem uz produkta vai pakalpojuma vienību (Alsiņa et al., 2011). Ražošanas izmaksu aprēķinā iekļautas gan tiešās ražošanas izmaksas, kas ir tieši saistītas ar konkrētu izmaksu objektu radīšanu, izmaksu procesu un aktivitāti, gan vispārējās jeb netiešās izmaksas, kas nav tieši saistītas ar konkrētās produkcijas ražošanu, bet ir nosacīti saistītas ar ražošanas procesu un tiek ieskaitītas ražošanas pašizmaksā, izmantojot pieskaitījuma likmi (Vītola & Soopa, 2002; Alsiņa et al., 2011). Netiešo izmaksu noteikšana un sadalīšana pa kalkulāciju objektiem veikta atbilstoši saražotās produkcijas apjomam vai laika periodam.

Ražošanas izmaksu kalkulācijā izmantoti empīriskie dati, kas iegūti ilglaicīgos novērojumos (tehnikas pakalpojumu sniedzēju un servisa kompāniju sniegtā informācija par tehnikas uzturēšanas izmaksām), un publicēti dati, kas ietver tehnikas izmaksu analīzi. Izmaksu posteņus veido ieguldījumu izmaksas, personāla izmaksas un operacionālās jeb uzturēšanas izmaksas (Brinker et al., 2002; Alsiņa et al., 2011; Ackerman et al., 2014).

Lai iespējami precīzāk aprēķinātu mežizstrādes tehnoloģiskā procesa izmaksas un izmaksu modelis būtu piemērots dažādiem apstākļiem, aprēķinos izmantoti tādi specifiski rādītāji, kā mašīnu ražīgums un to ietekmējošie faktori – vidējā nozāģētā koka caurmērs, nozāģēto koku skaits, vidējās kravas lielums, tehnikas pārbraucienu skaits gadā, vidējais izvešanas ceļa garums, vidējais pārvietošanās ātrums.

Kubikmetra (m^3) pārrēķiniem berkubikmetros (ber. m^3) izmanto koeficientu 2.5. Kravas lielums iegūts, veicot kravu svērumus, vai arī aprēķināts, par pamatu ņemot sagatavoto kokmateriālu dimensijas.

Ražošanas izmaksu aprēķina modelis paredzēts stundu (efektīvās stundas, motorstundas un plānotās darba stundas) un vienības izmaksu aprēķināšanai katrai no mežizstrādes tehnoloģiskā procesa fāzēm vai mežizstrādes tehnoloģiskajam procesam kopumā.

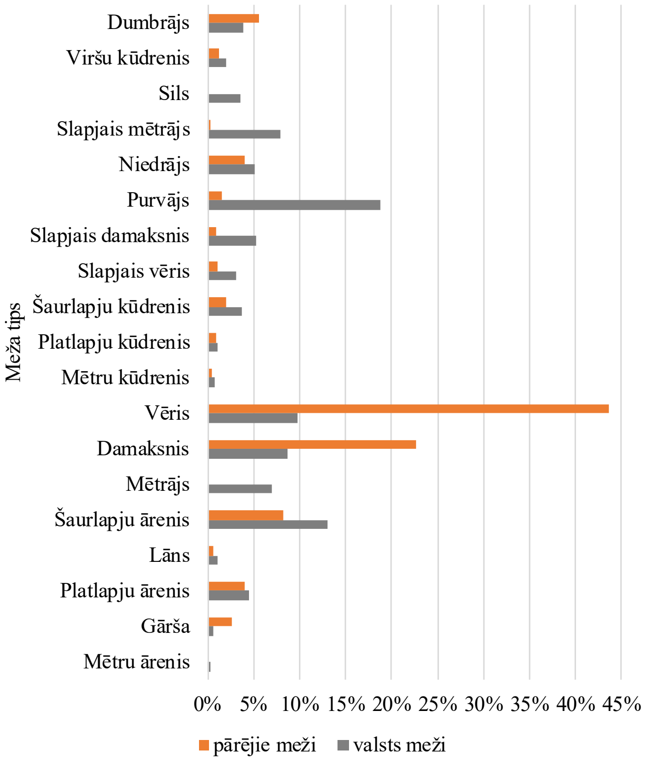
3. REZULTĀTI UN TO ANALĪZE

3.1. Starpcirtēs pieejamie resursi un to izvērtējums

Saskaņā ar MSI 3. cikla (2014–2019) datiem meža platības, kuru valdaudzes koku augstums ir 9–12 m, aizņem 7% (234 tūkst. ha ar kopējo stumbru krāju 15 524 tūkst. m^3) no kopējām meža platībām valstī. Lielākā daļa jeb 63% (149 tūkst. ha) šādu mežaudžu atrodas pārējo īpašnieku mežos.

Aprēķini parāda, ka starpcirtē teorētiski pieejamie enerģētiskās koksnes resursi, kas koncentrēti meža platībās, kurās koku skaits vai šķērslaukums pēc plānoto tehnoloģisko koridoru ierīkošanas nesamazinās zem minimālā koku skaita vai šķērslaukuma, veido 7054 tūkst. m^3 stumbru koksnes (4091 tūkst. t$_{sausnas}$ virszemes biomasas, no kuras valsts mežos atrodas vien 27% (1927 tūkst. m^3 stumbru koksnes vai 1109 tūkst. t$_{sausnas}$ virszemes biomasas), bet pārējos mežos teorētiski pieejami 5127 tūkst. m^3 stumbru koksnes vai 2982 tūkst. t$_{sausnas}$ virszemes biomasas.

Kopējais teorētiskais koku virszemes biomasas apjoma sadalījums pa meža tipiem (saskaņā ar MSI 3. cikla datiem) attēlots 3.1. attēlā. Lielākā daļa (59%) no kopējiem teorētiski pieejamajiem koku virszemes biomasas resursiem atrodas sausieņos. Valsts mežos sausieņos atrodas 30% no kopējiem resursiem, bet pārējās meža platībās – 69%. Silā (*Cladinoso-callunosa*), kur atrodas 4% no valsts mežos teorētiski pieejamajiem enerģētiskās koksnes resursiem, to ieguve starpcirtēs nav ieteicama, ierobežojot organisko vielu iznesi no meža (Skudra & Dreimanis, 1993). Meža platībās, kas nav valsts meži, silā (*Cladinoso-callunosa*) un mētrājā (*Vacciniosa*) nav pieejami resursi, kas būtu izmantojami enerģētiskās koksnes ražošanai. No augsnes nestspējas viedokļa sausieņi ir piemēroti mašinizētai mežizstrādei neatkarīgi no gadalaika (Saliņš & Rasnacis, 1985; Saliņš, 1987; Zālītis & Jansons, 2013; Liepa et al., 2014). Purvaiņos atrodas 16% no kopējiem resursiem, attiecīgi 28% no enerģētiskās koksnes resursiem atrodas valsts mežos, bet 11% – pārējo īpašnieku mežos. Liekņā (*Filipendulosa*) nav teorētiski pieejamo resursu enerģētiskās koksnes ražošanai. Kaut gan purvaiņu meža tipos koncentrēto resursu īpatsvars ir salīdzinoši liels, apstākļi nav piemēroti mašinizētai starpcirtei augstā gruntsūdens līmeņa dēļ (Saliņš, 1987; Liepa et al., 2014). Āreņos enerģētiskās koksnes resursi veido 14% no kopējiem teorētiski pieejamajiem resursiem, attiecīgi 18% (valsts mežos) un 12% (pārējos mežos). Viršu ārenī (*Callunosa mel.*) nav sastopamas meža platības ar 9–12 m augstiem kokiem, kurās teorētiski varētu iegūt enerģētiskās koksnes resursus, savukārt mētru ārenī (*Vacciniosa mel.*) resursi pieejami vien valsts mežu platībās. No augsnes nestspējas viedokļa, mašinizētu starpcirti var veikt gan vasarā, gan ziemā (Saliņš et al., 1987; Liepa et al., 2014). Slapjaiņos koncentrētie teorētiskie enerģētiskās koksnes resursi (veido 6% no kopējiem) atrodas 16% valsts mežos un 2% pārējās meža platībās. Grīnī (*Cladinoso-sphagnosa*) un slapjajā gāršā (*Dryopteriosa*) nav pieejami teorētiski iegūstamie enerģētiskās koksnes resursi.



3.1. att. **Starpcirtē teorētiski pieejamās virszemes biomasas sadalījums pa meža tipiem platībās ar 9–12 m augstiem kokiem**

No augsnes nestspējas viedokļa mašinizēta starpcirte šajos mežos iespējama visos gadalaikos (Saliņš & Rasnacis, 1985; Saliņš, 1987; Liepa et al., 2014), tomēr mežus būtiski var ietekmēt klimatisko apstākļu izmaiņas, tādējādi enerģētiskās koksnes savākšanu padarot tehnoloģiski sarežģītu. Kūdreņos atrodas salīdzinoši maz (5%) no kopējā teorētiski pieejamā resursu potenciāla (8% valsts un 5% pārējo īpašnieku mežos). Viršu kūdrenis (*Callunosa turf. mel.*), kurā atrodas 1% no kopējiem teorētiski pieejamajiem resursiem, nav piemērots enerģētiskās koksnes ieguvei. Kūdreņos mašinizēta starpcirte iespējama vien ziemā, sala periodā (Saliņš et al., 1987; Liepa et al., 2014).

Līdzšinējie pētījumi parāda, ka vidējā nocērtamā stumbra koksnes krāja meža platībās ar 9–12 m augstiem kokiem ir 30–50 m^3 (Lazdiņš et al., 2013). Saskaņā ar veiktajiem aprēķiniem, lielāka vidējā nocērtamā stumbru koksnes krāja (meža platībās izcērtot kokus līdz minimālajam koku skaitam vai šķērslaukumam) valsts mežos ir mazāka (20 $m^3\ ha^{-1}$) nekā pārējos mežos (30 $m^3\ ha^{-1}$). Lielākā nocērtamā stumbru koksnes krāja (31 $m^3\ ha^{-1}$) raksturīga purvaiņiem, valsts mežos tā ir 31 $m^3\ ha^{-1}$ un atkarībā no meža tipa variē no 20 $m^3\ ha^{-1}$ purvājā (*Sphagnosa*) līdz 42 $m^3\ ha^{-1}$ dumbrājā (*Dryopterioso-caricosa*). Pārējās purvaiņu meža platībās vidējā krāja ir 31 $m^3\ ha^{-1}$ jeb no vidēji 14 $m^3\ ha^{-1}$ purvājā (*Sphagnosa*) līdz 43 $m^3\ ha^{-1}$ niedrājā (*Caricoso-phragmitosa*). Tāpat salīdzinoši liela vidējā nocērtamā stumbru koksnes krāja (26 m^3 ha^{-1}) raksturīga sausieņiem. Valsts mežos tā ir 17 m^3 ha^{-1} jeb no vidēji 9 m^3 ha^{-1} gāršā (*Aegopodiosa*) līdz 30 m^3 ha^{-1} silā (*Cladinoso-callunosa*). Savukārt pārējās sausieņu meža platībās vidējā nocērtamā krāja ir 31 m^3 ha^{-1} jeb no vidēji 25 m^3 ha^{-1} lānā (*Myrtillosa*) līdz 35 m^3 ha^{-1} vērī (*Oxalidosa*). Slapjaiņos vidējā nocērtamā stumbru koksnes krāja ir 20 m^3 ha^{-1}, valsts mežos tie ir vidēji 18 m^3 ha^{-1} jeb no vidēji 8 m^3 ha^{-1} slapjajā gāršā (*Dryopteriosa*) līdz 30 m^3 ha^{-1} slapjajā mētrājā (*Vaccinioso-sphagnosa*). Pārējos mežos slapjaiņos vidējā nocērtamā stumbru koksnes krāja ir 29 m^3 ha^{-1}, no vidēji 13 m^3 ha^{-1} slapjajā vērī (*Myrtillosa-polytrichosa*) līdz 50 m^3 ha^{-1} slapjajā gāršā (*Dryopteriosa*). Āreņos vidējā nocērtamā stumbru koksnes krāja ir 19 m^3 ha^{-1}. Valsts mežos āreņos tie ir vidēji 20 m^3 ha^{-1} jeb no vidēji 8 m^3 ha^{-1} mētru ārenī (*Vacciniosa mel.*) līdz 28 m^3 ha^{-1} platlapju ārenī (*Mercurialiosa mel.*). Pārējos mežos āreņos vidējā nocērtamā krāja ir 25 m^3 ha^{-1}, no vidēji 22 m^3 ha^{-1} šaurlapju ārenī (*Myrtillosa mel.*) līdz 28 m^3 ha^{-1} platlapju ārenī (*Callunosa mel.*). Saskaņā ar veiktajiem aprēķiniem vismazākā vidējā nocērtamā stumbru koksnes krāja (16 m^3 ha^{-1}) ir kūdreņos. Valsts mežos kūdreņos tie ir 19 m^3 ha^{-1}, no 8 m^3 ha^{-1} mētru kūdrenī (*Vacciniosa turf. mel.*) līdz 26 m^3 ha^{-1} platlapju kūdrenī (*Oxalidosa turf. mel.*). Pārējos kūdreņu mežos nocērtamā vidējā krāja ir 20 m^3 ha^{-1} jeb no 7 m^3 ha^{-1} platlapju kūdrenī (*Oxalidosa turf. mel.*) līdz 50 m^3 ha^{-1} mētru kūdrenī (*Vacciniosa turf. mel.*).

Analizējot teorētiski pieejamos stumbra koksnes krājas resursus meža platībās ar 9–12 m augstiem kokiem, atkarībā no valdošās koku sugas, jāsecina, ka valsts mežos lielākā daļa (69%) resursu atrodas skuju koku audzēs – 45% priežu, 24% egļu audzēs. Lapu koku audzēs atrodas 31% no resursiem. Pārējos mežos teorētiski pieejamie nocērtamās stumbra koksnes resursi koncentrēti lapu koku audzēs (87%), visvairāk meža platībās, kur valdošā suga ir baltalksnis (38%). Skuju koku audzēs pārējos mežos atrodas 13% no teorētiski pieejamā resursu potenciāla.

Tehniski pieejamie enerģētiskās koksnes resursu izvērtējums parāda, ka meža platībās ar 9–12 m augstiem kokiem mašinizētā starpcirtē tehniski pieejami 757 tūkst. t ciršanas atlieku un 886 tūkst. m^3 malkas. Valsts mežos atrodas 20% no tehniski pieejamajiem resursiem, lielākā daļa resursu koncentrēta pārējos mežos (605 tūkst. t mežizstrādes atlieku un 715 tūkst. m^3 malkas).

Tehnoloģiski pieejamo resursu izvērtējums parāda, ka mašinizētā starpcirtē tehnoloģiski pieejami 530 tūkst. t ciršanas atlieku un 798 tūkst. m^3 malkas jeb kopā 4588 tūkst. MWh enerģētiskās koksnes, pārvēršot to primārajā enerģijā. Tikai 19% no tehnoloģiski pieejamajiem enerģētiskās koksnes resursiem koncentrēti valsts mežos. Lielākā daļa jeb 3686 tūkst. MWh tehnoloģiski pieejamās primārās enerģijas resursu koncentrēta pārējās meža platībās. 27% no kopējiem tehnoloģiski pieejamajiem resursiem iegūstami ziemā, un mazākā daļa (38%) no tikai ziemā iegūstamiem resursiem atrodas valsts meža platībās.

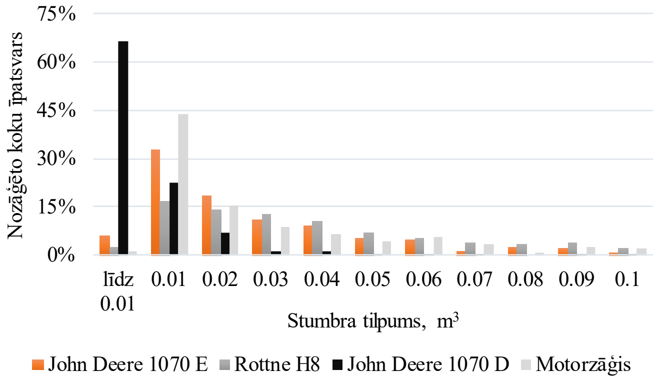
Pieņemot, ka šos resursus iegūst 5 gadu laikā, vidējais gada laikā iegūstamās primārās enerģijas daudzums ir 180 tūkst. MWh valstij piederošās un 737 tūkst. MWh pārējās meža platībās, neskaitot krājas pieaugumu enerģētiskās koksnes sagatavošanai piemērotajās platībās.

3.2. Mašinizētas starpcirtes ražīguma rādītāji

3.2.1. Sagatavoto kokmateriālu raksturojums

Mašinizētā starpcirtē, izmantojot John Deere 1070 E, nozāģēto koku īpatsvars, kuru stumbra tilpums nav lielāks par 0.1 m^3, veido 94%. Darbus veicot ar Rottne H8 un John Deere 1070 D, nozāģēto koku īpatsvars (stumbra tilpums nepārsniedz 0.1 m^3) ir 82.7% un 99.8% no kopējā nozāģēto koku skaita. Salīdzinot ar datiem, kas iegūti daļēji mehanizētos kopšanas darbos, izmantojot motorzāģi, secināts, ka audzēs, kuru vidējā koka augstums ir 9–12 m, arī lielākajai daļai jeb 94.4% nozāģēto koku stumbru, tilpums nav lielāks par 0.1 m^3 (3.2. att.). Šī atziņa atbilst iepriekš veiktos pētījumos secinātajam, ka audzēm, kurās kaut kādu iemeslu dēļ nav veikta sistemātiska kopšana, raksturīgs liels sīkkoksnes īpatsvars, kas negatīvi ietekmē mežizstrādes mašīnas ražīguma rādītājus (Lazdāns et al., 2006).

Starpcirtēs nozāģēto koku dimensiju un sagatavotā kokmateriālu apjomu raksturojošie rādītāji doti 3.1. tabulā. Ar mežizstrādes mašīnu John Deere 1070 E nozāģēti 16.7 tūkst. koku, sagatavojot 591 m^3 kokmateriālu, vidējā nozāģētā koka augstums bija 12.3 m, bet stumbra $D_{1.3}$ = 8.8 cm (vidējais stumbra tilpums 0.04 m^3). Ar mežizstrādes mašīnu Rottne H8 pētījuma ietvaros nozāģēti 17.9 tūkst. koku, sagatavojot 1089 m^3 kokmateriālu, vidējā nozāģētā koka augstums bija 11.4 m, bet stumbra $D_{1.3}$ = 10.2 cm (vidējais stumbra tilpums 0.07 m^3). Platībās, kurās izmantota mežizstrādes mašīna John Deere 1070 D, nozāģēti 13.4 tūkst. koku, sagatavojot 86 m^3 kokmateriālu, vidējā nozāģētā koka augstums bija 8.0 m, bet stumbra $D_{1.3}$ = 4.3 cm (vidējais stumbra tilpums 0.01 m^3). Starpcirtē, kas veikta ar John Deere 1070 D un Bracke C.16 darba galvu, nozāģēto koku skats ir salīdzinoši liels, tomēr sagatavotais kokmateriālu apjoms ir mazs. Situāciju varētu skaidrot ar to, ka salīdzinoši lielu īpatsvaru no nozāģētajiem kokiem (3.2. att.) veido pamežs un sīkkoki, kurus saskaņā ar darba uzdevumu nebija paredzēts zāģēt, ja vien tie



3.2. att. **Nozāģēto koku īpatsvara sadalījums pa stumbra tilpuma grupām** netraucē darbu izpildi. Tāpat darba uzdevumā bija paredzēts kokmateriālus gatavot no kokiem, kuru $D_{1.3} > 3$ cm. Starpcirtē nozāģēto koku dimensiju un sagatavoto kokmateriālu apjoma raksturojums dots 3.1. tabulā. Analizējot sagatavoto kokmateriālu apjomu sadalījumā pa stumbra tilpuma grupām, konstatēts, ka lielāko daļu (no 67.6% ar Rottne H8 līdz 95.3% ar John Deere 1070 D) kokmateriālu sagatavo, zāģējot kokus, kuru stumbra tilpums nepārsniedz 0.15 m^3. Līdzīga situācija novērota, izmantojot motorzāģi (Kalēja et al., 2015), kad 98.3% no sagatavotajiem kokmateriāliem iegūti, zāģējot kokus, kuru stumbru tilpums nepārsniedz 0.15 m^3.

3.1. tabula

Koku dimensiju un sagatavotā kokmateriālu apjoma raksturojums

Mežizstrādes mašīna	Audzes kods	Koku skaits, gab.	Vidējā nozāģētā koka caurmērs, cm	Vidējā nozāģētā koka augstums, m	Sagatavotais kokmateriālu apjoms, m^3	Vidējā nozāģētā stumbra tilpums, m^3
John Deere 1070 E	502-427-6	3706	8.2 ± 0.09	11.6 ± 0.09	102	0.03 ± 0.001
	502-434-1	5364	9.4 ± 0.07	12.9 ± 0.05	209	0.04 ± 0.001
	503-329-1	579	9.5 ± 0.19	12.7 ± 0.16	33	0.06 ± 0.003
	503-432-8	3203	7.7 ± 0.07	11.3 ± 0.07	83	0.03 ± 0.001
	503-479-12	3499	9.3 ± 0.07	12.8 ± 0.06	153	0.04 ± 0.001
	503-481-6	397	7.5 ± 0.19	11.1 ± 0.20	11	0.03 ± 0.002
Rottne H8	503-300-12	8228	10.0 ± 0.05	11.4 ± 0.02	488	0.06 ± 0.001
	503-317-7	3845	10.4 ± 0.07	11.5 ± 0.03	233	0.06 ± 0.001
	503-318-17	1022	11.3 ± 0.14	11.9 ± 0.06	73	0.07 ± 0.002
	503-318-30	3318	9.7 ± 0.08	11.2 ± 0.04	176	0.05 ± 0.001
	503-329-1	1474	11.3 ± 0.13	11.9 ± 0.05	119	0.08 ± 0.002
John Deere 1070 D	502-427-6	13 454	4.3 ± 0.05	8.0 ± 0.05	86	0.01 ± 0.0004

3.2.2. Mežizstrādes mašīnu vidējie ražīguma rādītāji

Kopumā mašinizētas starpcirtes darba laika uzskaite veikta 456 motorstundas.

Analizējot vidējos ražīguma rādītājus atšķirīgām mežizstrādes mašīnām, jāsecina, ka starpcirtē, izmantojot John Deere 1070 E, efektīvajā darba stundā apstrādāti 158 koki, sagatavojot vidēji 5.6 m^3 kokmateriālu. Vidējais sasniegtais ražīgums ir 5.8 m^3 (vidēja nozāģētā stumbra tilpums 0.03 m^3) efektīvajā darba stundā (neskaitot laiku, kas patērēts iebraukšanai audzē un izbraukšanai no tās). Vidējais efektīvais darba laiks no kopējā darba laika (maiņas ilguma) ir 83.5%, iebraukšanai un izbraukšanai no audzes tērējot 4.6% no efektīvā darba laika.

Strādājot ar mašīnu Rottne H8, vidēji efektīvajā stundā apstrādāts 81 koks, sagatavojot vidēji 5.0 m^3 kokmateriālu. Vidējais sasniegtais ražīgums ir 5.3 m^3 E_{15} h^{-1} (vidējā nozāģētā koka stumbra tilpums 0.06 m^3), neskaitot laiku, kas patērēts iebraukšanai audzē un izbraukšanai no tās. Vidējais efektīvais darba laiks no kopējā darba laika ir 83.7%, iebraukšanai un izbraukšanai no audzes tērējot 6.1% no efektīvā darba laika. Kā liecina rezultāti, efektīvā darba laika īpatsvars kopējā darba laikā raksturojams kā salīdzinoši liels un ir lielāks par līdzīgos pētījumos (Sirén, 2003) mašinizētās starpcirtēs uzrādīto (81.6%).

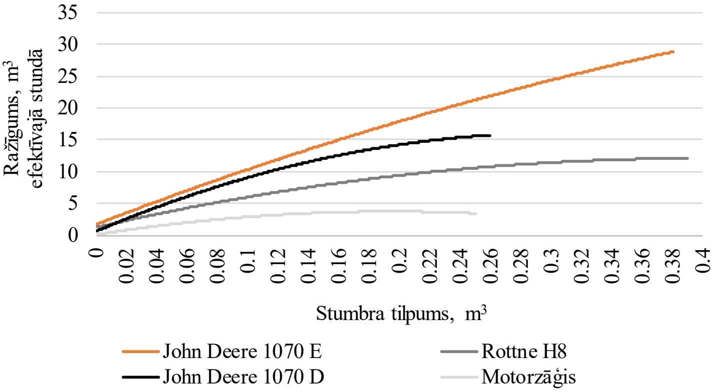
Ar meža mašīnu John Deere 1070 D vidēji efektīvajā stundā apstrādāts 271 koks, sagatavojot vidēji 1.7 m^3 kokmateriālu. Vidējais sasniegtais ražīgums ir 1.8 m^3 E_{15} h^{-1} (vidējā nozāģētā koka tilpums 0.01 m^3), neskaitot laiku, kas patērēts iebraukšanai audzē un izbraukšanai no tās. Vidējais efektīvais darba laiks no kopējā darba laika ir 75.2%, iebraukšanai un izbraukšanai no audzes patērēti 3.4% no efektīvā darba laika. Kaut arī efektīvajā darba stundā apstrādāto koku skaits ir salīdzinoši liels, ražīgumu būtiski ietekmēja nozāģēto koku dimensijas, kas atbilst līdzīgos pētījumos izdarītajiem secinājumiem (Sirén, 2003). Tāpat operatori pilnībā nav sekojuši metodiskajiem norādījumiem, zāģējot kokus, kuru $D_{1.3} < 3$ cm, arī tad, ja tie netraucē kokmateriālu novietošanai vai zāģēšanai (3.2. tab.).

3.2. tabula

Mežizstrādes mašīnām raksturīgu rādītāju kopsavilkums sadalījumā pa mežaudzēm

Mežizstrādes mašīna	Audzes kods	Nostrādātās motorstundas	Vidējais ražīgums, koki E_{15} h^{-1}	Efektīvais darba laiks no kopējā darba laika, %	Iebraukšana un izbraukšana, % E_{15}	Vidējais ražīgums, m^3 E_{15} h^{-1}	Vidējais ražīgums (neskaitot braukšanu), m^3 E_{15} h^{-1}
John Deere 1070 E	502-427-6	22.3	174 ± 4	95.6	3.0	4.8 ± 0.1	4.9 ± 0.1
	502-434-1	41.8	164 ± 3	78.4	3.7	6.4 ± 0.1	6.6 ± 0.1
	503-329-1	6.1	117 ± 5	80.3	6.7	6.6 ± 0.3	7.1 ± 0.3
	503-432-8	25.1	155 ± 4	82.7	5.2	4.0 ± 0.1	4.2 ± 0.1
	503-479-12	28.6	146 ± 3	83.6	5.9	6.4 ± 0.2	6.8 ± 0.2
	503-481-6	3.2	151 ± 5	81.4	8.8	4.3 ± 0.2	4.7 ± 0.2
Rottne H8	503-300-12	120.4	75 ± 3	91.3	7.4	4.4 ± 0.2	4.8 ± 0.2
	503-317-7	54.7	94 ± 2	75.1	6.0	5.7 ± 0.1	6.0 ± 0.1
	503-318-17	12.6	96 ± 2	84.5	2.5	6.9 ± 0.2	7.1 ± 0.2
	503-318-30	54.8	82 ± 3	74.2	3.6	4.3 ± 0.3	4.5 ± 0.2
	503-329-1	20.1	84 ± 2	86.7	6.0	6.8 ± 0.2	7.2 ± 0.1
John Deere 1070 D	502-427-6	66.1	271 ± 4	75.2	3.4	1.7 ± 0.1	1.8 ± 0.1

Salīdzinot vidējos ražīguma rādītājus atšķirīgām starpcirtē izmantotām mežizstrādes mašīnām, atkarībā no nozāģētā stumbra tilpuma (3.3. att.) konstatēts, ka vislabākie rezultāti sasniegti, darbus veicot ar John Deere 1070 E, kas aprīkots ar H 754 darba galvu, kam seko John Deere 1070 D ar Bracke C16.b darba galvu un Rottne H8, kas aprīkota ar EGS 405 darba galvu. Būtiskas atšķirības ($p < 0.05$) konstatētas, salīdzinot ražīguma rādītājus mežizstrādes mašīnām John Deere 1070 E un Rottne H8. Kaut arī promocijas darba ietvaros veiktajos izmēģinājumos kopšanas darbi, izmantojot motorzāģi, netika veikti, ražīguma rādītāju salīdzināšanai izmantoti dati, kas iegūti līdzīgos pētījumos (Kalēja et al., 2015). Kopumā ražīguma rādītāji, izmantojot motorzāģi, ir būtiski mazāki ($p < 0.05$ salīdzinājumā ar John Deere 1070 E; $p < 0.05$ salīdzinājumā ar John Deere 1070 D; $p < 0.05$ salīdzinājumā ar Rottne H8) nekā mašinizētas starpcirtes ražīguma rādītāji. Palielinoties nozāģētā stumbra tilpumam, palielinās ražīgums, tomēr, sasniedzot noteiktas koku dimensijas (John Deere 1070 E – 0.33 m^3; Rottne H8 – 0.32 m^3; John Deere 1070 D – 0.16 m^3), ražīguma rādītāji vairs nepalielinās.



3.3. att. **Vidējo ražīguma rādītāju salīdzinājums attiecīgā stumbra tilpuma grupā starpcirtē izmantotajām mežizstrādes mašīnām un rokas motorzāģim**

Ar regresijas funkciju var izskaidrot 91.5% (John Deere 1070 E), 81.9% (Rottne H8) un 80.4% (John Deere 1070 D) no izmantoto mašīnu ražīguma rādītāju izmaiņām. Izmantojot motorzāģi, 50.3% no ražīguma rādītāju izmaiņām skaidrojamas ar regresijas funkciju. Veicot regresijas vienādojuma būtiskuma novērtējumu, F-testa p-vērtība visos gadījumos ir mazāka par 0.05, kas nozīmē, ka regresijas vienādojumi statistiski nozīmīgi izskaidro vidējo ražīguma rādītāju izmaiņas, atkarībā no zāģējamo koku caurmēra vai tilpuma. Starpcirtē izmantoto mašīnu un motorinstrumentu ražīguma rādītāju regresijas vienādojumu koeficienti doti 3.3. tabulā.

3.3. tabula

Starpcirtē izmantotajām mežizstrādes mašīnām un motorzāģim raksturīgo vidējo ražīguma rādītāju regresijas analīzes rezultāti

Koeficients	Koeficienta vērtība	Standartkļūda	t-testa faktiskā vērtība	p-vērtība
John Deere 1070 E				
a	0.895868	1.071575	0.836028709	0.409338255
b	91.19156	14.47364	6.300525578	4.56023E^{-07}
c	–49.6721	40.70066	–1.220424181	0.231221528
Rottne H8				
a	1.712063049	0.682744814	2.507617799	0.017094225
b	53.8443728	9.040072109	5.956188419	9.8169E^{-07}
c	–69.75723927	24.73321021	–2.820387595	0.007947637
John Deere 1070 D				
a	0.637783567	1.46680713	0.43481079	0.67210702
b	100.7931133	31.43759951	3.206132621	0.008362893
c	–163.9584908	121.6288765	–1.348022736	0.204755484
Motorzāģis				
a	0.095346751	0.675377142	0.141175567	0.889299216
b	37.64778433	13.14094294	2.864922593	0.010295621
c	–97.0220595	55.29421225	–1.754651266	0.096325984

Analizējot darba laika elementu īpatsvaru efektīvajā darba laikā, sagatavojot 1 m^3 kokmateriālu, konstatēts, ka nozāģēto koku atzarošana/garumošana un sniegšanās pēc zāģējamā koka aizņēmusi salīdzinoši visvairāk laika, attiecīgi no 20.6% ar John Deere 1070 E līdz 31.6% ar Rottne H8 un no 12.8% ar Rottne H8 līdz 33.6% ar John Deere 1070 E. Vismazāk efektīvā laika tērēts tādu darba elementu izpildei kā zaru novietošana (no 0.1% ar John Deere 1070 E līdz 1.6% ar Rottne H8), kas skaidrojams ar labiem darba apstākļiem, un zāģēšanai (no 3% ar Rottne H8 līdz 8.1% ar John Deere 1070 E). Iebraukšanai audzē, pārbraucieniem pa audzi un izbraukšanai no audzes tērētais laiks aprēķināts kā vidējā vērtība katrai no starpcirtē izmantotajām mežizstrādes mašīnām. Šos rādītāju lielā mērā ietekmē cirsmas platība. Efektīvais darba laiks, kas tērēts iebraukšanai un izbraukšanai no audzes, bijis no 1.3% ar John Deere 1070 E līdz 2.2% ar Rottne H8 un no 2.1% ar John Deere 1070 E līdz 3.9% ar Rottne H8.

3.2.3. Darba metodes ietekme uz ražīguma rādītājiem

Starpcirtē salīdzinātas 2 darba metodes. Pirmā darba metode paredz gatavot darba uzdevumā noteiktos sortimentus, enerģētiskās koksnes gatavošanai izmantojot koku galotnes un stumbrus, kuri nav piemēroti citu, kvalitātes prasībām atbilstošu, kokmateriālu sortimentu gatavošanai. Tāpat darba metode paredz enerģētiskās koksnes gatavošanā maksimāli izmantot stumbru uzkrāšanas funkciju. Otrā darba metode paredz no visiem nozāģētajiem kokiem gatavot enerģētisko koksni (daļēji atzarotu sīkkoksni), maksimāli izmantojot stumbru uzkrāšanas funkciju.

Strādājot ar pirmo darba metodi (mežizstrādes mašīnas John Deere 1070 E un Rottne H8), sagatavoti 1176 m^3 koksnes (17 724 darba cikli), bet ar otro (mežizstrādes mašīnas John Deere 1070 E un John Deere 1070 D) – 119 m^3 koksnes (3138 darba cikli). Lielāki vidējie ražīguma rādītāji sasniegti, starpcirtē izmantojot otro darba metodi, nekā strādājot ar pirmo darba metodi. Mežizstrādes mašīnām raksturīgu rādītāju salīdzinājums starp izmantotajām darba metodēm atspoguļots 3.4. tabulā.

3.4. tabula

Mežizstrādes mašīnām raksturīgu rādītāju salīdzinājums izmantoto darba metožu griezumā

Mežizstrādes mašīna	Darba metode	Novērojumu skaits	Efektīvais darba laiks no kopējā darba laika, %	Sagatavotais kokmateriālu apjoms, m^3	Vidējais ražīgums, m^3 E_{15} h^{-1}	Vidējā nozāģētā stumbra tilpums, m^3	Vidējā nozāģētā koka caurmērs, cm	Koku skaits, gab.	Vidējais nozāģēto stumbru skaits darba ciklā, gab.
John Deere 1070 E	1.	6247	85.7	396.6	5.4 ± 0.2	0.05 ± 0.1	8.6 ± 0.3	12 167	2.0 ± 0.1
	2.	500	61.0	33.4	4.0 ± 0.3	0.05 ± 0.1	8.3 ± 0.2	837	1.5 ± 0.1
Rottne H8	1.	11 477	82.1	779.5	5.0 ± 0.2	0.07 ± 0.1	10.2 ± 0.5	13 081	1.2 ± 0.1
John Deere 1070 D	2.	2638	75.2	86.0	1.7 ± 0.1	0.01 ± 0.1	4.0 ± 0.3	13 454	5.2 ± 0.3

Salīdzinot vidējos ražīguma rādītājus attiecīgā stumbra tilpuma grupā, starpcirtē izmantojot 1. darba metodi, labāki rādītāji iegūti, izmantojot mežizstrādes mašīnu John Deere 1070 E. Atšķirības ir statistiski būtiskas ($p \leq 0.05$). Būtiski lielāki vidējie ražīguma rādītāji sasniegti, gan apstrādājot mazu dimensiju kokus (koka tilpums grupā >0.01 m^3 uzrādītais ražīguma rādītājs Rottne H8, salīdzinājumā ar John Deere 1070 E, ir par 33% mazāks), gan lielākus (koka tilpums grupā 0.06–0.07 m^3 uzrādītais ražīguma rādītājs Rottne H8, salīdzinājumā ar John Deere 1070 E, ir par 29% mazāks). Stumbra tilpumam sasniedzot 0.45 m^3, mežizstrādes mašīnai John Deere 1070 E ražīguma rādītāji pārstāj pieaugt (3.4. att.).

Ar regresijas funkciju var izskaidrot 90.3% (John Deere 1070 E) un 62.6% (Rottne H8) no starpcirtē izmantoto mašīnu ražīguma rādītāju izmaiņām. Regresijas vienādojuma būtiskuma novērtējums parāda, ka F-testa p-vērtība visos gadījumos ir mazāka par 0.05, kas nozīmē, ka regresijas vienādojumi statistiski nozīmīgi izskaidro vidējo ražīguma rādītāju izmaiņas. Pirmajai darba metodei raksturīgie vidējo ražīguma rādītāju regresijas analīzes rezultāti katrai no starpcirtē izmantotajām mežizstrādes mašīnām doti 3.5. tabulā.

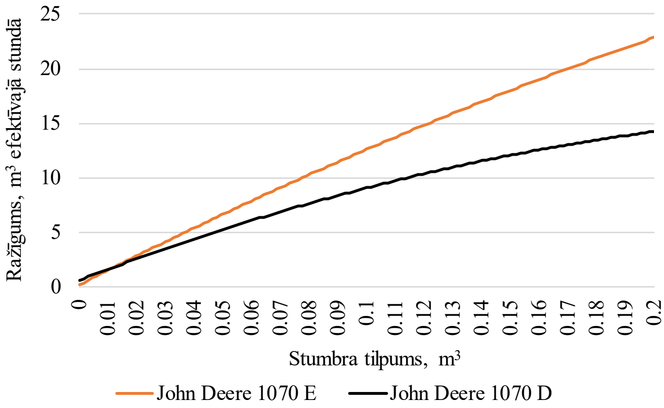
3.4. att. **Vidējo ražīguma rādītāju salīdzinājums mežizstrādes mašīnām attiecīgā stumbra tilpuma grupā pirmajai darba metodei**

3.5. tabula

Pirmajai darba metodei raksturīgo vidējo ražīguma rādītāju regresijas analīzes rezultāti

Koeficients	Koeficienta vērtība	Standartkļūda	t-testa faktiskā vērtība	p-vērtība
John Deere 1070 E				
a	–0.392485877	1.071786405	–0.36619785	0.716360811
b	117.1869614	7.931463586	14.77494792	$7.40103E^{-17}$
c	–117.2486243	11.87811014	–9.870983088	$8.77875E^{-12}$
Rottne H8				
a	1.215406733	1.261608711	0.96337852	0.339499356
b	49.87584282	8.167626856	6.106528089	$1.01938E^{-07}$
c	–40.14429025	11.2784911	–3.559367108	0.000766239

Salīdzinot vidējos ražīguma rādītājus attiecīgā stumbra tilpuma grupā, starpcirtē izmantojot 2. darba metodi, redzams, ka labāki rādītāji iegūti, izmantojot mežizstrādes mašīnu John Deere 1070 E, turklāt atšķirības ir statistiski būtiskas ($p < 0.05$) (3.5. att.). Mežizstrādes mašīna John Deere 1070 E uzrāda būtiski lielākus vidējos ražīguma rādītājus, gan apstrādājot mazu dimensiju kokus (ja stumbra tilpums <0.01 m^3, ražīguma rādītājs John Deere 1070 D, salīdzinājumā ar John Deere 1070 E, ir par 29% mazāks), gan lielākus (ja stumbra tilpums ir vidēji 0.26 m^3, ražīguma rādītājs John Deere 1070 D salīdzinājumā ar John Deere 1070 E ir par 47% mazāks). Salīdzinoši mazs vidējā nozāģētā koka tilpums (vien 0.01 m^3) ir viens no būtiskākajiem faktoriem, kas ietekmējis John Deere 1070 D ražīguma rādītājus, neskatoties uz to, ka operatori aktīvi izmantojuši stumbru uzkrāšanas mehānismu (vidēji 5.2 darba ciklā apstrādāti koki), vidējais ražīgums ir relatīvi neliels. Stumbra tilpumam sasniedzot 0.6 m^3, ražīguma rādītāji nepalielinās arī, strādājot ar John Deere 1070 E.



3.5. att. **Vidējo ražīguma rādītāju salīdzinājums attiecīgā stumbra tilpuma grupā otrajai darba metodei**

Ar regresijas vienādojumu var izskaidrot 96.1% (John Deere 1070 E) un 80.4% (John Deere 1070 D) no ražīguma rādītāju izmaiņām, starpcirtē izmantojot 2. darba metodi. Regresijas vienādojuma būtiskuma novērtējums parāda, ka F-testa p-vērtība visos gadījumos ir mazāka par 0.05, kas nozīmē, ka regresijas vienādojumi statistiski nozīmīgi izskaidro vidējo ražīguma rādītāju izmaiņas. Otrajai metodei raksturīgie vidējo ražīguma rādītāju regresijas analīzes rezultāti, katrai starpcirtē izmantotajai mežizstrādes mašīnai doti 3.6. tabulā.

3.6. tabula

Otrajai darba metodei raksturīgo vidējo ražīguma rādītāju regresijas analīzes rezultāti

Koeficients	Koeficienta vērtība	Standartkļūda	t-testa faktiskā vērtība	p-vērtība
John Deere 1070 E				
a	1.253042767	1.084604249	1.155299518	0.260361827
b	113.2956835	12.03230992	9.415954568	3.56682E^{-09}
c	–49.89734084	22.9636665	–2.172882142	0.040836327
John Deere 1070 D				
a	0.637783567	1.46680713	0.43481079	0.67210702
b	100.7931133	31.43759951	3.206132621	0.008362893
c	–163.9584908	121.6288765	–1.348022736	0.204755484

3.2.4. Operatora ietekme uz ražīguma rādītājiem

Līdzīgos pētījumos secināts, ka operatoru darba ieradumiem ir būtiska ietekme uz meža mašīnu ražīguma rādītājiem (Kärhä et al., 2004), tādēļ, analizējot darba metodes ietekmi, ņemts vērā arī operatoru sniegums, izmantojot dažādas darba metodes.

Strādājot ar mežizstrādes mašīnu John Deere 1070 E, izmantojot 1. darba metodi, kas paredz gatavot standarta sortimentus un daļēji atzarotos sīkkoksnes sortimentus, maksimāli izmantojot stumbru uzkrāšanas mehānismu, veica divi operatori (turpmāk tekstā A un B). Savukārt ar mežizstrādes mašīnu Rottne H8 strādāja četri operatori (turpmāk tekstā C, D, E un F).

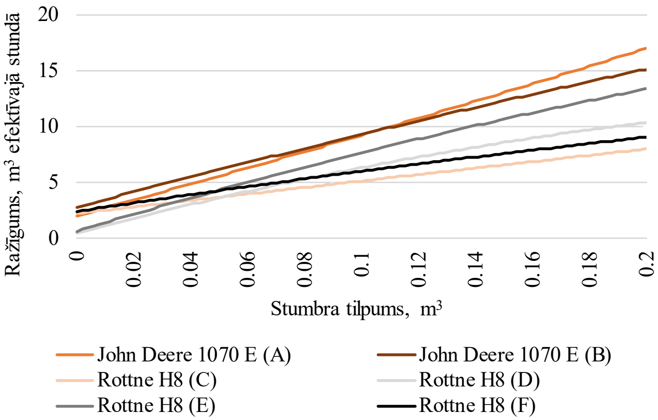
Labākos vidējos ražīguma rādītājus (5.4 m^3 efektīvajā stundā pie vidējā stumbra tilpuma 0.05 m^3) uzrādīja mežizstrādes mašīna John Deere 1070 E. Abu operatoru uzrādītie vidējie ražīguma rādītāji ir līdzīgi, tomēr, analizējot vidējo ražīguma rādītāju izmaiņas dažādās stumbra tilpuma grupās (3.6. att.), apstrādājot kokus, kuru tilpums ir lielāks par 0.1 m^3, vērojamas statistiski būtiskas ($p \leq 0.05$) atšķirības, un operatora A uzrādītie vidējie ražīguma rādītāji ir ievērojami labāki. Arī mežistrādes mašīnas Rottne H8 operatoru uzrādītie vidējie ražīguma rādītāji dažādās stumbra tilpuma grupās statistiski būtiski ($p \leq 0.05$) atšķirās un vidējais ražīgums atkarībā no operatora bija no 4.2 m^3 (vidējā nozāģētā stumbra tilpums 0.06 m^3) operatoram C līdz 6.8 m^3 (vidējā nozāģētā stumbra tilpums 0.08 m^3) operatoram E (3.7. tab.).

3.7. tabula

Mežizstrādes mašīnu operatoriem raksturīgo rādītāju salīdzinājums, starpcirtē izmantojot pirmo darba metodi

Mežizstrādes mašīna	Operators	Novērojumu skaits	Efektīvais darba laiks no kopējā darba laika, %	Sagatavotais kokmateriālu apjoms, m^3	Vidējais ražīgums, m^3 E_{15} h^{-1}	Vidējā nozāģētā stumbra tilpums, m^3	Vidējā nozāģētā koka caurmērs, cm	Koku skaits, gab.	Vidējais nozāģēto stumbru skaits darba ciklā, gab.
John Deere 1070 E	A	2578	86.7	169	5.4 ± 0.1	0.05 ± 0.1	8.7 ± 0.1	5143	2.0 ± 0.1
	B	3669	84.6	227	5.4 ± 0.1	0.05 ± 0.1	8.5 ± 0.1	7024	1.9 ± 0.1
Rottne H8	C	3256	80.7	197	4.2 ± 0.1	0.06 ± 0.1	9.7 ± 0.1	3614	1.2 ± 0.1
	D	1355	87.9	103	5.2 ± 0.1	0.07 ± 0.1	10.6 ± 0.1	1612	1.2 ± 0.1
	E	1493	83.0	124	6.8 ± 0.1	0.08 ± 0.1	11.0 ± 0.1	1726	1.2 ± 0.1
	F	5373	81.4	356	5.0 ± 0.1	0.07 ± 0.1	10.1 ± 0.1	6129	1.2 ± 0.1

Atšķirības uzrādītajos ražīguma rādītājos skaidrojamas ar atšķirīgu pieeju zāģējamo koku izvēlei, kas ietekmē nogāšanas un atzarošanas laiku, kā arī darba laika izmantošanas efektivitāti. Operatoram, kurš uzrādījis sliktākos ražīguma rādītājus, novērots arī mazākais efektīvā darba laika īpatsvars no kopējā darba laika (80.7%). Izmantojot vienādojumu ražīguma rādītāju aprēķināšanai pie atšķirīga zāģējamo koku tilpuma (no 0.01 līdz 0.10 m^3), operatoru ražīguma rādītāji pieaug no 1.3 līdz 6.2 m^3 E_{15} h^{-1} operatoram C; no 1.1 līdz 6.9 m^3 E_{15} h^{-1} operatoram D; no 1.4 līdz 9.0 m^3 E_{15} h^{-1} operatoram E un no 1.5 līdz 7.3 m^3 E_{15} h^{-1} operatoram F (3.6. att.).



3.6. att. **Mežizstrādes mašīnu operatoru vidējo ražīguma rādītāju salīdzinājums, strādājot ar pirmo darba metodei**

Ar regresijas vienādojumu var izskaidrot 94.6% John Deere 1070 E, operators A, 86.1% John Deere 1070 E, operators B, 79.3% Rottne H8, operators C, 46.9% Rottne H8, operators D, 65.7% Rottne H8, operators E, un 65.7% Rottne H8, operators F, ražīguma rādītāju izmaiņas, mašinizētā starpcirtē izmantojot 1. darba metodi. Regresijas vienādojuma būtiskuma novērtējums parāda, ka F-testa p-vērtība visos gadījumos ir mazāka par 0.05, kas nozīmē, ka regresijas vienādojumi statistiski nozīmīgi izskaidro vidējo ražīguma rādītāju izmaiņas. Operatoriem raksturīgie vidējo ražīguma rādītāju regresijas analīzes rezultāti doti 3.8. tabulā.

3.8. tabula

Pirmajai darba metodei raksturīgo vidējo ražīguma rādītāju regresijas analīzes rezultāti sadalījumā pa operatoriem

Koeficients	Koeficienta vērtība	Standartkļūda	t-testa faktiskā vērtība	p-vērtība
John Deere 1070 E (A)				
a	2.042517457	1.275798071	1.600972367	0.118914112
b	69.09181806	10.68001269	6.469263669	$2.44067E^{-07}$
c	28.10805641	17.60256374	1.596816056	0.119839834
John Deere 1070 E (B)				
a	2.800532314	1.505424111	1.86029458	0.074647829
b	68.07231263	11.54399308	5.896773512	$3.74428E^{-06}$
c	–32.10077992	16.5174589	–1.943445425	0.063301939
Rottne H8 (C)				
a	2.224266406	0.799775124	2.781114763	0.008383649
b	29.36166259	8.385868773	3.501326265	0.00120053
c	–2.55393094	18.72031472	–0.136425641	0.892205023
Rottne H8 (D)				
a	0.488907745	1.665267292	0.293591153	0.770804278
b	67.13056831	14.63665764	4.586468437	$5.55678E^{-05}$

Koeficients	Koeficienta vērtība	Standartkļūda	t-testa faktiskā vērtība	p-vērtība
c	–88.34044146	26.81592348	–3.294327772	0.002264308
Rottne H8 (E)				
a	0.657544265	1.790313837	0.36727877	0.715132759
b	76.44044839	12.69852825	6.019630532	$2.91973E^{-07}$
c	–65.08940487	18.68802088	–3.482947996	0.001116028
Rottne H8 (F)				
a	0.657544265	1.790313837	0.36727877	0.715132759
b	76.44044839	12.69852825	6.019630532	$2.91973E^{-07}$
c	–65.08940487	18.68802088	–3.482947996	0.001116028

Mašinizētā starpcirtē, izmantojot 2. darba metodi, kas paredz gatavot tikai enerģētisko koksni, darbus veica divi mežizstrādes mašīnas John Deere 1070 E operatori (A un B) un viens John Deere 1070 D operators (G). Labākos vidējos ražīguma rādītājus (4.5 m^3 E$_{15}$ h^{-1} pie vidējā stumbra tilpuma 0.05 m^3) uzrādīja John Deere 1070 E operators B (3.9. tab.).

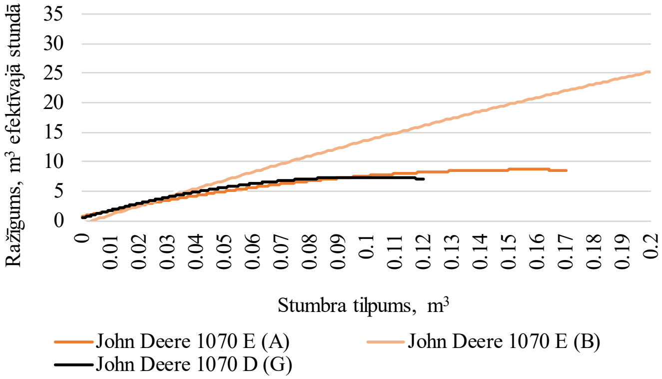
3.9. tabula

Mežizstrādes mašīnu operatoriem raksturīgo rādītāju salīdzinājums, starpcirtē izmantojot otro darba metodi

Mežizstrādes mašīna	Operators	Novērojumu skaits	Efektīvais darba laiks no kopējā darba laika, %	Sagatavotais kokmateriālu apjoms, m^3	Vidējais ražīgums, m^3 E$_{15}$ h^{-1}	Vidējā nozāģētā stumbra tilpums, m^3	Vidējā nozāģētā koka caurmērs, cm	Koku skaits, gab.	Vidējais nozāģēto stumbru skaits darba ciklā, gab.
John Deere 1070 E	A	20	53.4	1	3.5 ± 0.1	0.04 ± 0.1	7.4 ± 0.1	28	1.4 ± 0.1
	B	480	68.7	33	4.5 ± 0.1	0.05 ± 0.1	9.3 ± 0.1	809	1.7 ± 0.1
John Deere 1070 D	G	2638	75.2	86	1.7 ± 0.1	0.01 ± 0.1	4.0 ± 0.1	13 454	5.2 ± 0.1

Kaut arī vidējie ražīguma rādītāji operatoriem ir atšķirīgi, salīdzinot ražīguma rādītājus, kādi sasniegti, apstrādājot dažāda tilpuma stumbrus (3.7. att.), statistiski būtiskas atšķirības starp operatoriem nav konstatētas ($p > 0.05$). Izmantojot vienādojumu ražīguma rādītāju aprēķināšanai pie dažādiem stumbra tilpumiem (no 0.01 līdz 0.10 m^3), operatoru uzrādītie ražīguma rādītāji pieaug no 1.7 līdz 7.8 m^3 E$_{15}$ h^{-1} John Deere 1070 E, operators A; no 2.1 līdz 13.8 m^3 E$_{15}$ h^{-1} John Deere 1070 E, operators B; no 1.9 līdz 10.9 m^3 E$_{15}$ h^{-1} John Deere 1070 D, operators G.

Ar regresijas vienādojumu var izskaidrot 65.9% John Deere 1070 E, operators A, 96.4% John Deere 1070 E, operators B un 80.4% John Deere 1070 D, operators G no ražīguma rādītāju izmaiņām, starpcirtē izmantojot 2. darba metodi.



3.7. att. **Mežizstrādes mašīnu operatoru vidējo ražīguma rādītāju salīdzinājums, strādājot ar otro darba metodei**

Regresijas vienādojuma būtiskuma novērtējums parāda, ka F-testa p-vērtība visos gadījumos ir mazāka par 0.05, kas nozīmē, ka regresijas vienādojumi statistiski nozīmīgi izskaidro vidējo ražīguma rādītāju izmaiņas. Operatoriem raksturīgie vidējo ražīguma rādītāju regresijas analīzes rezultāti doti 3.10. tabulā.

3.10. tabula

Otrajai darba metodei raksturīgo vidējo ražīguma rādītāju regresijas analīzes rezultāti sadalījumā pa operatoriem

Koeficients	Koeficienta vērtība	Standartkļūda	t-testa faktiskā vērtība	p-vērtība
John Deere 1070 E (A)				
a	0.739434	1.422371	0.51986	0.621776
b	100.7864	47.88097	2.104936	0.07993
c	–320.846	262.7422	–1.22115	0.267834
John Deere 1070 E (B)				
a	–0.503	1.568134	–0.32138	0.752086
b	152.7976	17.95734	8.508921	2.47E^{-07}
c	–119.708	36.40862	–3.28791	0.004636
John Deere 1070 D (G)				
a	0.637784	1.466807	0.434811	0.672107
b	100.7931	31.4376	3.206133	0.0083663
c	–163.958	121.6289	–1.34802	0.204755

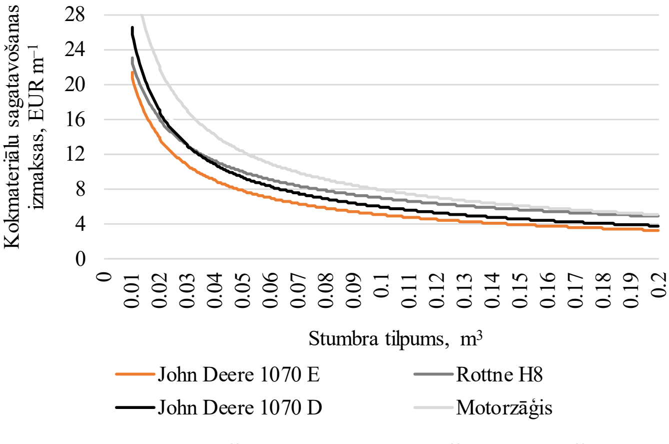
Strādājot ar 1. darba metodi, mežizstrādes mašīnas John Deere 1070 E sasniegtie ražīguma rādītāji atkarībā no nozāģēto stumbru tilpuma izmēģinājumos iesaistītajiem operatoriem atšķiras par 1.2% (stumbra tilpums 0.05 m^3) līdz 38% (stumbra tilpums 0.07 m^3).

Izmantojot 2. darba metodi, mežizstrādes mašīnas John Deere 1070 E operatoru sasniegtie ražīguma rādītāji atkarībā no nozāģēto stumbru tilpuma atšķiras no 0.4% (stumbra tilpums 0.04 m^3) līdz 59% (stumbra tilpums 0.02 m^3).

3.3. Mašinizētas starpcirtes ekonomiskā efektivitāte

Viens no galvenajiem faktoriem, kas ietekmē mežizstrādes mašīnas izvēli mašinizētā starpcirtē meža platībās ar 9–12 m augstiem kokiem, ir darbu izmaksas. Pakalpojumu pircējiem, tāpat kā pakalpojumu sniedzējiem aizvien aktuāls ir jautājums par mežizstrādes mašīnu ražīguma un ekonomiskā izdevīguma palielināšanu. Līdzšinējie pētījumi pierādījuši, ka tehnoloģiju izmantošana ļauj par vismaz 16% palielināt ražīgumu (Bergström, 2009; Bergström et al., 2010; Lazdiņš, 2012), tādējādi uzlabojot mašinizētas starpcirtes un enerģētiskās koksnes sagatavošanas ekonomisko izdevīgumu.

Tā kā starpcirtēs galvenokārt iegūst enerģētiskās koksnes sagatavošanai piemērotu sīkkoksni (apstrādājamo stumbru tilpums ir no 0.01 līdz 0.10 m^3), būtiski ir meklēt līdzsvaru starp kokmateriālu sagatavošanas izmaksām un tirgus cenu, par kādu sagatavotos kokmateriālus iespējams realizēt. Veicot mašinizētas kokmateriālu sagatavošanas izmaksu analīzi, izmantoti izmēģinājumos iegūtie vidējie ražīguma rādītāji un aprēķinātas efektīvās darba stundas izmaksas katrai no izmantotajām mežizstrādes mašīnām. Abām vidējās klases meža mašīnām vidējās efektīvas darba stundas izmaksas saskaņā ar aprēķiniem ir 49 EUR, savukārt mazās klases meža mašīnas efektīvas darba stundas izmaksas ir 46 EUR, t.i. par 6% mazākas. Darba stundas izmaksas būtiski ietekmē pieņēmumi par operatoru atalgojumu un mašīnu tehnisko gatavību un izmantošanas efektivitāti, kas var dubultot aprēķinātās darba stundas izmaksas. Iegūtie rezultāti parāda, ka, izmantojot vidējas klases mežizstrādes mašīnu John Deere 1070 E, kokmateriālu sagatavošanas izmaksas ir mazākas nekā abām pārējām izmantotajām mežizstrādes mašīnām (3.8. att.).



3.8. att. **Kokmateriālu sagatavošanas izmaksas dažādām mežizstrādes mašīnām atkarībā no nozāģētā stumbra tilpuma**

Dažādu valstu pētnieki veikuši darba ražīguma pētījumus, lai izstrādātu pēc iespējas precīzākus kokmateriālu ražošanas izmaksu aprēķina modeļus, kas ļauj prognozēt sagaidāmās un aktuālās ražošanas izmaksas. Enerģētiskās koksnes ražošanas izmaksu aprēķināšanai izmantots papildināts un pielāgots COST projekta FP0902 aktivitātes ietvaros izstrādāts izmaksu kalkulācijas bāzes modelis, kas paredz izmaksu kalkulāciju gan atsevišķām mežizstrādes tehnoloģiskā procesa daļām, gan mežizstrādes tehnoloģiskajam procesam kopumā (Kalēja et al., 2018b).

Kokmateriālu sagatavošanā salīdzinātas izmaksas trīs izmantotajām mežizstrādes mašīnām ar katrai mašīnai raksturīgajām izmaksām un ražīguma rādītājiem. Kokmateriālu sagatavošanas izmaksas sastāv no 3 izmaksu pozīciju grupām un plānotās peļņas. Darbaspēka izmaksas veido lielāko daļu no mežizstrādes mašīnu gada kopējām izmaksām un ir no 37% (John Deere 1070 E) līdz 41% (Rottne H8). Ieguldījumu izmaksas ir otrs lielākais izmaksu postenis un atkarībā no izmantotās meža mašīnas ir no 29% (Rottne H8) līdz 34% (John Deere 1070 D). Kopējās ekspluatācijas izmaksas ir no 21% (Rottne H8) līdz 25% (John Deere 1070 E un John Deere 1070 D).

Mašinizētas mežizstrādes darbos, izmantojot vidējas klases mežizstrādes mašīnas John Deere 1070 E un John Deere 1070 D, pie sasniegtajiem katrai mašīnai raksturīgajiem vidējiem ražīguma rādītājiem, gada laikā (2880 efektīvās darba stundas) iespējams sagatavot 14 tūkst. m^3 apaļo kokmateriālu un 6 tūkst. ber. m^3 enerģētiskās koksnes, strādājot ar John Deere 1070 E un 5 tūkst. m^3 apaļo kokmateriālu un 1 tūkst. ber. m^3 enerģētiskās koksnes, strādājot ar John Deere 1070 D. Mazās klases mežizstrādes mašīna Rottne H8 gada laikā (vidējais sasniegtais ražīgums 5 m^3 E_{15} h^{-1}; 2880 efektīvās darba stundas) sagatavo 15 tūkst. m^3 apaļo kokmateriālu un 6 tūkst. ber. m^3 enerģētiskās koksnes. Vidējās kokmateriālu sagatavošanas izmaksas būtiski ietekmē mašīnu ražīgums (3.11. tab.). Mazākās kokmateriālu sagatavošanas izmaksas sasniegtas, izmantojot John Deere 1070 E mežizstrādes mašīnu (vidējais ražīgums 5.6 m^3 E_{15} h^{-1}). Izmantojot mazās klases mežizstrādes mašīnu Rottne H8, vidējās kokmateriālu sagatavošanas izmaksas ir par 11% (vidējais ražīgums 5 m^3 E_{15} h^{-1}) lielākas nekā vidējās klases mežizstrādes mašīnai John Deere 1070 E ar H 754 darba galvu. Savukārt, John Deere 1070 D vidējais ražīgums (1.7 m^3 E_{15} h^{-1}) atstājis būtisku ietekmi uz kokmateriālu ražošanas izmaksām, salīdzinājumā ar John Deere 1070 E – tās palielinājušās par 72%. Kokmateriālu sagatavošanas izmaksu salīdzinājums starpcirtē izmantotajām mežizstrādes mašīnām parādīts 3.11. tabulā.

3.11. tabula

Kokmateriālu sagatavošanas izmaksu salīdzinājums dažādām mežizstrādes mašīnām

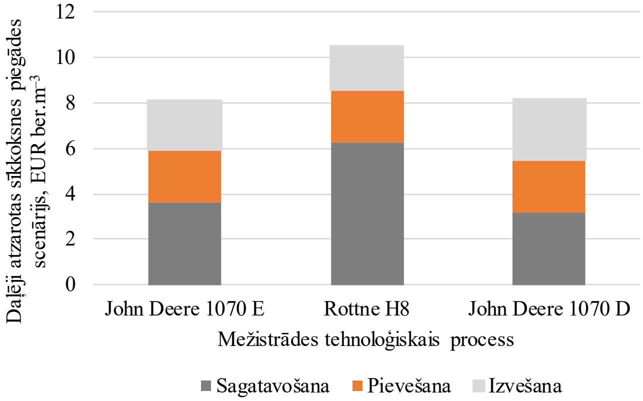
Rādītāji	John Deere 1070 E	Rottne H8	John Deere 1070 D
Kopējās izmaksas, EUR gadā	141 399	131 300	142 477
Ieguldījumi	45 720	38 281	46 747
Darbaspēks	53 363	53 363	53 363
Ekspluatācijas izmaksas	35 583	33 403	35 583
Plānotā peļņa	6733	6252	6785
Ražīgums, m^3 E_{15} h^{-1}	5.6	5.0	1.7
Kopējais sagatavotais kokmateriālu apjoms, m^3 gadā	17 521	15 488	5319
apaļie kokmateriāli	13 568	11 740	4359
enerģētiskās koksne no stumbra atliekām	1050	1209	52
enerģētiskā koksne no mežizstrādes atliekām	1411	1247	428
mizas un citi atlikumi	1492	1291	480
Enerģētiskā koksne ber. m^3 gadā	5906	5896	1152
Vidējās kokmateriālu sagatavošanas izmaksas, EUR m^{-3}	7.6	8.5	26.8

Analizējot vidējās efektīvās darba stundas izmaksas, sagatavojot kokmateriālus, labāki rādītāji iegūti, starpcirtē izmantojot John Deere 1070 E un Rottne H8 (46 EUR E_{15} h^{-1}), savukārt mežizstrādes mašīnai John Deere 1070 D vidējās darba stundas izmaksas bija lielākas (49 EUR E_{15} h^{-1}). Par 10% samazinoties mežizstrādes mašīnu noslodzei (efektīvo darba stundu skaitu) gadā, vidējās efektīvās darba stundas izmaksas mežizstrādes mašīnai Rottne H8 palielinās par 3 EUR E_{15} h^{-1}, bet vidējas klases mežizstrādes mašīnām John Deere 1070 D un John Deere 1070 E – par 4 EUR E_{15} h^{-1}.

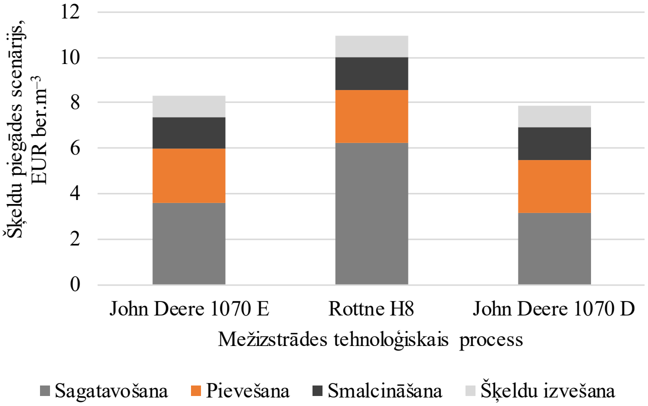
Salīdzinot dažādu mežizstrādes mašīnu un tehnoloģisko procesu izmaksas, lietderīgi veikt salīdzinājumu relatīvā izteiksmē, jo, piemēram, atalgojums un plānotā tehniskā pieejamība un noslodze var būtiski ietekmēt darba stundas izmaksas, attiecīgi, arī salīdzinājumu.

Kopējās enerģētiskās koksnes ražošanas izmaksas ietver ne vien sagatavošanas, bet arī pievešanas, smalcināšanas un izvešanas, jeb mežistrādes tehnoloģiskā procesa izmaksas. Aprēķinos izmantoti līdzšinējos pētījumos iegūtie vidējie rādītāji, kas raksturo ieguldījuma, darbaspēka un ekspluatācijas izmaksas, kā arī vidējie ražīguma rādītāji. Enerģētiskās koksnes piegādē galapatērētājam iespējams izvēlēties divus piegādes scenārijus. Scenāriju izvērtējumā pieņemts, ka visām mežizstrādes mašīnām vidējā nozāģētā koka $D_{1.3} = 8$ cm. Pirmais no scenārijiem paredz piegādāt daļēji atzarotu sīkkoksni, kuras pārstrādi veic galapatērētājs. Izmantojot šo scenāriju, atkarībā no izvēlētās mežizstrādes mašīnas, kokmateriālu sagatavošanas, piegādes un izvešanas izmaksas ir no 8.1 (John Deere 1070 E) līdz 10.5 (Rottne H8) EUR ber. m^{-3} (3.9. att.).

Saskaņā ar otro scenāriju enerģētisko koksni smalcina augšgala krautuvē un gala patērētājam piegādā šķeldu veidā. Kokmateriālu sagatavošanas, pievešanas, smalcināšanas un sagatavoto šķeldu izvešanas izmaksas atkarībā no izmantotās mežizstrādes mašīnas ir no 7.9 (John Deere 1070 E) līdz 11.0 (Rottne H8) EUR ber. m^{-3} (3.10. att.).



3.9. att. **Ražošanas izmaksas daļēji atzarotas sīkkoksnes piegādes scenārijā**



3.10. att. **Ražošanas izmaksas šķeldu piegādes scenārijā**

Līdzšinējie pētījumi liecina, ka daļēji atzarotas sīkkoksnes piegādes scenārijs ir viena no iespējām, kā sagatavotos kokmateriālus nogādāt galapatērētājam (Kalēja et al., 2014). Promocijas darba ietvaros veiktie aprēķini parāda, ka, izvēloties daļēji atzarotas sīkkoksnes piegādes scenāriju, mežizstrādes tehnoloģiskā procesa izmaksas iespējams samazināt no 2% (John Deere 1070 E) līdz 5% (Rottne H8). Kaut arī iegūtie rezultāti parāda, ka noteiktos apstākļos daļēji atzarotas sīkkoksnes piegādes scenārija izmantošana ļautu samazināt mežizstrādes tehnoloģiskā procesa izmaksas, Latvijā praksē šis scenārijs netiek izmantots, un līdzīgos pētījumos pierādīts, ka kokvedēju mazā ietilpība no ekonomiskā viedokļa padara to izmantošanu mazāk efektīvu salīdzinājumā ar šķeldu vedēju (Kalēja et al., 2014). Enerģētiskās koksnes gatavošanā, izmantojot John Deere 1070 D, šķeldu piegādes scenārijs salīdzinājumā ar daļēji atzarotas sīkkoksnes piegādes scenāriju ļauj par 2% samazināt mežizstrādes tehnoloģiskā procesa izmaksas. Šķeldu piegādes scenārijs kā ekonomiski efektīvākais atzīts arī līdzīgos pētījumos (Kalēja et al., 2014) un praksē to izmanto mežizstrādes tehnoloģiskajā procesā.

Pētījuma rezultāti apstiprina darbā izvirzīto tēzi par enerģētiskās koksnes sagatavošanas rentabilitāti, izvēloties atbilstošu tehniku. Vidējās klases mežizstrādes mašīna John Deere 1070 E ar standarta darba galvu, kas aprīkota ar papildu satvērējiem, izmēģinājumos nodrošināja relatīvi mazākas kokmateriālu un enerģētiskās koksnes ražošanas izmaksas, neatkarīgi no izmantotās darba metodes (vidējās kokmateriālu sagatavošanas izmaksas 7.6 EUR m^{-3}; vidējā nozāģētā koka augstums 12.3 m; $D_{1.3}$ = 8.8 cm; vidējais stumbra tilpums 0.04 m^3). Tajā pašā laikā standarta tehnikas izmantošana teorētiski ļauj palielināt tehnikas izmantošanas efektivitāti un samazināt tehnikas pārvietošanas izmaksas, veicot mežizstrādi arī starpcirtēs un galvenajā cirtē nelielu dimensiju koku audzēs.

Ar Bracke C.16 darba galvu aprīkotās John Deere 1070 D mežizstrādes mašīnas izmantošana izrādījās salīdzinoši neefektīvs risinājums (vidējās kokmateriālu sagatavošanas izmaksas 26.8 EUR m^{-3}), taču šīs tehnikas vienības efektivitāti būtiski ietekmēja ievērojami mazākas nozāģējamo koku dimensijas (vidējā nozāģētā koka augstums 8 m; $D_{1.3}$ = 4.3 cm; vidējais stumbra tilpums 0.01 m^3) pie vienādiem audzes parametriem, kas savukārt izriet no darba metodes. Strādājot ar vidējas klases mežizstrādes mašīnu, kas aprīkota ar Bracke C.16 darba galvu, bija jānozāģē arī mazu dimensiju kokus, kā rezultātā palielinās darba laika patēriņš gan kokmateriālu sagatavošanas, gan izvešanas procesā. Bracke C.16 darba galvas pielietošanas efektivitāti var būtiski palielināt darba metodes izmaiņas, izmantojot kādu no simetriskās kopšanas metodēm un izvairoties no mazāko koku un krūmu zāģēšanas.

SECINĀJUMI

1. Saskaņā ar MSI 3. cikla (2014–2019) datiem mežaudzes, kurās valdaudzes vidējā koku augstums ir 9–12 m, aizņem 7% no kopējās meža platības Latvijā. Lielākā daļa jeb 63% šādu meža platību atrodas pārējo īpašnieku mežos. Teorētiski pieejamie enerģētiskās koksnes resursi šādos mežos ir 7054 tūkst. m^3 (virszemes biomasa 4091 tūkst. $t_{sausnas}$), tajā skaitā valsts mežos atrodas vien 27% jeb 1927 tūkst. m^3 (virszemes biomasas 1109 tūkst. $t_{sausnas}$), bet pārējos mežos teorētiski pieejami 5127 tūkst. m^3 (virszemes biomasas 2982 tūkst. $t_{sausnas}$).

2. Tehnoloģiski pieejamie resursi attiecīgajās meža platībās atbilst 530 tūkst. t ciršanas atlieku un 798 tūkst. m^3 malkas jeb kopā 4588 tūkst. MWh enerģētiskās koksnes, pārvēršot to primārajā enerģijā, un tikai 19% no resursiem koncentrēti valsts mežos. Šim resursu veidam ir neliela saimnieciskā nozīme, taču mašinizēta starpcirte laikus neizkoptās meža platībās, gatavojot enerģētisko koksni, var sekmēt mežaudžu vērtības pieaugumu nākotnē.

3. Mašinizētā starpcirtē vislabākie ražīguma rādītāji sasniedzami, izmantojot darba metodi, kas no visiem nozāģētajiem kokiem paredz gatavot daļēji atzarotus sīkkoksnes sortimentus. Būtiski ($p = 0.01 < 0.05$) labāki vidējie ražīguma rādītāji izmēģinājumos sasniegti, izmantojot vidējās klases mežizstrādes mašīnu John Deere 1070 E, kas aprīkota ar H 754 darba galvu, t.i. izplatītāko vidējās klases mežizstrādes risinājumu kopšanas cirtēs Latvijā.

4. Mazās klases mežizstrādes mašīnas (Rottne H8 ar EGS 405 darba galvu) kopējās izmaksas gada griezumā ir līdz 16% mazākas, nekā vidējas klases mežizstrādes mašīnas (John Deere 1070 E ar H 754 darba galvu) izmaksas, un to lielā mērā ietekmē salīdzinoši mazākas ieguldījumu izmaksas. Tomēr, starpcirtē izmantojot John Deere 1070 E mežizstrādes mašīnu, vidējās enerģētiskās koksnes sagatavošanas izmaksas, pateicoties labākiem ražīguma rādītājiem, ir par 15% mazākas.

5. Vidējās klases mežizstrādes mašīna John Deere 1070 E ar H 754 darba galvu izmēģinājumos nodrošināja relatīvi mazākas enerģētiskās koksnes ražošanas izmaksas, neatkarīgi no izmantotās darba metodes. Ar Bracke C.16 darba galvu aprīkotās John Deere 1070 D mežizstrādes mašīnas izmantošana izrādījās salīdzinoši neefektīvs risinājums, taču šīs mašīnas efektivitāti būtiski ietekmēja ievērojami mazākas nozāģējamo koku dimensijas pie vienādiem audzes parametriem, kas savukārt izriet no darba metodes. Efektivitāti var būtiski palielināt, izmantojot kādu no simetriskās kopšanas metodēm un izvairoties no mazāko koku un krūmu zāģēšanas.

6. Mežizstrādes mašīnu noslodze (efektīvo darba stundu skaits) gadā būtiski ietekmē efektīvās darba stundas vidējās izmaksas. Par 10% samazinot mašīnu noslodzi, mazās klases mežizstrādes mašīnai Rottne H8 efektīvās darba stundas izmaksas palielinās par 6%, bet vidējas klases mežizstrādes mašīnām John Deere 1070 D un John Deere 1070 E par 7–8%. Tajā pašā laikā standarta tehnikas izmantošana ļauj palielināt tehnikas izmantošanas efektivitāti un samazināt tehnikas pārvietošanas izmaksas, veicot mežizstrādi arī starpcirtēs un galvenajā cirtē nelielu dimensiju koku audzēs.
7. Kaut arī aprēķinu rezultāti parāda, ka noteiktos apstākļos daļēji atzarotas sīkkoksnes piegāde ļautu samazināt mežizstrādes tehnoloģiskā procesa izmaksas par 2% (John Deere 1070 E) līdz 5% (Rottne H8), Latvijā šo scenāriju praksē neizmanto. Enerģētisko koksni galapatērētājam galvenokārt piegādā, izmantojot šķeldu piegādes scenāriju, kas pētījuma ietvaros atzīts kā ekonomiski pamatots mežizstrādes tehnoloģiskā procesa risinājums, enerģētiskās koksnes gatavošanā izmantojot galvenokārt mazu dimensiju kokus.

PATEICĪBAS

Promocijas darba autore izsaka pateicību darba zinātniskajiem vadītājiem Dr.silv. Andim Lazdiņam un Dr.sc.ing Ziedonim Sarmulim par atbalstu un sniegtajiem padomiem darba izstrādē un tā kvalitātes pilnveidošanā. Pateicība Latvijas Lauksaimniecības universitātes Meža fakultātes profesoram (Emeritus) Dr.sc.ing. Alfonam Grīnfeldam par atbalstu un noderīgajiem padomiem, uzsākot doktorantūras studiju procesu.

Darba autore izsaka pateicību Latvijas Valsts mežzinātnes institūtam “Silava” par iespēju izstrādāt darbu paralēli tiešo darba pienākumu veikšanai, kā arī par iespēju promocijas darba izstrādē izmantot akciju sabiedrības “Latvijas valsts meži” pasūtītā pētījuma “Meža darbu mašinizācijas un biokurināmā pētījumu programma” ietvaros iegūtos datus.

Darba autore izsaka pateicību Latvijas Valsts mežzinātnes institūta “Silava” Meža atjaunošanas un ieaudzēšanas un Meža darbu un meža enerģētikas radošo grupu kolēģiem par palīdzību empīrisko materiālu ievākšanā un pēcapstrādē.

1. GENERAL DESCRIPTION OF THE THESIS

1.1. Relevance of the topic

Historically, the owners have managed the forest in such a way as to ensure the sustainable availability of resources and obtain the most economically important forest product – timber. The growing demand for wood products makes it necessary to look for new, scientifically and practically based solutions for the improvement of forestry practices and wood supplies. Wood biofuel is dominant renewable energy resource in Latvia, which still has the greatest potential for increasing use. Changes in the approach to the use of wood could promote the development of Latvia's energy sector by achieving the goals set in the Sustainable Development Strategy of Latvia until 2030, which are related to increasing the share of energy produced using renewable energy to 40% of gross final energy consumption. Previous research shows that the largest theoretically obtainable unused wood biofuel reserves in thinnings are found in stands between 21 and 30 years of age. As different technical and technological solutions are possible in the use of these resources, it is important to evaluate not only the theoretical but also the technological and economic availability of resources before expanding production. The mechanization of thinnings, which is generally linked to the extraction of wood biofuel, is mainly hampered by economic factors. Previous studies in the Nordic countries have shown that the productivity of harvesters of similar size and capacity achieved under similar conditions does not differ significantly, which suggests that medium-sized harvesters, which are currently widely used in the final felling areas in Latvia, can be used in mechanized thinnings for the production of wood biofuel. The topicality of the research is determined also by the fact that there is still an unanswered question about the most suitable technical and technological solution for wood biofuel extraction in mechanized thinning, evaluating the factors influencing machine productivity, as well as evaluating the economic benefits of mechanized thinning.

1.2. The aim, tasks and thesis of the Doctoral Thesis

The aim of the Doctoral Thesis is to investigate, which factors have significant impact on productivity and costs of biofuel production, to evaluate wood resources in forest stands, where thinning has been delayed, and to elaborate proposals for mechanization of thinnings.

The following research tasks of the doctoral thesis were set:

1. To estimate the available wood resources in young stands, where thinning has been delayed, and the technologically available wood biofuel resources in such stands in Latvia.

2. To investigate, which factors affect productivity of forest operations and prime cost of wood biofuel production in thinning implemented either mechanically or using a chainsaw.
3. To evaluate the impact of different mechanization solutions on the profitability of wood biofuel production.

The following research hypothesis has been proposed in the study: in forest stands, where pre-commercial thinning has been delayed, mechanized biofuel production is feasible.

1.3. Scientific novelty and practical significance of the Doctoral Thesis

Although wood biofuel, which can be obtained by means of mechanized thinnings, is one of the sources of renewable energy in Latvia, the use of which still has potential, production costs are relatively high and hinder the use of this resource. In order to efficiently manage the biomass resources in young forest stands, it is necessary to find the most suitable technologically and economically viable harvesting solutions, which at the same time do not have adverse effect on the growth of forest stands. At present, in Latvia, the calculation of felling costs is not performed using a unified cost calculation model. Typically, production cost calculations are performed by each service provider for each production phase individually with limited knowledge about possible optimization solutions.

The results obtained in the research provide an insight into the technological solutions and working methods of mechanized thinning in the forest areas, where mainly wood biofuel can be obtained. The cost calculation model, which has been supplemented and adapted for the calculation of costs in felling works within the framework of the research, provides an opportunity to perform economic evaluation of wood biofuel production, as well as allows to calculate the total costs of the technological process of the logging.

Research in this direction provides a broader picture of which factors must be considered more carefully and which must be given more attention to in order to make wood biofuel's harvesting during mechanized thinning even more efficient from both a forestry and an economic point of view. Using the production cost calculation model developed within the scope of the Doctoral Thesis, the calculated values are comparable and evaluable in each of the cost positions, which provides an opportunity to identify items that could be reduced by changing or adapting the technology.

1.4. Approbation of research results

The research results have been published in six scientific articles and presented in seven scientific conferences.

1.5. Structure and volume of the Doctoral Thesis

The structure of the Thesis is formed in accordance with the research tasks set in the Thesis paper. The paper consists of three chapters, the first of them reflects the description of the problem in research conducted by other authors and their conclusions; an insight into the availability of wood biofuel's resources in Latvia and the possibilities to use these resources; the history of the organization of logging operations and the used technologies as well as the possibilities of current mechanized logging; the current achievements in performing mechanized thinning, as well as the factors influencing the productivity of mechanized logging; the role of wood biofuel in the context of renewable energy resources and the role of this resource in the national economy. The second chapter describes the methodology of determining theoretically, technically and technologically available resources of wood biofuel; the research objects are described, as well as the installation of sample plots and the methodology of data collection; a description of the harvesters used in the mechanized logging, a description of the selected working methods and conditions, as well as the methods of data collection during the trials and analysis of obtained data; the model for calculating the costs of wood biofuel production. Within the framework of the research the model for calculating the costs has been adapted to the technological processes of logging in Latvia. In the third chapter, the assessment of wood biofuel resources is performed; productivity indicators obtained by mechanized thinning are evaluated and the factors which the most significantly affect the productivity and costs it are identified; an assessment of wood biofuel production costs has been performed and recommendations for extraction of biofuel are provided.

The volume of the dissertation is 72 pages; information is summarized in 23 tables and 24 figures, 95 literature sources were used, 7 conclusions were formulated at the end of the work and 9 appendices were added.

2. MATERIAL AND METHODS

2.1. Determining the availability of wood biofuel resources

In the assessment of the theoretical, technical and technological availability of resources, the data of National Forest Inventory 3rd cycle (2014–2019) obtained in forest areas with 9–12 m high trees were used.

In this research, the theoretically available wood biofuel resources are treated as the resources available in forest stands where the number of trees or basal area after the harvesting of strip roads does not decrease below the minimum threshold of number of trees or basal area according to national legislation. Theoretically, this kind of wood biofuel resources is also available in nature protection areas.

When extracting the technically available wood biofuel resources from the theoretically available resources, the further calculations do not include forest areas where, based on the forest type, the extraction of trees during thinning is not recommended, e.g. stand types *Cladinoso-callunosa*, *Callunosa turf. mel.* and *Callunosa mel.*, as well as from the technological point of view it is not easy to implement wood biofuel extraction in forest stand types with wet organic soils, specifically, *Cladinoso-sphagnosa, Vaccinioso-sphagnosa*. Protected nature territories are also excluded from the calculation (Lazdiņš et al., 2012).

Technically available resources are a part of technologically available biomass, separated from production losses (in average 30% for felling residues and 5% for firewood; Adamovičs et al., 2009). The biomass resources that can be extracted only when soil is frozen have been separately allocated (Lazdiņš et al., 2012).

2.2. Description of research objects

In accordance with the goal of the research and the defined tasks, 10 forest stands in state forests with a total area of 27.8 ha were selected for the collection of empirical material. The trial objects are concentrated in Central part of Latvia (Vidusdaugava region). The average tree height of the superior stand (9–12 m) and stand density (number of trees ≥2000 pieces ha^{-1}) were used as stand selection criteria. Three deciduous stands were selected for trials – silver birch (*Betula pendula* Roth) and 7 coniferous stands – Norway spruce (*Picea abies* (L.) H.Karst.) and Scots pine (*Pinus sylvestris* L.).

Empirical material for the research was collected in 2013 and 2014.

All selected stands have been cut down to the minimum number of trees or basal areas by thinning "from below", which involves cutting of the smallest and non-viable trees outside the striproads.

The striproads are spacing at a distance of 15, 18, 20 or 30 m from each other. "Ghost paths" are used for harvesting if the distance between striproads exceeds 20 m.

2.3. Description of the forest machinery used in the research

Within the framework of the research, mechanized thinnings was performed using 3 different harvesters, the heads of which are additionally equipped with stem accumulating device.

With a medium-sized harvester John Deere 1070 E (unladen weight 15.5 tons, engine power 136 kW at 1900 rpm min.^{-1}), equipped with H754 head (weight 820 kg, maximum stem diameter 55 cm, 5 moving knives, 1 fixed knife, 4 feed rollers, maximum boom deflection 10 m), work time records for 127 working hours were obtained within the scope of the research.

With a medium-sized harvester John Deere 1070 D (unladen weight 14.1 tons, engine power 136 kW at 1900 rpm min.^{-1}), equipped with a Bracke C16.b head (weight 570 kg, maximum stem diameter 26 cm, maximum boom deflection 10 m), work time records for 66 working hours were obtained within the scope of the research.

With a small-size harvester Rottne H8 (unladen weight 10.2 tons, engine power 125 kW at 2000 rpm min.^{-1}), equipped with EGS 406 head (weight 480 kg, maximum stem diameter 33 cm, 2 moving knives, 2 feed rollers, maximum boom deflection 7 m), work time records for 262 working hours were obtained within the scope of the study.

2.4. Description of working methods used in the research

Two working methods were used in the experiments. Both methods consider leaving of undergrowth trees, as long as they do not interfere with the thinning. Also, regardless of the choice of method, when sawing trees that are not intended for the production of standard timber, the stem accumulating device is used to the maximum. The term “partly delimbed stem wood” means wood biofuel (not longer than 6 m) made from undelimbed tops, logging residues and undergrowth trees with average diameter at breast height (DBH) < 6 cm.

The first of the used working methods envisages the production of all timber assortments according to the product groups adopted by JSC “Latvia’s State Forests”. While working with this method, assortments of partly delimbed stem wood (length from 2.5 to 3 m, minimum top diameter – 3 cm) were produced.

The second working method envisages the production of partly delimbed stem wood biofuel from all felled trees, except for undergrowth trees with DBH < 4 cm.

2.5. Accounting work time of mechanized thinning and calculation of productivity indicators

The chronometric timing method has been used to acquire data on the work time use in thinning, which considers recording the use of direct work time and is intended for logging of the duration and sequence of the basic elements of the work process at their cyclic repetition. To determine the duration of work elements, continuous timing was performed, which is suitable for the study of work operation elements continuing for at least 10 seconds (Bludiņš & Rudze, 1979). During the time studies the engine time of the harvesters is adjusted to record operating hours, stopping the timing when the engine is stopped and resuming it as soon as the engine is restarted.

The work time consumption is determined for each work cycle separately. When recording work time, additional information fields are filled in on the field computer, providing information on the diameter of the felled tree at the cutting site (D_0) using a Rottne H8 or DBH using buth John Deere harvesters. Information fields on the number of trees processed per work cycle were also filled in, notes on interruptions in work, moving the machine to another strip road were also made, as well as name or ID of an operator who performed thinning.

Productivity indicators were calculated from work time accounting data separately for different stands, harvesters, working methods and operators. Stand wise and single tree data are used in the productivity estimates.

The use of working day (shifts) includes all the work time looged during the study when the engine is running. Productive work time is obtained by deducting the inefficient work time from the total work time. The inefficient work time is spent for repairs (provided that the engine of the harvester continues to run at the time of recording the work time) and the time spent on activities not direct associated with harvesting operation.

2.6. Calculation of wood biofuel production costs

For cost calculation, the model developed within the COST project FP0902 (Ackerman et al., 2014) was used, however, it was supplemented with standard economic methods and adapted for cost calculation in felling works, as well as for trading of produced materials, covering the whole technological process of logging (Kalēja et al., 2018a).

In the calculation model, costs are distributed by their types or cost items per unit of a product or service (Alsiņa et al., 2011). The calculation of production costs includes both direct production costs that are directly related to the creation of specific cost objects, cost process and activity, and general or indirect costs that are not directly related to the production of the specific product, but are conditionally related to the production process and are included in production costs using the addition rate (Vītola & Soopa, 2002; Alsiņa et al., 2011). The determination and distribution of indirect costs by calculation objects was performed according to the volume of production or time period.

The production cost calculation uses empirical data obtained from long-term observations (information provided by technical service providers and service companies on technical maintenance costs) and published data which includes machine cost analysis. Cost items include investment costs, personnel costs, and operating or maintenance costs (Brinker et al., 2002; Alsiņa et al., 2011; Ackerman et al., 2014).

In order to calculate the costs of the logging technological process as accurately as possible and the cost model would be suitable for different conditions, specific indicators such as machine productivity and factors influencing it – average diameter of felled trees, number of felled trees, average load size, number of equipment relocation per year, average delivery distance and average driving speed were used in calculations.

For the conversion of cubic meters (m^3) to lose volume cubic meters (LV m^3) a coefficient of 2.5 is used in the calculations following to practical experience in biomass terminals. The load size is determined by load weighing or calculated on the basis of the dimensions of the loaded timber.

The production cost calculation model is intended for calculating hourly (productive hours, operating hours and planned working hours) and unit costs for each of the phases of the logging technological process.

3. RESULTS AND DISCUSION

3.1. Evaluation availability of wood biofuel resources

According to the National forest inventory (NFI) 3rd cycle (2014–2019) data, forest areas with tree height of 9–12 m occupy 7% of all forests (234 thous. ha with a total stem volume of 15,524 thous. m^3). Most or 63% (149 thous. ha) of such forest stands are located in the forests owned by private companies, persons and municipalities.

Calculations show that the theoretically available wood biofuel resources in thinnings concentrated in forest areas, where the number of trees or basal area does not decrease below the minimum threshold after strip roads are harvested, amount to 7,054 thous. m^3 of stem wood (4,091 thous. $tons_{dry}$ above-ground biomass, of which only 27% is located in state forests (1,927 thous. m^3 of stem wood or 1,109 thous. $tons_{dry}$ above-ground biomass). In other forests the theoretically available stock is 5,127 thous. m^3 of stem wood or 2,982 thous. t_{dry} above-ground biomass.

The total theoretical distribution of theoretically available tree above-ground biomass by forest stand types according to NFI 3rd cycle data is shown in Figure 3.1. Most (59%) of the total theoretically available above-ground tree biomass is located on dry mineral soils (*Vacciniosa, Myrtillosa, Hylocomiosa, Oxalidosa* and *Aegopodiosa*), including 30% in state forests. In poor mineral soils *Cladinoso-callunosa* (poor mineral soil), where 4% of the theoretically available wood biofuel resources are located mainly in state forests, the extraction in thinning is not recommended due to risk of significant reduction of the stock of organic matter (Skudra & Dreimanis, 1993). In private and municipal forests, growing stock available for extraction in delayed thinning in the *Cladinoso-callunosa* and *Vacciniosa* forest types is negligible.

In forest types with organic soils (*Sphagnosa, Caricoso-phragmitosa* and *Dryopterioso-caricosa*) 16% of the theoretically available resources are located. These figures differ by ownership – in the state forests 28% of the theoretically available wood biofuel resources are located in forests with organic soils and only 11% in forests of other owners. Although the proportion of resources concentrated in these forest types is relatively high, the conditions are not suitable for mechanized thinning due to potentially low soil bearing capacity (Saliņš, 1987; Liepa et al., 2014). In forest types with drained mineral soils (*Vacciniosa mel., Myrtillosa mel.* and *Mercurialiosa mel.*) 14% of the total theoretically available wood biofuel resources ar located. This share is bigger in state forests (18%) and smaller in other forests (12%). In nutrient poor *Vacciniosa mel.* the resources are available only in the state forests. From the point of view of soil bearing capacity, mechanized thinning can be done both in summer and in winter (Saliņš et al., 1987; Liepa et al., 2014).

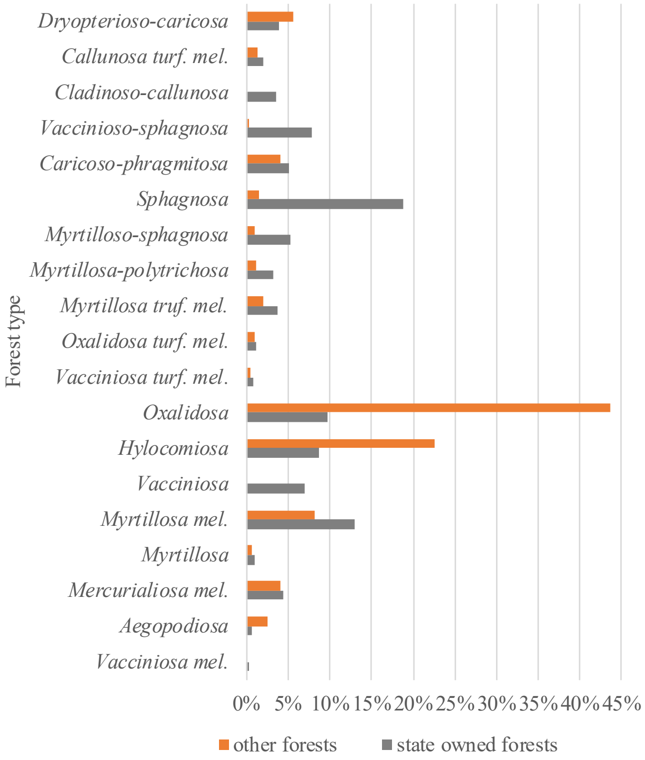


Fig. 3.1. **Structure of biomass theoretically available above-ground in thinnings by forest stand type in areas with 9 to 12 m hight trees**

Theoretically available wood biofuel resources located in forests with wet mineral soils (*Myrtilloso-sphagnosa, Vaccinioso-sphagnosa* and *Myrtillosa-polytrichosa*) are 6% of the total. This figure is much higher in state forests (16%) and only 2% in other forests. No theoretically available wood biofuel resources are found in forests with nutrient poor wet mineral soil (*Cladinoso-sphagnosa*) and the richest forests with wet mineral soil (*Dryopteriosa*). From the point of view of soil bearing capacity, mechanized thinning in forests with wet mineral soils is possible in all seasons (Saliņš & Rasnacis, 1985; Saliņš, 1987; Liepa et al., 2014), however, forests can be significantly affected by changes in climatic conditions, thus making wood biofuel collection technologically difficult and highly risky from silvicultural point of view due to ruts formation. The share of theoretically available biofuel resources in forest types with drained organic soils (*Callunosa turf. mel., Vacciniosa turf. mel., Myrtillosa truf.mel.* and *Oxalidosa turf. mel.*) are relatively small (5%) of the total. No significant difference is found between state (8% of the total) and other (5%) forests. Nutrient poor drained organic soils (stand type *Callunosa turf. mel.*) holding 1% of the total theoretically available resources, is not suitable for wood biofuel production. In forest types on drained organic soils mechanized biofuel extraction in thinning is possible only in winter, during the frost period (Saliņš et al., 1987;

Liepa et al., 2014). In the most cases distribution of resources follows to proportion of distribution of the forest types.

Previous studies show that the average extractable stock of stem wood in forest areas with 9–12 m high trees is 30–50 m^3 (Lazdiņš et al., 2013). According to the calculations, the higher average volume of stem wood (by cutting down trees in forest areas up to the minimum threshold of number of trees or basal area) in state forests is smaller (20 m^3 ha^{-1}) than in other forests (30 m^3 ha^{-1}). The largest average volume of extractable stock of stem wood (31 m^3 ha^{-1}) is characteristic in forest types with organic soils, in state forests it is 31 m^3 ha^{-1} and depending on the forest type varies from 42 m^3 ha^{-1} in *Dryopterioso-caricosa* to 20 m^3 ha^{-1} in *Sphagnosa*. In other forest stand types with organic soils, the average stock is 31 m^3 ha^{-1}, or from an average of 14 m^3 ha^{-1} in *Sphagnosa* to 43 m^3 ha^{-1} in *Caricoso-phragmitosa*. Also, a relatively large average extractable stock of stem wood (26 m^3 ha^{-1}) is characteristic for stand with dry mineral soils. In state forests it is 17 m^3 ha^{-1}, or from an average of 9 m^3 ha^{-1} in *Aegopodiosa* to 30 m^3 ha^{-1} in *Cladinoso-callunosa*. In turn, in other forest areas on dry mineral soils, the average felling stock is 31 m^3 ha^{-1}, or from an average of 25 m^3 ha^{-1} in *Myrtillosa* to 35 m^3 ha^{-1} in *Oxalidosa*. In forest stand types with wet mineral soils, the average extractable stock of stem wood is 20 m^3 ha^{-1}, and in state forests it is on average 18 m^3 ha^{-1}, or from an average of 8 m^3 ha^{-1} in *Dryopteriosa* to 30 m^3 ha^{-1} in *Vaccinioso-sphagnosa*. In other forests with wet mineral soils, the average stem wood volume to be harvested is 29 m^3 ha^{-1}, from an average of 13 m^3 ha^{-1} in *Myrtillosa-polytrichosa* to 50 m^3 ha^{-1} in *Dryopteriosa*. In forest types on drained mineral soils, the average stem wood stock to be felled is 19 m^3 ha^{-1}. In the state forests in the open air they are on average 20 m^3 ha^{-1}, or from an average of 8 m^3 ha^{-1} in the arena of *Vacciniosa mel.* to 28 m^3 ha^{-1} in the arena of *Mercurialiosa mel*. In other forests on drained mineral soils, the average extractable stock of stem wood is 25 m^3 ha^{-1}, from an average of 22 m^3 ha^{-1} in *Myrtillosa mel.* to 28 m^3 ha^{-1} in *Callunosa mel*. According to the calculations, the smallest average extractable stock of stem-wood (16 m^3 ha^{-1}) is observed in forest types on wet organic soils (*Sphagnosa, Caricoso-phragmitosa* and *Dryopterioso-caricosa*). In state forests on wet organic soils they are 19 m^3 ha^{-1}, from 8 m^3 ha^{-1} in *Vacciniosa turf. mel.* to 26 m^3 ha^{-1} in *Oxalidosa turf. mel*. In other forests with organic soils, the average stock to be felled is 20 m^3 ha^{-1}, or from 7 m^3 ha^{-1} in *Oxalidosa turf. mel.* to 50 m^3 ha^{-1} in *Vacciniosa turf. mel*.

Analyzing the theoretically available stem wood volume resources in forest areas with average tree height of 9–12 m, depending on the dominant tree species, it must be concluded that in state forests the majority (69%) of resources are located in coniferous stands – respectively, 45% in pine stands and in 24% spruce stands. Deciduous stands contain 31% of the resources. In other forests, the theoretically available stem wood resources are concentrated mainly in deciduous tree stands (87%), mostly in forest areas where the dominant species is white alder (38%). Coniferous stands in other forests account for 13% of the theoretically available resource potential.

The assessment of technically available wood biofuel resources shows that in forest areas with the average tree height of 9–12 m 757 thous. tons of felling residues and 886 thous. m^3 of firewood are technically available for mechanized thinning. State forests holds 20% of technically available resources, but the most of the resources are concentrated in other forests (605 thous. tons of logging residues and 715 thous. m^3 of firewood).

The evaluation of technologically available resources shows that 530 thous. tons of felling residues and 798 thous. m^3 of firewood, or a total of 4588 thous. MWh of primary energy is available for mechanised thinning. Only 19% of technologically available wood biofuel resources are concentrated in state forests. Most or 3686 thous. MWh technologically available primary energy resources are concentrated in other forest areas. 27% of the total technologically available resources can be extracted in winter and less than half (38%) of the resources accessible only in winter are located in the state forest.

Assuming that these resources are extracted within 5 years, the average amount of primary energy accesible every year is 180 thous. MWh in state-owned and 737 thous. MWh in other forests, excluding potential increase of stock in areas suitable for wood biofuel production.

3.2. Productivity indicators of mechanized thinning

3.2.1. Characteristics of prepared timber

When using John Deere 1070 E with felling head in mechanized thinning, the proportion of felled trees with a stem volume not exceeding 0.1 m^3 is 94%. When working with Rottne H8 with felling head and John Deere 1070 D with accumulating Bracke C.16 head, the proportion of felled trees with stem volume not exceeding 0.1 m^3 is 82.7% and 99.8% of the total number of felled trees, respectively. Comparing the data obtained in thinning using chainsaws, it was concluded that in stands with an average tree height of 9–12 m, the stem volume of most or 94.4% of the felled trees does not exceed 0.1 m^3 (Fig. 3.2). This finding is in line with conclusions of earlier studies about considerable proportion of undergrowth trees in stands that have not been systematically maintained and about negative effect of the undergrowth trees on the productivity of harvesters (Lazdāns et al., 2006).

Indicators characterizing the dimensions of trees felled in thinning and the extracted stock is given in Table 3.1. In total 16.7 thous. trees were felled with a John Deere 1070 E harvester resulting in 591 m^3 of timber extracted. The average height of the felled tree was 12.3 m, but the DBH = 8.8 cm (average stem volume 0.04 m^3). Within the scope of the Rottne H8 trials 17.9 thous. trees were felled resulting in 1,089 m^3 of timber extracted, the average height of the felled tree was 11.4 m, but the DBH = 10.2 cm (average stem volume 0.07 m^3). In the areas where the John Deere 1070 D harvester with Bracke C.16 was used, 13.4 thous. trees were felled resulting in 86 m^3 of biomass. The average height of the felled trees was 8.0 m, but the DBH = 4.3 cm (average stem volume 0.01 m^3). In thinning with a John Deere 1070 D with Bracke C.16 harvesting head, the number of the felled trees is relatively large, however, the amount of biomass produced is relatively small. The situation could be explained by the fact that a relatively large proportion of the felled trees (Fig. 3.2) are undergrowth and small trees, which according to the terms of reference were not intended to be sawn, unless they interfere with the execution of works. Working with Bracke C.16 this requirement is not easy to fulfil.

Table 3.1

Characterization of dimensions and volume of extracted trees

Harvester	Stand code	Number of trees, pcs.	Average diameter of felled tree, cm	Average height of felled tree, m	Volume of logs produced, m³	Volume of average processed tree, m³
John Deere 1070 E	502-427-6	3706	8.2 ± 0.09	11.6 ± 0.09	102	0.03 ± 0.001
	502-434-1	5364	9.4 ± 0.07	12.9 ± 0.05	209	0.04 ± 0.001
	503-329-1	579	9.5 ± 0.19	12.7 ± 0.16	33	0.06 ± 0.003
	503-432-8	3203	7.7 ± 0.07	11.3 ± 0.07	83	0.03 ± 0.001
	503-479-12	3499	9.3 ± 0.07	12.8 ± 0.06	153	0.04 ± 0.001
	503-481-6	397	7.5 ± 0.19	11.1 ± 0.20	11	0.03 ± 0.002
Rottne H8	503-300-12	8228	10.0 ± 0.05	11.4 ± 0.02	488	0.06 ± 0.001
	503-317-7	3845	10.4 ± 0.07	11.5 ± 0.03	233	0.06 ± 0.001
	503-318-17	1022	11.3 ± 0.14	11.9 ± 0.06	73	0.07 ± 0.002
	503-318-30	3318	9.7 ± 0.08	11.2 ± 0.04	176	0.05 ± 0.001
	503-329-1	1474	11.3 ± 0.13	11.9 ± 0.05	119	0.08 ± 0.002
John Deere 1070 D	502-427-6	13 454	4.3 ± 0.05	8.0 ± 0.05	86	0.01 ± 0.0004

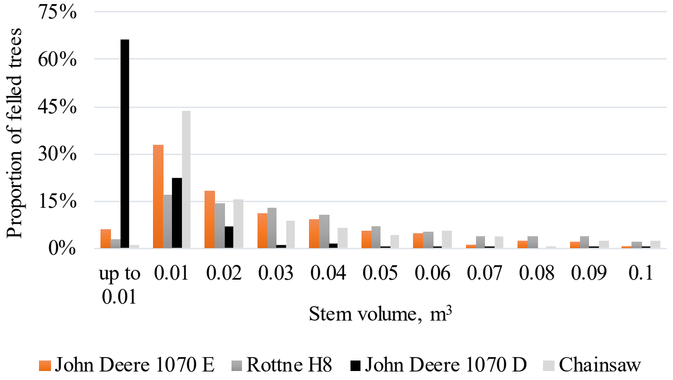


Fig. 3.2. **Relative distribution of felled trees by stem volume**

The characteristics of the dimensions of the trees felled during the trials and the volume of the extracted yield are given in Table 3.1 visualizing the extracted volume by the stem volume groups, it was found that most of the volume prepared timber (from 67.6% with Rottne H8 to 95.3% with John Deere 1070 D) is produced from trees with a stem volume not exceeding 0.15 m^3. A similar situation was observed in trials with chainsaw (Kalēja et al., 2015), when stem volume of 98.3% of sawn trees did not exceeding 0.15 m^3.

3.2.2. Average productivity of harvesters

In total duration of time studies during the research corresponded to 456 operating hours.

In average 158 trees were processed in the productive hour using John Deere 1070 E resulting in 5.6 m^3 of timber extracted. The average productivity per productive work hour (excluding the time spent entering and leaving the stand) is 5.8 m^3 (average volume of the processed tree 0.03 m^3). The average productive work time of the total work time (duration of shift) is 83.5%, while 4.6% of the productive work time is spent to enter and to leave the stand.

When working with the Rottne H8 harvester, 81 trees were processed in an average per productive hour producing of 5.0 m^3 of timber extracted. The average achieved productivity is 5.3 $m^3\ E_{15}\ h^{-1}$ (average volume of the felled tree stem 0.06 m^3), excluding the time spent entering and leaving the stand. The average productive work time of the total work time is 83.7%, including 6.1% of the productive work time entering and leaving the stand. According to the results, the share of productive work time in total work time is relatively high and is higher than found (81.6%) in similar studies in mechanized thinnings (Sirén, 2003).

With the John Deere 1070 D harvester 271 trees were processed in an average productive hour resulting in productivity of 1.7 $m^3\ E_{15}\ h^{-1}$ of wood biofuel. The average achieved productivity is 1.8 $m^3\ E_{15}\ h^{-1}$ (average volume of felled tree 0.01 m^3), if the time spent entering and leaving the stand is excluded from calculation. The average share of productive work time of the total work time is 75.2%, including 3.4% of the productive work time spent for entering and leaving the stand. Although the number of trees processed per productive work hour is relatively high, productivity was significantly affected by the small dimensions of the felled trees, which is in line with the findings of similar studies (Sirén, 2003). Also, operators did not fully follow the methodological instructions by cutting trees with the DBH < 3 cm, even if they do not interfere with the harvesting operations (Table 3.2).

Comparing the average productivity indicators of different harvesters used in the trials, depending on the volume of the felled stem, is provided in Figure 3.3. The best results were achieved with John Deere 1070 E equipped with H 754 felling head, followed by John Deere 1070 D with Bracke C16.b head and Rottne H8 with EGS 405 felling head. Significant differences ($p < 0.05$) were found when comparing productivity of John Deere 1070 E and Rottne H8 harvesters. Although comparative studies using a chainsaw did not take place in the research trials, data obtained in other stands with similar tree dimensions were used to compare productivity (Kalēja et al., 2015). Overall, chainsaw productivity is significantly lower ($p < 0.05$ compared to John Deere 1070 E, John Deere 1070 D and Rottne H8). As the volume of the felled stem increases, the productivity increases, however, when certain tree dimensions are reached (for John Deere 1070 E – 0.33 m^3; for Rottne H8 – 0.32 m^3; and for John Deere 1070 D – 0.16 m^3), productivity remains at the same level.

Table 3.2

Summary of indicators by forest stand specific to forest machinery

Harvester	Stand code	Engine hours worked	Average productivity, trees E_{15} h^{-1}	Productive work time of total work time, %	Driving in and out, % E_{15}	Average productivity, m^3 E_{15} h^{-1}	Average productivity (excluding driving), m^3 E_{15} h^{-1}
John Deere 1070 E	502-427-6	22.3	174 ± 4	95.6	3.0	4.8 ± 0.1	4.9 ± 0.1
	502-434-1	41.8	164 ± 3	78.4	3.7	6.4 ± 0.1	6.6 ± 0.1
	503-329-1	6.1	117 ± 5	80.3	6.7	6.6 ± 0.3	7.1 ± 0.3
	503-432-8	25.1	155 ± 4	82.7	5.2	4.0 ± 0.1	4.2 ± 0.1
	503-479-12	28.6	146 ± 3	83.6	5.9	6.4 ± 0.2	6.8 ± 0.2
	503-481-6	3.2	151 ± 5	81.4	8.8	4.3 ± 0.2	4.7 ± 0.2
Rottne H8	503-300-12	120.4	75 ± 3	91.3	7.4	4.4 ± 0.2	4.8 ± 0.2
	503-317-7	54.7	94 ± 2	75.1	6.0	5.7 ± 0.1	6.0 ± 0.1
	503-318-17	12.6	96 ± 2	84.5	2.5	6.9 ± 0.2	7.1 ± 0.2
	503-318-30	54.8	82 ± 3	74.2	3.6	4.3 ± 0.3	4.5 ± 0.2
	503-329-1	20.1	84 ± 2	86.7	6.0	6.8 ± 0.2	7.2 ± 0.1
John Deere 1070 D	502-427-6	66.1	271 ± 4	75.2	3.4	1.7 ± 0.1	1.8 ± 0.1

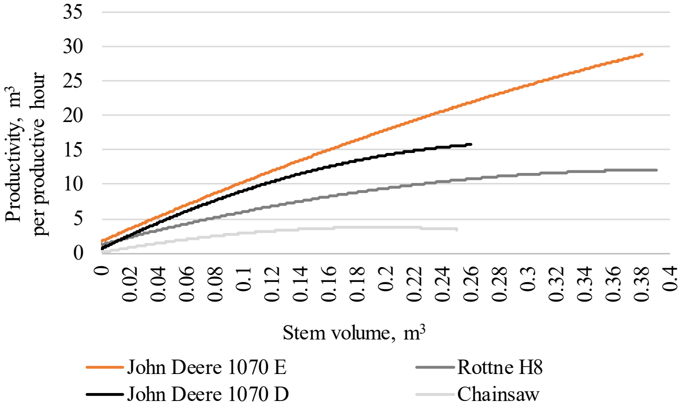


Fig. 3.3. **Comparison of average productivity of harvester and chainsaw in thinning by stem volume group**

The regression function can explain 91.5% (John Deere 1070 E), 81.9% (Rottne H8) and 80.4% (John Deere 1070 D) of the changes in the productivity depending from dimensions of extracted trees. When using a chainsaw, 50.3% of the changes in productivity can be explained by the regression function. When assessing the significance of the regression equation, the p-value of the F-test is less than 0.05 in all cases, which means that the regression equations statistically significantly explain the changes in the productivity, depending on the DBH or volume of the processed trees. The coefficients of the regression equations characterizing the performance of the machines and a chainsaw used in thinning are given in Table 3.3.

Table 3.3

Results of regression analysis of average productivity of harvesters and chainsaws in thinning

Coefficient	Value of coefficient	Standard error	Actual value of the t-test	p-value
John Deere 1070 E				
a	0.895868	1.071575	0.836028709	0.409338255
b	91.19156	14.47364	6.300525578	$4.56023E^{-07}$
c	–49.6721	40.70066	–1.220424181	0.231221528
Rottne H8				
a	1.712063049	0.682744814	2.507617799	0.017094225
b	53.8443728	9.040072109	5.956188419	$9.8169E^{-07}$
c	–69.75723927	24.73321021	–2.820387595	0.007947637
John Deere 1070 D				
a	0.637783567	1.46680713	0.43481079	0.67210702
b	100.7931133	31.43759951	3.206132621	0.008362893
c	–163.9584908	121.6288765	–1.348022736	0.204755484
Chainsaw				
a	0.095346751	0.675377142	0.141175567	0.889299216
b	37.64778433	13.14094294	2.864922593	0.010295621
c	–97.0220595	55.29421225	–1.754651266	0.096325984

Comparing the proportion of work time elements in the productive time per 1 m^3, it was found that delimbing/cross-cutting and boom-out are the most time consuming operations, respectively, from 20.6% with John Deere 1070 E to 31.6% with Rottne H8 and from 12.8 % with Rottne H8 to 33.6% with John Deere 1070 E. The least time consuming work element is transferring of tops and branches to another location, e.g. strip road (from 0.1% with John Deere 1070 E to 1.6% with Rottne H8). This is explained by good work conditions. The next the least time consuming operation is felling (from 3% with Rottne H8 to 8.1% with John Deere 1070 E). The time spent entering, moving in the stand and leaving the stand is calculated as the average value for each of the harvesters used in the thinning. These indicators are greatly influenced by the stand shape and size. The productive time spent entering and leaving the stand ranged from 1.3% for John Deere 1070 E to 2.2% for Rottne H8 and from 2.1% for John Deere 1070 E to 3.9% for Rottne H8.

3.2.3. Influence of the working method on productivity indicators

Two working methods were compared in the thinning. The first working method envisages the production of the assortments specified in the standard work order by JSC “Latvia’s State Forests” and production of wood biofuel from tree tops and stems, which are not suitable for the production of other roundwood assortments. The working method also envisages the maximum use of stem accumulating device in the production of energy wood. The second work method envisages the production of wood biofuel (partly delimbed stem wood) from all felled trees ensuring maximum use of stem accumulating device. Harvester with Bracke C.16 felling head produces undelimbed biomass. Crosscutting is done if extracted stems are longer than 6 m.

While working with the first working method (John Deere 1070 E and Rottne H8 harvesters), 1,176 m^3 of timber was extracted (17,724 work cycles), and with the second method (John Deere 1070 E and John Deere 1070 D harvesters) – 119 m^3 of biomass was extracted (3,138 work cycles). Higher average productivity was achieved using 2nd working method. A comparison of forest machine-specific indicators between the working methods used is presented in Table 3.4.

Table 3.4

Comparison of harvester productivity and stand parameters by working method applied

Harvester	Working method	Number of observations	Productive work time of total work time, %	Amount of logs produced, m^3	Average productivity, $m^3 E_{15} h^{-1}$	Volume of average felled tree, m^3	Diameter of average felled tree, cm	Numer of trees, pcs.	Average number of processed trees per work cycle, pcs.
John Deere 1070 E	1.	6247	85.7	396.6	5.4 ± 0.2	0.05 ± 0.1	8.6 ± 0.3	12 167	2.0 ± 0.1
	2.	500	61.0	33.4	4.0 ± 0.3	0.05 ± 0.1	8.3 ± 0.2	837	1.5 ± 0.1
Rottne H8	1.	11 477	82.1	779.5	5.0 ± 0.2	0.07 ± 0.1	10.2 ± 0.5	13 081	1.2 ± 0.1
John Deere 1070 D	2.	2638	75.2	86.0	1.7 ± 0.1	0.01 ± 0.1	4.0 ± 0.3	13 454	5.2 ± 0.3

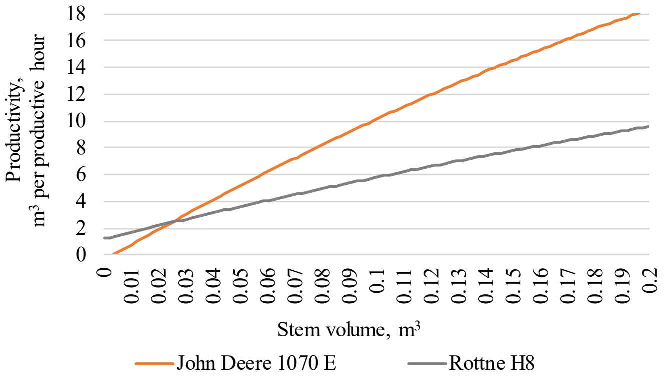


Fig. 3.4. **Comparison of average harvesters' productivity indicators by the stem volume group for the first working method**

Comparing the average productivity in the group of the respective stem volume, using the 1st working method during thinning, better result was achieved using John Deere 1070 E harvester with H 754 felling head. The difference is statistically significant ($p \leq 0.05$). Significantly higher average productivity values were achieved both when processing small dimensional trees (Rottne H8 reported 33% lower productivity compared to John Deere 1070 E in the group of wood volume >0.01 m^3) and bigger (in the group of wood volume 0.06– 0.07 m^3 the productivity of the Rottne H8 is 29% lower than that of the John Deere 1070 E). When the volume of the stem reaches 0.45 m^3, the productivity of John Deere 1070 E harvester stops increasing (Fig. 3.4).

Comparing the average productivity indicators in the respective stem volume group, using 2nd working method in thinning, better productivity was achieved using John Deere 1070 E harvester with felling head, moreover, the difference is statistically significant ($p < 0.05$, Fig. 3.5). John Deere 1070 E harvester shows significantly

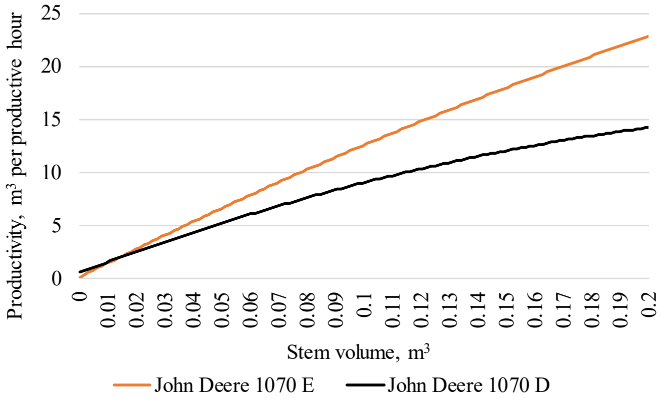


Fig. 3.5. **Comparison of average harvester productivity by the stem volume groups for the second working method**

higher average productivity, both for small trees (if the stem volume is <0.01 m^3, the productivity of John Deere 1070 D with Bracke C.16 felling head is by 29% lower than that of John Deere 1070 E) and bigger (if the average volume of a stem is 0.26 m^3, the productivity of John Deere 1070 D is by 47% lower than of John Deere 1070 E). The relatively small average volume of processed wood (only 0.01 m^3) is one of the main factors influencing the productivity of John Deere 1070 D – despite the operators' active use of the stem accumulating mechanism (on average 5.2 trees treated in a work cycle), the average productivity is relatively low. When the stem volume reaches 0.6 m^3, productivity of John Deere 1070 E also stops to increase.

The regression equation can explain 90.3% (John Deere 1070 E) and 62.6% (Rottne H8) of the changes in productivity using 1st working method in thinning. The assessment of the significance of the regression equation shows that the p-value of the F-test is less than 0.05 in all cases, which means that the regression equations statistically significantly explain the changes in the productivity. The results of the regression analysis of the productivity of 1st working method for each of the harvesters is given in Table 3.5.

Table 3.5

Results of regression analysis of average productivity indicators characteristic for the first working method

Coefficient	Value of coefficient	Standard error	Actual value of the t-test	p-value
John Deere 1070 E				
a	–0.392485877	1.071786405	–0.36619785	0.716360811
b	117.1869614	7.931463586	14.77494792	7.40103E^{-17}
c	–117.2486243	11.87811014	–9.870983088	8.77875E^{-12}
Rottne H8				
a	1.215406733	1.261608711	0.96337852	0.339499356
b	49.87584282	8.167626856	6.106528089	1.01938E^{-07}
c	–40.14429025	11.2784911	–3.559367108	0.000766239

The regression equation can explain 96.1% (John Deere 1070 E) and 80.4% (John Deere 1070 D) of the changes in productivity using 2nd working method in thinning. The assessment of the significance of the regression equation shows that the p-value of the F-test is less than 0.05 in all cases, which means that the regression equations statistically significantly explain the changes in the productivity. The results of the regression analysis of the productivity of 2nd working method for each of the harvesters is given in Table 3.6.

Table 3.6

Results of regression analysis of average productivity indicators of the second working method

Coefficient	Value of coefficient	Standard error	Actual value of the t-test	p-value
John Deere 1070 E				
a	1.253042767	1.084604249	1.155299518	0.260361827
b	113.2956835	12.03230992	9.415954568	3.56682E^{-09}
c	–49.89734084	22.9636665	–2.172882142	0.040836327
John Deere 1070 D				
a	0.637783567	1.46680713	0.43481079	0.67210702
b	100.7931133	31.43759951	3.206132621	0.008362893
c	–163.9584908	121.6288765	–1.348022736	0.204755484

3.2.4. Influence of the harvester operators on productivity indicators

Similar studies have concluded that operators' work habits have a significant impact on forest machine productivity (Kärhä et al., 2004), so the performance of operators using different working methods has been taken into account when analyzing the impact of working methods on the productivity.

Work with John Deere 1070 E harvester using 1st working method, which involves the production of standard assortments and partly delimbed log assortment, using to a maximum stem accumulating device, was performed by two operators (hereinafter A and B). Rottne H8 harvester, on the other hand, was operated by four operators (hereinafter – C, D, E and F).

The average productivity of John Deere 1070 E harvester acquired by both operators is similar, however, when analyzing the changes in average productivity in different stem volume groups (Fig. 3.6) statistically significant ($p \leq 0.05$) differences are observed, when processing trees with a volume of more than 0.1 m^3, the average productivity reported by operator A are significantly better. The average productivity reported by different operators of Rottne H8 harvester also differed statistically significantly ($p \leq 0.05$) in different stem volume groups and the average productivity, depending on the operator, ranged from 4.2 m^3 (average stem volume 0.06 m^3) for operator C to 6.8 m^3 the volume of the felled stem 0.08 m^3) for operator E (Table 3.7).

The differences in the productivity can be explained by a different approach to the choice of trees to be processed, which affects the time of felling and delimbing, as well as the efficiency of the use of work time. The operator who has demonstrated the worst productivity indicators also has the lowest share of productive time in total work time (80.7%). Using the equation to calculate productivity at different volumes of processed trees (from 0.01 to 0.10 m^3), the productivity of operators increases from 1.3 to 6.2 m^3 E$_{15}$ h^{-1} for operator C; from 1.1 to 6.9 m^3 E$_{15}$ h^{-1} for operator D; from 1.4 to 9.0 m^3 E_{15} h^{-1} for operator E and from 1.5 to 7.3 m^3 E_{15} h^{-1} for operator F (Fig. 3.6).

Table 3.7

Comparison of indicators characteristic of harvester operators using the first working method in thinning

Harvester	Operator	Number of observations	Productive work time of total work time, %	Amount of timber prepared, m^3	Average productivity, m^3 E_{15} h^{-1}	Volume of average extracted tree ,m^3	Average diameter of felled tree, cm	Number of trees, pcs.	Average number of felled stems per work cycle, pcs.
John Deere 1070 E	A	2578	86.7	169	5.4 ± 0.1	0.05 ± 0.1	8.7 ± 0.1	5143	2.0 ± 0.1
	B	3669	84.6	227	5.4 ± 0.1	0.05 ± 0.1	8.5 ± 0.1	7024	1.9 ± 0.1
Rottne H8	C	3256	80.7	197	4.2 ± 0.1	0.06 ± 0.1	9.7 ± 0.1	3614	1.2 ± 0.1
	D	1355	87.9	103	5.2 ± 0.1	0.07 ± 0.1	10.6 ± 0.1	1612	1.2 ± 0.1
	E	1493	83.0	124	6.8 ± 0.1	0.08 ± 0.1	11.0 ± 0.1	1726	1.2 ± 0.1
	F	5373	81.4	356	5.0 ± 0.1	0.07 ± 0.1	10.1 ± 0.1	6129	1.2 ± 0.1

The regression equation can explain 94.6% of John Deere 1070 E, operator A; 86.1% John Deere 1070 E, operator B; 79.3% Rottne H8, operator C; 46.9% Rottne H8, operator D; 65.7% Rottne H8, operator E; and 65.7% Rottne H8, operator F, changes in productivity depending from dimensions of processed trees when using 1st working method in mechanized thinning. The assessment of the significance of the regression equation shows that the p-value of the F-test is

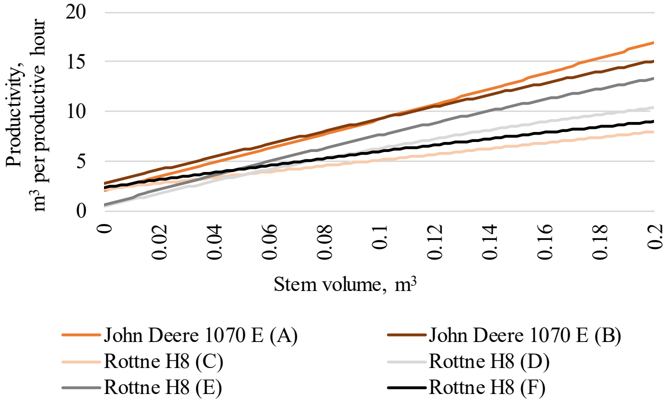


Fig. 3.6. **Comparison of average productivity indicators of harvester operators using the first working method**

less than 0.05 in all cases, which means that the regression equations statistically significantly explain the changes in the productivity. The results of the regression analysis of the average productivity indicators typical for operators can be seen in Table 3.8.

Table 3.8

Results of regression analysis of average productivity indicators characteristic for the first working method in division by operators

Coefficient	Value of coefficient	Standard error	Actual value of the t-test	p-value
John Deere 1070 E (A)				
a	2.042517457	1.275798071	1.600972367	0.118914112
b	69.09181806	10.68001269	6.469263669	$2.44067E^{-07}$
c	28.10805641	17.60256374	1.596816056	0.119839834
John Deere 1070 E (B)				
a	2.800532314	1.505424111	1.86029458	0.074647829
b	68.07231263	11.54399308	5.896773512	$3.74428E^{-06}$
c	–32.10077992	16.5174589	–1.943445425	0.063301939
Rottne H8 (C)				
a	2.224266406	0.799775124	2.781114763	0.008383649
b	29.36166259	8.385868773	3.501326265	0.00120053
c	–2.55393094	18.72031472	–0.136425641	0.892205023
Rottne H8 (D)				
a	0.488907745	1.665267292	0.293591153	0.770804278
b	67.13056831	14.63665764	4.586468437	$5.55678E^{-05}$
c	–88.34044146	26.81592348	–3.294327772	0.002264308
Rottne H8 (E)				
a	0.657544265	1.790313837	0.36727877	0.715132759
b	76.44044839	12.69852825	6.019630532	$2.91973E^{-07}$
c	–65.08940487	18.68802088	–3.482947996	0.001116028
Rottne H8 (F)				
a	0.657544265	1.790313837	0.36727877	0.715132759
b	76.44044839	12.69852825	6.019630532	$2.91973E^{-07}$
c	–65.08940487	18.68802088	–3.482947996	0.001116028

Using 2nd working method, which envisages the production of only wood biofuel in the mechanized thinning, the work was performed by two John Deere 1070 E operators (A and B) and one John Deere 1070 D operator (G). The best average productivity (4.5 m^3 E_{15} h^{-1} at an average stem volume of 0.05 m^3) was shown by John Deere 1070 E operator B (Table 3.9).

Table 3.9

Comparison of indicators characteristic of harvester operators using the second working method in thinning

Forrest machine	Operator	Number of observations	Productive work time of total work time, %	Amount of timber prepared, m^3	Average productivity, m^3 E_{15} h^{-1}	Volume of average felled tree, m^3	Average diameter of felled tree, cm	Number of trees, pcs.	Average number of trees processed felled per work cycle, pcs.
John Deere 1070 E	A	20	53.4	1	3.5 ± 0.1	0.04 ± 0.1	7.4 ± 0.1	28	1.4 ± 0.1
	B	480	68.7	33	4.5 ± 0.1	0.05 ± 0.1	9.3 ± 0.1	809	1.7 ± 0.1
John Deere 1070 D	G	2638	75.2	86	1.7 ± 0.1	0.01 ± 0.1	4.0 ± 0.1	13 454	5.2 ± 0.1

Although the average productivity for the operators differed when comparing the productivity achieved when processing stems of different volumes (Fig. 3.7), no statistically significant differences were found between operators ($p > 0.05$). Using the equation to calculate productivity rates at different stem volumes (from 0.01 to 0.10 m^3), the productivity rates reported by operators increase from 1.7 to 7.8 m^3 E_{15} h^{-1} John Deere 1070 E, operator A; from 2.1 to 13.8 m^3 E_{15} h^{-1} John Deere 1070 E, operator B; from 1.9 to 10.9 m^3 E_{15} h^{-1} John Deere 1070 D, operator G.

The regression equation can explain 65.9% of John Deere 1070 E, operator A; 96.4% John Deere 1070 E, operator B; and 80.4% of John Deere 1070 D, operator G, changes in productivity when working with 2nd working method. The assessment of the significance of the regression equation shows that the p-value of the F-test is less than 0.05 in all cases, which means that the regression equations

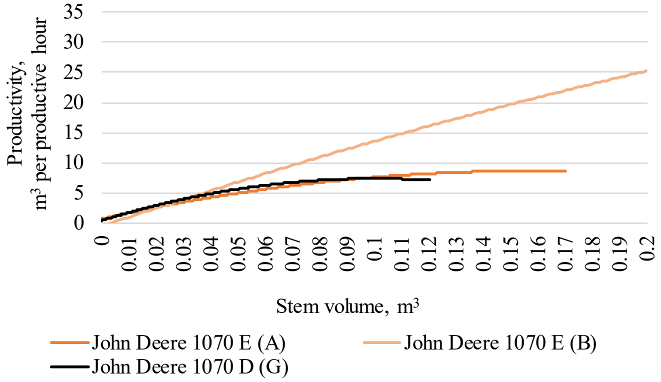


Fig. 3.7. **Comparison of average productivity values of harvester operators working with the second working method**

statistically significantly explain the changes in the average productivity. Operator-specific results of regression analysis of average productivity are provided in Table 3.10.

Table 3.10

Results of regression analysis of average productivity indicators characteristic for the second working method by harvester operators

Coefficient	Value of coefficient	Standard error	Actual value of the t-test	p-value
John Deere 1070 E (A)				
a	0.739434	1.422371	0.51986	0.621776
b	100.7864	47.88097	2.104936	0.07993
c	–320.846	262.7422	–1.22115	0.267834
John Deere 1070 E (B)				
a	–0.503	1.568134	–0.32138	0.752086
b	152.7976	17.95734	8.508921	$2.47E^{-07}$
c	–119.708	36.40862	–3.28791	0.004636
John Deere 1070 D (G)				
a	0.637784	1.466807	0.434811	0.672107
b	100.7931	31.4376	3.206133	0.0083663
c	–163.958	121.6289	–1.34802	0.204755

When using 1st working method, the productivity achieved by John Deere 1070 E harvester varies from 1.2% (stem volume 0.05 m^3) to 38% (stem volume 0.07 m^3) for the operators involved in the tests, depending on the volume of the processed trees.

Using 2nd working method, the productivity achieved by John Deere 1070 E forestry machine operators varies from 0.4% (stem volume 0.04 m^3) to 59% (stem volume 0.02 m^3), depending on the volume of the logs cut.

3.3. Economic efficiency of mechanized thinning

One of the main factors influencing the choice of a harvester for mechanized thinning in forest areas with 9–12 m high trees is labour costs. The issue of increasing the productivity and economic profitability of harvesters is still relevant for service buyers, as well as for service providers. Previous research has shown that the use of technology allows to increase productivity by at least 16% (Bergström, 2009; Bergström et al., 2010; Lazdiņš, 2012), thus improving the economic benefits of mechanized thinning and wood biofuel production.

Thinning mainly produces small wood suitable for the production of wood biofuel (the volume of the most of stems is from 0.01 to 0.10 m^3), therefore it is important to find a balance between the costs of timber production and the market price at which the produced timber can be sold. In the analysis of the costs of mechanized timber preparation, the average productivity indicators obtained in the experiments were used and the cost of productive hours for each of the used harvesters was calculated. For both medium-sized harvesters, the average effective hourly cost is calculated to be EUR 49, while the cost-effective hourly cost for a small-sized harvester is EUR 46, i.e. 6% smaller. Hourly labour costs are significantly affected by assumptions about operators' remuneration, the technical readiness and efficiency of machinery, which can double the estimated hourly labour costs. The obtained results show that the timber preparation costs of John Deere 1070 E medium-sized harvester are lower than with the other two harvesters used (Fig. 3.8).

Researchers from different countries have carried out productivity studies in order to develop the most accurate possible models for calculating timber production costs, which allow predicting expected and actual production costs. To calculate the costs of wood biofuel production, the supplemented and adapted cost calculation base model developed within the activity of COST project FP0902 is used, which envisages cost calculation both for individual logging operations and system costs of the logging (Kalēja et al., 2018b).

In timber preparation, the costs of all tested harvesters were compared with the costs and productivity values specific to each machine. Timber production costs consist of three groups of cost items and projected profit. Labour costs account for the largest share of the total annual cost of forestry machinery and range from 37% (John Deere 1070 E) to 41% (Rottne H8). Investment costs are the second largest cost item and range from 29% (Rottne H8) to 34% (John Deere 1070 D), depending on the harvester used. Total operating costs range from 21% (Rottne H8) to 25% (John Deere 1070 E and John Deere 1070 D), respectively.

Using medium-sized harvesters John Deere 1070 E and John Deere 1070 D in mechanized logging operations, at the achieved average productivity of each machine, it is possible to prepare during the year (2,880 productive work hours), respectively 14 thous. m^3 of timber and 6 thous. LV m^3 of wood biofuel, working with John Deere 1070 E, and 5 thous. m^3 of timber and 1 thous. LV m^3 of wood

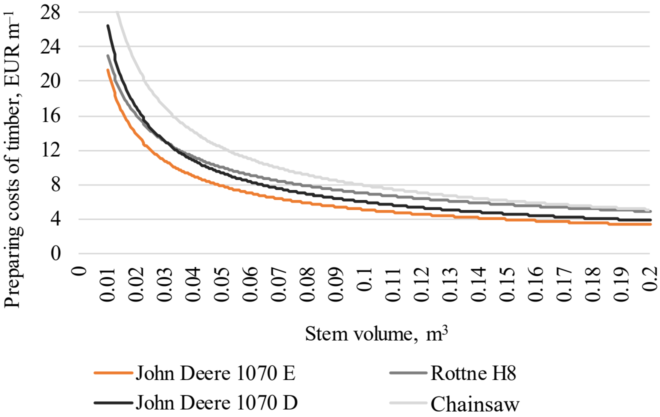


Fig. 3.8. **Timber production costs by different harvesters depending on the volume of the extracted trees**

biofuel when working with John Deere 1070 D. The small-sized harvester Rottne H8 prepares 15 thous. m^3 of timber and 6 thous. LV m^3 of wood biofuel per year (average achieved productivity 5 m^3 E$_{15}$ h^{-1}; 2,880 productive work hours). Average timber preparation costs are significantly affected by machine productivity (Table 3.11). The lowest timber production costs were achieved using John Deere 1070 E harvester (average productivity 5.6 m^3 E$_{15}$ h^{-1}). With Rottne H8 harvester, the average timber production costs are 11% (average capacity 5 m^3 E$_{15}$ h^{-1}) higher than with John Deere 1070 E harvester with H 754 head. On the other hand, the average productivity of John Deere 1070 D (1.7 m^3 E$_{15}$ h^{-1}) has had a significant impact on timber production costs, compared to John Deere 1070 E – they have increased by 72%. A comparison of timber preparation costs for harvesters used in thinnings is shown in Table 3.11.

Table 3.11

Comparison of timber production costs for different harvesters

Indicators	John Deere 1070 E	Rottne H8	John Deere 1070 D
Summary of costs, EUR per year	141 399	131 300	142 477
Investment cots	45 720	38 281	46 747
Labour costs	53 363	53 363	53 363
Operational cots	35 583	33 403	35 583
Profit margin	6733	6252	6785
Productivity, m^3 E$_{15}$ h^{-1}	5.6	5.0	1.7
Total amount of roundwood, m^3 per year	17 521	15 488	5319
roundwood	13 568	11 740	4359
solid biofuel and stem residues	1050	1209	52
biofuel and logging residues	1411	1247	428
bark and other residues	1492	1291	480
Biofuel, LV m^3 per year	5906	5896	1152
Average timber preparation costs, EUR LV m^{-3}	7.6	8.5	26.8

The smaller average effective hourly labour costs for timber preparation were calculated for John Deere 1070 E and Rottne H8 (EUR 46 E$_{15}$ h^{-1}) in thinning, while the John Deere 1070 D harvester had higher average hourly labour costs (EUR 49 E$_{15}$ h^{-1}). With a 10% reduction in harvester work load (productive hours) per year, the average productive hour cost of Rottne H8 harvester increases by EUR 3 E$_{15}$ h^{-1} and for John Deere 1070 D and John Deere 1070 E harvesters – by EUR 4 E$_{15}$ h^{-1}.

When comparing the costs of different harvesters and technological processes, it is useful to make a comparison in relative terms, because wages and planned technical availability and workload can have a significant impact on hourly labour costs and the whole comparison results.

The total costs of wood biofuel production include not only the costs of production, but also the costs of forwarding, comminution and delivery, or the technological process of logging. The calculations use average values obtained in earlier studies, which characterize investment, labour and operating costs, as well as average productivity. It is possible to choose two delivery scenarios in the supply of wood biofuel to the final consumer. It is assessed in the scenario evaluation that the average DBH = 8 cm for all harvesters. The first of the scenarios involves the supply of partly delimbed logs to the consumer. In this scenario, the costs of timber production, delivery and removal ranges from EUR 8.1 LV m^{-3} (John Deere 1070 E) to EUR 10.5 LV m^{-3} (Rottne H8, Fig. 3.9).

In the 2nd scenario, the wood biofuel is shredded at the roadside and delivered to a consumer in the form of chips. The costs of production, forwarding, chipping and delivery of produced chips ranges from EUR 7.9 LV m^{-3} (John Deere 1070 E) to EUR 11.0 LV m^{-3} (Rottne H8, Fig. 3.10).

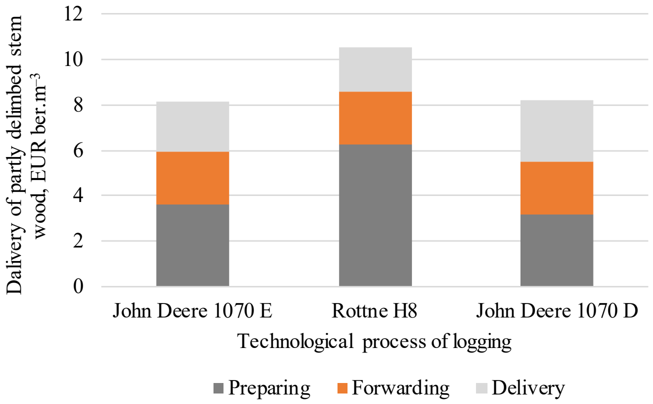


Fig. 3.9. **Production costs in partly delimbed stem wood supply scenario**

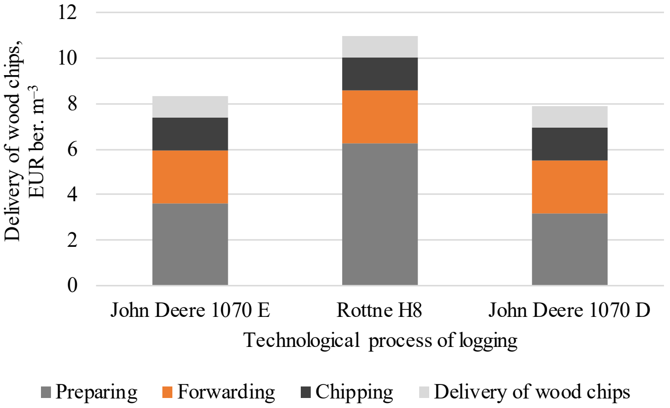


Fig. 3.10. **Production costs in wood chips supply scenario**

Previous studies show that the scenario of delivery of partly delimbed logs is one of the possibilities to deliver the prepared timber to a consumer (Kalēja et al., 2014). The calculations made in the thesis show that by choosing the scenario of delivery of partly delimbed logs, the costs of the biomass delivery can be reduced from 2% (John Deere 1070 E) to 5% (Rottne H8). Although the obtained results show that in certain conditions the use of the partly delimbed logs supply scenario would reduce the costs of logging, in Latvia this approach is not used in practice and similar studies show that small capacity of roundwood trucks makes their use less economically efficient (Kalēja et al., 2014). Production of wood biofuel using John Deere 1070 D in the wood chips supply scenario reduces the costs of the logging process by 2% compared to the whole tree supply scenario. The chip supply scenario has also been recognized as the most cost-effective in similar studies (Kalēja et al., 2014) and in this approach is also used in practice.

The results of the research confirm the hypothesis of the study about the profitability of wood biofuel production by choosing the appropriate technique. John Deere 1070 E harvester with a H 754 felling head equipped with additional grippers demonstrated relatively the smallest timber and energy wood production costs, regardless of the working method applied (average timber preparation costs EUR 7.6 m^{-3}; average extracted tree height 12.3 m, $D_{1.3} = 8.8$ cm, average stem volume 0.04 m^3). At the same time, the use of standard equipment theoretically allows to increase the efficiency of the use of equipment and reduce the costs of relocation of equipment, performing logging in thinnings and regenerative felling of small trees, e.g. grey alder stands.

The use of John Deere 1070 D harvester with a Bracke C.16 head proved to be a relatively inefficient solution (average biomass production costs EUR 26.8 m^{-3}), but the efficiency of this unit was significantly affected by significantly smaller dimensions of the felled trees (average felled tree height 8 m; $D_{1.3} = 4.3$ cm; average stem volume 0.01 m^3) at the same stand parameters, which in turn comes from the working method. When working with a medium-sized harvester equipped with a Bracke C.16 head also have to be extracted resulting in an increased work time consumption during harvesting and forwarding of biomass. The efficiency of the Bracke C.16 head can be significantly increased by changing the working method using one of the symmetrical working methods and avoiding the extraction of the smallest trees and shrubs.

CONCLUSIONS

1. According to the data of the 3rd cycle of the National Forest Inventory (2014– 2019), forest stands with an average tree height of 9–12 m occupy 7% of the total forest area in Latvia. Most, or 63%, of such forest areas are in the forests of owned by companies, private persons and municipalities. The theoretically available wood biofuel resources in these forests are 7,054 thous. m^3 (above-ground biomass 4,091 thous. t_{dry} matter), of which only 27% or 1,927 thous. m^3 (above-ground biomass 1,109 thous. t_{dry} matter) are in state forests, but in other forests theoretically 5,127 thous. m^3 (above-ground biomass 2,982 thous. t_{dry} matter) are available.
2. Technologically available resources in the respective forest areas correspond to 530 thous. tons of felling residues and 798 thous. m^3 of firewood, or a total of 4,588 thous. MWh of primary energy and only 19% of resources are concentrated in state forests. This type of resource has little economic importance, but mechanized thinning in poorly managed forest stands can contribute to the increase of the value of forest stands in the future.
3. In mechanized thinning, the highest productivity can be achieved by using a working method that envisages production of partly delimbed stems from all extracted trees. Significantly ($p = 0.01 < 0.05$) better performance in the experiments was achieved using a middle size harvester John Deere 1070 E with an H 754 head, i. e. the most common medium-sized logging solution in thinning in Latvia.
4. The total annual cost of a small-sized harvester (Rottne H8 with EGS 405 head) is up to 16% lower than that of a medium-sized harvester (John Deere 1070 E with H 754 head) and is largely influenced by relatively lower investment costs. However, when using a John Deere 1070 E harvester for thinning, the average cost of production of wood biofuel is 15% lower due to better productivity.
5. The medium-sized harvester John Deere 1070 E with H 754 head ensured relatively lower wood biofuel production costs, regardless of the working method used. The use of a John Deere 1070 D harvester with a Bracke C.16 head proved to be a relatively inefficient solution, but the efficiency of this machine was significantly affected by large proportion of small dimension trees and bushes felled, which, in turn, was a result of the working method applied. Efficiency can be significantly increased by using one of the symmetrical maintenance methods and by avoiding cutting the smallest trees and shrubs.
6. The work load of harvesters (number of productive hours) per year significantly affects the average cost of a productive hour. By reducing machine load by

10%, the cost of effective hour of Rottne H8 harvester increases by 6% and by 7–8% – of the John Deere 1070 D and John Deere 1070 E harvesters. At the same time, the use of standard equipment allows to increase the efficiency of the harvesters' use, reduce the costs of relocation of machines and increase diversity of economic activities.

7. Although the results of the study prove that in certain circumstances the supply of partly delimbed stem wood would allow to reduce the prime cost of harvesting and delivery of biomass by 2% using John Deere 1070 E and by 5% using Rottne H8, in Latvia this scenario is not used in practice due to other circumstances. Wood biofuel is mainly supplied to the final consumer using a wood chips supply scenario, which has been recognized in the study as an economically viable solution in wood biofuel targeted thinning.

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COMPARISON OF COSTS IN PRE-COMMERCIAL THINNING USING MEDIUM-SIZED AND SMALL-SIZED HARVESTERS

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The aim of this study is to compare productivity and costs of medium-sized and small-sized harvesters in pre-commercial thinning. In this study the data on harvesting productivity were obtained in stands, where biofuel was prepared using two medium-sized and two small-sized harvesters equipped with different harvester heads. In total 677 m^3 of wood was prepared with medium-sized harvester, but with small-sized harvesters 1 164 m^3 of wood was prepared. Although the total annual costs of small-class harvesters are lower by 16 %, comparing with middle-class harvesters, the productivity rates shown by the middle-class harvester John Deere 1070 E (equipped with H 754 harvester head) are significantly higher and the average wood preparation costs are lower, comparing with the other harvesters employed.

Keywords: *medium-sized harvesters, small-sized harvesters, productivity, thinning*

INTRODUCTION

According to the sustainable development strategy of Latvia until 2030, in 2020 40 % of the final energy consumption should be provided by the renewables (Atjaunojamie…, 2010; Latvijas..., 2014). Small-dimension wood is the main biofuel resource to be obtained in pre-commercial thinning (Iwarsson Wide, 2008) and can significantly increase the use of local renewable resources (Lazdāns, 2008; Lazdiņš, 2014; Lazdiņš, 2015). As the previous studies show, that amount of unused small-dimension wood is significant and in pre-commercial thinning constitutes from 700 to 900 thousand m³ annually (Lazdāns, 2006). The largest potential of energy wood in Latvia is concentrated in forest stands, whose age ranges from 21 to 30 years (the average tree height of the stand ranges from 10 to 11 m) (Lazdāns, 2006; Lazdiņš, 2013). Several different technical and technological solutions are possible regarding extraction of energy wood (Lazdiņš, 2012). Nowadays the energy wood and logs prepared in thinnings are delivered to industrial manufacture, which is related to certain quality standards, therefore also in Latvia, following the example of other Nordic countries, in the recent years pre-commercial thinnings are increasingly mechanized, however this process is slow and to a great extent influenced by the lack of qualified labour force and the large investments. Nowadays harvesters are built and classified according to their tasks and the suitability of the machine type for a certain felling type is mainly determined by machine dimensions, its ability to move in the felling site and its engine power. In Latvia medium-sized harvesters are mainly used in logging, because the machines are relatively compact and can be adapted to both thinnings and final fellings. In other Nordic countries in mechanized pre-commercial thinnings, where mostly energy wood is obtained, small and medium-sized harvesters, which are intended for processing of individual trees or whose felling heads are additionally equipped with the mechanism of accumulating several stems, are most frequently used (Kärhä, 2004). As there are no technical obstacles for preparation and processing of small-dimension wood, the main problem is economic efficiency (Lazdāns, 2006). The aim of this study is to compare productivity and cost of medium-sized and small-sized harvesters in pre-commercial thinning.

MATERIAL AND METHODS

The first part of the trials was done in summer, autumn and winter of 2013 in the central part of Latvia (in the vicinity of Skrīveri) in ten forest stand areas managed by the JSC "Latvian State Forests" (hereafter LSF). Similarly, data were collected in the summer of 2017 in the northern part of Latvia (in the vicinity of Līgatne) from trials in two private forest stands. Trial stands were selected by the average tree height of the dominant stand (ranges from 9 to 11 m), stand density (the number of trees equals to or exceeds 2000 trees ha^{-1}) and terrain suitable for mechanized logging. The study compares the data on productivity obtained in pre-commercial thinning using two medium-sized and two small-sized harvesters equipped with different types of felling heads. John Deere 1070 E is a medium-sized harvester (mass: 15.5 t, engine power: 136 kW), equipped with the H 754 harvester head (weight: 820 kg, felling diameter: 55 cm, boom reach: 9 m). John Deere 1070 D is a medium-sized harvester (mass: 14.1 t, engine power: 136 kW), equipped with the Bracke C16.b harvester head (weight: 570 kg, felling diameter: 26 cm, boom reach: 9 m). Rottne H8 is a small-sized harvester (mass: 10.2 t, engine power: 125 kW), equipped with the EGS 406 harvester head (weight: 480 kg, felling diameter: 33 cm, boom reach: 7 m). Vimek 404 SE is a small-sized harvester (mass: 4.5 t, engine power: 50 kW), equipped with the KETO Forst ECO harvester head (weight: 305 kg, felling diameter: 30 cm, boom reach: 4.6 m). All the harvester heads are equipped with an accumulating device. Time study of harvesting was carried out manually by continuous time study method using hand-held data logger Allegro CX. Total working time (E_0) represents the duration of the shift, but productive working time (E_{15}) is calculated by deducting the time spent on repairs and non-work activities. The average productivity figures, which are represented by the volume of timber produced per productive working hour in the relevant stem volume group, are plotted using the polynomial regression function represented by the equation 1:

$$y = a + b * x + c * x^2 \tag{1}$$

Where *y*- productivity, m³ E_{15} h^{-1}; *x*- stem volume, m³; *a, b, c* – regression coefficients.

Prime cost calculation of harvesting was done according to the calculation models used in similar studies carried out previously (Ackerman et al., 2014; Kalēja et al., 2018). In the cost calculation it was assumed that harvester is employed 24 hours a day (each of the 2 operators works two 6-hour shifts). The average work productivity of each unit of the machinery was used for cost calculation. In order to determine the significance level of data, T - test and Wilcoxon signed-rank test were used.

RESULTS AND DISCUSSION

Small and medium-sized harvesters are more suitable for thinnings, where dimensions of felled trees are relatively small. Trial results show that the volume of most of the felled stems does not exceed 0.1 m^3. When working with John Deere 1070 E harvester, 16.7 thousand trees were felled and 591 m^3 of wood were prepared (the average tree height: 12.3 m; $d_{1.3}$: 8.8 cm, stem volume: 0.04 m^3). Within the scope of the study 17.9 thousand trees were felled using Rottne H8 harvester and 1 089 m^3 of wood were prepared (the average tree height: 11.4 m; $d_{1.3}$: 10.2 cm; stem volume: 0.07 m^3). In areas, where John Deere 1070 D harvester was used in thinnings, 13.4 thousand trees were felled, preparing 86 m^3 of wood (the average tree height: 8.0 m; $d_{1.3}$: 4.3 cm; stem volume: 0.01 m^3). When using Vimek 404 SE harvester, 3.9 thousand trees were felled, preparing 75 m^3 of wood (the average tree height: 10.7 m; $d_{1.3}$: 7.2 cm; stem volume: 0.02 m^3). The number of trees felled with John Deere 1070 D harvester is relatively large, however the amount of prepared wood is small, which could be explained by the large share of undergrowth and small-dimension wood ($d_{1.3}$ smaller than 3 cm) in the total amount of felled trees, which were not supposed to be felled according to the task of the study, except for cases, when it interferes with thinning. When analysing the average productivity rates of middle-class harvesters, on average 158 trees per productive hour were processed, preparing 5.6 m^3 of wood (the average productive time – 83.5 %; time consumed for driving in and driving out – 4.6 % of the total working time), using John Deere 1070 E harvester. When using John Deere 1070 D harvester, on average 271 trees per productive hour were felled, preparing 1.7 m^3 of wood (the average productive time – 75.2 %; time for driving in and driving out – 3.4 % of the total working time). In similar studies that were carried out in Sweden and Finland in pre-commercial thinnings using middle-sized harvesters the average productivity rates range from 3.8 m^3 $E_{15}\,h^{-1}$ (the average stem volume: 0.09 m^3; (Sirén, 2003)) to 9.5 m^3 $E_{15}\,h^{-1}$ (the average stem volume: 0.05 m^3; (Bergström, 2014)). Productivity rates shown by John Deere 1070 D harvester are rather low and most likely the productivity has been influenced by the average stem volume of felled trees (0.01 m^3), as well as by operator skills, when preparing small-dimension wood in forest stands (Kärhä, 2004). In trials that were carried out with Rottne H8 harvester on average 81 trees were processed per productive hour, preparing 5.0 m^3 of wood (the average productive time – 83.7 %; time for driving in and driving out – 6.1 % of the total working time). When using Vimek 404 ES harvester, on average 180 trees per productive working hour were processed, preparing 3.6 m^3 of wood (the average productive time – 91.0 %; time for driving in and driving out – 3.0 % of the total working time). Small-sized harvesters in pre-commercial thinnings have been studied in other countries as well and their productivity rates range from 5.6 m^3 $E_{15}\,h^{-1}$ (the average stem volume 0.07 m^3;(Kärhä, 2004)) to 8.8 m^3 $E_{15}\,h^{-1}$ (the average stem volume 0.09 m^3; (Sirén, 2003)). Latvian researchers have participated in a study, which involved trials conducted in Sweden with Vimek 404 T5 harvester with Keto Forest harvester head. The average productivity shown in these trials was 5.5 m^3 $E_{15}\,h^{-1}$

(Lazdiņš, 2016), which indicate that, when improving skills of the operators, productivity increases (Ovaskainen, 2009). Comparing the average productivity rates between different harvesters, when felling trees, whose stem volume does not exceed 0.1 m³, John Deere 1070 E harvester shows the best results in thinnings, followed by John Deere 1070 D, Vimek 404 SE and Rottne H8 harvester. Studies demonstrate that, when reaching certain stem dimensions, which correspond to the limit values of the use of harvesters, productivity ceases to increase or decreases (Nurminen, 2006). Similar results were obtained in these trials to (John Deere 1070 E – 0.33 m³; Rottne H8 – 0.32 m³; John Deere 1070 D – 0.16 m³; Vimek 404 SE – 0.10 m³), productivity starts to decrease (Fig. 1).

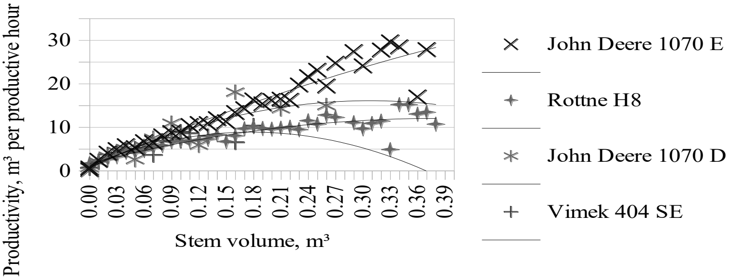

Figure 1. Comparison of average productivity of harvesters in different stem volume groups.

Significant differences were found, when comparing the average productivity of thinning carried out with John Deere 1070 E harvester. The average productivity rates of this machine are significantly higher than by John Deere 1070 D ($p = 0.008 < 0.05$); Vimek 404 SE ($p = 0.001 < 0.05$) and Rottne H8 ($p = 0.000003 < 0.05$). In thinning average productivity of John Deere 1070 D ($p = 0.041 < 0.05$)are significantly higher than productivity data obtained with Vimek 404 SE harvester. Regression analysis shows that the polynomial regression model explains 91.5 % (John Deere 1070 E); 81.9 % (Rottne H8); 80.4 % (John Deere 1070 D) and 81.9 % (Vimek 404 SE) of changes in productivity rates of harvesters in thinnings. Accordingly, the coefficients of linear regression equations of the average productivity rates of each harvester are shown in Table 1.

One of the main factors that influence the choice of a harvester is the costs of mechanized thinning. The total annual production costs of small-class harvesters are lower (119 504 EUR for Vimek 404 SE and 131 300 EUR for Rottne H8) than those of the middle-class harvesters (141 399 EUR for John Deere 1070 E and 142 477 for John Deere 1070 D). For Vimek 404 SE harvester the costs are up to 16 % lower than that of John Deere 1070 D harvester (the highest production costs), which are largely influenced by the low investment costs and operational costs (accordingly, 29 % and 21 % of the total costs). Personal costs for Vimek 404 SE harvester comprise the largest share of costs (45 % of the total production costs). For the rest of harvesters personal costs comprise from 37 % (John Deere 1070 E) to 41 % (Rottne H8) of the total costs. Operational costs are to a large extent influenced by the necessity of maintenance and repairs and their share of the total costs range from 21% (John Deere 1070 D and

Vimek 404 SE) to 25 % (John Deere 1070 E and Rottne H8). Also the profit of 5 % is included in the total costs. The lowest costs per working hour were shown by Vimek 404 SE harvesters (39 EUR), followed by John Deere 1070 E and Rottne H8 harvesters (46 EUR) and John Deere 1070 D harvester (49 EUR). At the corresponding average productivity rates preparation of 1 m^3 of wood with John Deere 1070 E costs 8.3 EUR (the average productivity – 5.6 m^3 E_{15}^{-1}), with Rottne H8 – 9.2 EUR (the average productivity – 5 m^3 E_{15}^{-1}), with Vimek 404 SE – 9.8 EUR (the average productivity 3.9 m^3 E_{15}^{-1}) and John Deere 1070 D- 29.1 EUR (the average productivity 1.7 m^3 E_{15}^{-1}). Changes in wood preparation costs depending on stem value are given in Fig.2.

Table 1. Results of regression analysis of average productivity characteristics of harvesters used in thinning

Harvester	Coefficient	Estimate of coefficient	Standard error of estimation	t-value	p- value
John Deere 1070 E	a	0.895868	1.071575	0.836028709	0.409338255
	b	91.19156	14.47364	6.300525578	4.56023E-07
	c	-49.6721	40.70066	-1.220424181	0.231221528
Rottne H8	a	1.712063049	0.682744814	2.507617799	0.017094225
	b	53.8443728	9.040072109	5.956188419	9.8169E-07
	c	-69.75723927	24.73321021	-2.820387595	0.007947637
John Deere 1070 D	a	0.637783567	1.46680713	0.43481079	0.67210702
	b	100.7931133	31.43759951	3.206132621	0.008362893
	c	-163.9584908	121.6288765	-1.348022736	0.204755484
Vimek 404 SE	a	1.285216303	0.785159549	1.636885528	0.127592473
	b	85.88025259	20.8986593	4.109366603	0.001447908
	c	-242.0962293	114.6937837	-2.11080515	0.056450717

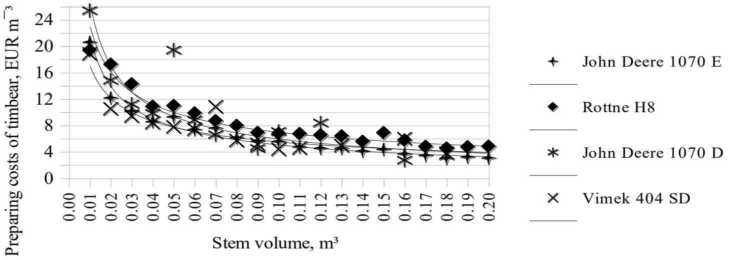

Figure 2. Wood preparation costs for different logging machines depending on stem volume

CONCLUSIONS

1. Comparing the harvesters used for thinning it was found that higher average productivity (5.6 m^3 $E_{15}h^{-1}$; stem volume 0.03 m^3) was achieved when using a medium-sized harvester John Deere 1070 E equipped with the H 754 harvester head. The average productivity shown by John Deere 1070 E is significantly higher ($p = 0.008 < 0.05$) than that of John Deere 1070 D equipped with the Bracke C16.b harvesting head. Comparing small-sized harvesters, higher productivity (5.0 m^3 $E_{15}h^{-1}$; stem volume 0.06 m^3) in thinning was achieved, when working with Rottne H8 equipped with the EGS 406 harvester head. Trials show that the average productivity is significantly influenced by operator skills.
2. The total annual costs of small-sized harvesters are lower than those of middle-class harvesters. The total costs of Vimek 404 SE harvester equipped with the KETO Forst ECO harvester head are up to 16 % lower comparing with those of John Deere 1070 D harvester equipped with the Bracke C16.b harvester head (the highest production cost). The total costs are influenced by the relatively low investment and operational costs to a large extent.
3. According to the trials conducted, at the level of middle-sized harvesters wood preparation costs in thinnings are lower, when working with John Deere 1070 E (8.3 EUR m^{-3}), but at the level of small-class harvesters – when working with Rottne H8 (9.2 EUR m^{-3}). This demonstrates that harvester productivity has a significant impact on wood preparation costs.

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Model for cost calculation and sensitivity analysis of forest operations

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Abstract. Forest operations include logging, off-road and road transport of round wood, harvesting residues and wood chips, soil scarification and pre-commercial thinning, as well as other less conventional operations like stump extraction and undergrowth removal before felling. The process of harvesting can involve different interfering phases with specific productivity parameters, which will have impact on the productivity of harvesting and delivery, as well on the prime cost of logs and forest biofuel. Detailed prime cost calculation allows to assess the impact of various factors on costs of the products, as well as to define threshold values for certain parameters affecting the productivity. The base model elaborated within the COST action FP0902 is complemented with standard economic methods and adopted to the harvesting process or any other forest or farming operation including systems consisting from several machines. The model is designed in a way, which is simple in use, easily extensible with additional parameters and machines and with possibility to change individual input data. The cost calculation section of the model consists from investments (base machines and equipment), labor costs (salaries, social charges, insurance and other payments) and operational costs (fuel, lubricants, maintenance, repair and other consumables). The average hourly cost is calculated according to forecast of number of working hours per year. Engine hours are used in calculation to synchronize input data with service statistics from dealers' centers. The parameters of the forest stands affecting productivity, like diameter or volume of an average extracted tree, number of relocations per year, average off-road transport distance, driving speed and other parameters are defined in the calculation. Productivity and load size can be set as fixed values or equations (in case if the sensitivity analysis should be done). The model calculates the hourly cost (productive, engine and proposed working hours) and the unit price for each phase of the work process. The sensitivity analysis demonstrates impact of various factors, like number of working hours per year, dimensions of the average extracted tree, forwarding and road transport distance, fuel price and fuel consumption as a default parameters or any other indicator, which can be added to the sensitivity analysis. The model is validated against the actual harvesting contracts and hourly cost of rental machines. Default parameters in the calculation are summaries of information provided by contractors or service companies.

Key words: cost calculation, forest operations, productivity.

INTRODUCTION

The harvesting process involves logging, off-road and road transport of round wood, harvesting residues and wood chips, as well as other less conventional operations like stump extraction and undergrowth removal before felling (Uusitalo, 2010; Sarmulis & Saveļjevs, 2015). This process can involve different interfering phases with specific productivity parameters, which will have impact on the productivity of the harvesting and materials' delivery, as well on the prime cost of logs and forest biofuel.

The prime cost of the harvesting is the total amount of utilized production resources expressed in monetary terms (Vītola & Soopa, 2002; Grīnfelds, 2004; Alsiņa et al., 2011). Detailed prime cost calculation allows to assess the impact of various factors on cost of the production, as well as to define threshold values for certain parameters affecting the productivity (Grīnfelds, 2004; Alsiņa et al., 2011).

Cost calculation models usually are complex tables consisting from the input and output sections. The input section of the model may consist from investments (base machines and equipment), labor costs (salaries, social charges, insurance, training and other payments), operational costs (fuel, lubricants, maintenance, repair and other consumables) and other input data, like productivity, characteristics of stands, forwarding and driving distance, road transport distance, average load size (FAO, 1992; Grīnfelds, 2004; Alsiņa et al., 2011; Ackerman et al., 2014). Production cost consists of direct and indirect costs. Direct production costs are directly related to creation of certain cost objects and depends from utilization rate of the machine or number of produced units. Generic or indirect production costs are not directly related to the production of the particular product but are conditionally linked to the production process and are included in the cost calculation of production using addition rate (Vītola & Soopa, 2002; Alsiņa et al., 2011). Determination and allocation of indirect costs by object of calculation is carried accordingly to the amount of production or period of production (Alsiņa et al., 2011). Output section of the cost calculation model usually represents hourly cost (productive, engine or proposed working hours) and the unit price for each phase of the harvesting process (Ackerman et al., 2014).

Sensitivity analysis is aimed on demonstration of impact of various factors, like number of working hours, dimensions of the average extracted tree, off-road and road transport distance, fuel price and fuel consumption or other factors.

Aim of this study is to create comprehensive cost calculation model, which can be used to evaluate multiple forest operations in different work conditions and to determine impact of changes in the system on the costs of production.

MATERIALS AND METHODS

The base model elaborated within the scope of COST action FP0902 (Ackerman et al., 2014) is complemented with standard economic methods and adapted for the harvesting process or any other forest operation including systems consisting from several machines.

The model is validated against actual harvesting contracts in state forests in Latvia and hourly cost of rental machines provided by the dealers' centres. The default utilization rate (engine hours per year) is also taken as average value of multiple machines utilized in state forests. Other default parameters in calculations are summaries of information provided by contractors, service companies or dealers.

Productivity data obtained in previous studies over the period 2013 to 2017 are used to create the default productivity equations for thinning and final felling in the prime cost calculation. To validate the model, it is assumed, that middle sized harvester (John

Deere 1270 with engine power 170 kW, boom max reach 10 m, operating weight 18 t and fuel consumption on average 12 L per E_{15}) with accumulating Moipu 300 felling head is used for harvesting. Middle class forwarder (John Deere 810 E with engine power 100 kW, operating weight 12.9 t, average load 7.9 m^3, max crane reach 8.7 m, fuel consumption on average 12 L per E_{15}) or larger forwarder (John Deere 810 D with engine power 86 kW, operating weight 11 t, average load 5.4 m^3, fuel consumption on average 12 L per E_{15}, with crane CF 1, max reach 8.7 m) is used for off-road transport of raundwood and harvesting residues. In validation of cost of roundwood delivery to the consumer logging truck (Volvo D13K with engine power 309 kW, average load 36.2 m^3, fuel consumption on average 18 L per E_{15}) with trailer and Loglift 96 S crane is used. In biofuel delivery scenario costs are validated against mobile chipper of biomass Bruks 1001 (engine power 336 kW, fuel consumption 68 L per E_{15}) mounted on a forwarder Timberjack 1410 (engine power 136 kW, fuel consumption on average 12 L per E_{15}) and truck Volvo D13K (engine power 309 kW, average load 90 bulk m^3, fuel consumption on average 18 L per E_{15}) with interchangeable containers is used to validate road transport cost of wood chips. The service costs, as well as default parameters for calculations are available from earlier studies (Kalēja et al., 2014; Lazdiņš & Zimelis, 2015).

It is also assumed in the model validation that the implemented forest operation is thinning in coniferous stand and conventional cut-to-length technology is applied.

Engine hours are used in calculation to synchronize input data with service statistics from dealers' centres. The engine hours are also used to synchronize all time elements in the calculation, respectively, it is mandatory parameter, which should be obtained during time studies.

Cost items of the calculation model include investment costs and labour costs (Brinker et al., 2002; Alsiņa et al., 2011; Ackerman et al., 2014). The purchase value of new machinery and equipment are used in the calculation by default, an example is shown in Table 1 (Uusitalo, 2010; Ackerman et al., 2014). Real figurea available from studies or provided by contractors are used to validate the model.

Table 1. Example of calculation of the investment costs

	Harvester	Forwarder of round wood	Log truck	Forwarder of harvesting residues	Chipper	Chip truck
Base machine price, € per unit	350,000	250,000	171,429	246,000	185,714	171,500
Depreciation period, engine hours	25,000	20,000	20,000	19,000	14,000	20,000
Type of equipment	felling head	tracks	-	tracks	chipper	-
Price of equipment, € per unit	30,000	18,500	-	18,500	255,500	-
Depreciation period, engine hours	10,000	12,000	-	12,000	14,000	-

The time frame during which the machine productivity and operating costs are economically justified is defined as the economic life time and in the calculation model is expressed in working hours or years (FAO, 1992) which are synchronized with engine hours.

Equipment is considered as variable costs because depreciation period (in working hours) of the equipment can differ from base machine, respectively the equipment should be changed several times during life time of the machine (FAO, 1992; Ackerman et al., 2014).

Depreciation period (*C*) of machinery and equipment in years is calculated (Eq. 1) by dividing proposed working hours (economic life time) with the forecast of engine hours per year according to the productivity indicators (Brinker et al., 2002).

$$C = \frac{B}{SX} \tag{1}$$

where *B* – depreciation period in engine hours; *SX* – productive hours per year.

To calculate residual value (*E*, expressed as a percentage of the purchase value) of harvesters and forwarders after end of economic life regression Eq. 2 is used (Bright, 2004; Spinelli et al., 2011).

$$E = 0.836 - 0.281 \cdot ln(C) \tag{2}$$

where *C* – depreciation period in engine hours.

For other machinery and equipment it is assumed by default, that the residual value (*E*) will be 15% of the purchase value.

Depreciation of machinery and equipment, calculated on a straight-line basis, is gradually attributed to the production costs (Alsiņa et al., 2011).

The residual value (*F*) estimated as a share of the purchase value of the machinery or equipment, is characterized by the expected resale values of the machine at the end of the economic life (FAO, 1992; Spinelli et al., 2011, Eq. 3).

$$F = A \cdot E \tag{3}$$

where *A* – base machine price, €; *E* – residual value, %.

Cost factor (*G*) is expressed in %. By default 5% depreciation rate (*D*) is used in the model to determine the annual investment cost of machinery and equipment (Eq. 4).

$$G = \frac{(D \cdot (1 + D)^c)}{(((1 + D)^c) - 1)} \tag{4}$$

where *C* – depreciation period, years; *D* – depreciation rate, %.

Annual costs of base machine and equipment (*H*) are calculated using Eq. 5.

$$H = G \cdot (A - F) \tag{5}$$

Labour costs consists of basic and supplementary wage of operator’s, employer's compulsory social contributions and operator’s benefits like training and insurance cost (Grīnfelds, 2004; Ackerman et al., 2014).

In calculation of labour costs, the average gross salary rate of the industry operator is used. The calculation of the production cost includes the social tax paid by employer, which according to Latvian legislation is 24.09% (State Social…, 1997) and is calculated from the salary rate (Alsiņa et al., 2011). In salary calculation it is also possible to set operators’ overtime with double payment rate (Labor Law, 2011).

Labour cost calculation also includes additional incomes, that means compensation for a travel to work (by default 0.2 € km^{-1}), daily allowance, by default 6.00 € per day (Procedures for…, 2010), trainings (186 € yr^{-1}) and other labour costs, like insurance and subsistence costs.

Relocation costs are considered for harvesters and forwarders using separate trailer and for chipper (and other machinery, if needed) on its own (by default trailer's speed is set to 40 km h^{-1}, relocation distance – 50 km in one direction and 50 moves per year.

The calculations also use indicators that characterize availability of the machine. The availability of the machine depends from time spent for repairs and maintenance (Uusitalo, 2010). By default availability is set to 80%. Working hours per year (SZ) of each machine are calculated using Eq. 6.

$$SZ = \left((11 \cdot 20) \cdot 80\%\right) \cdot SH \cdot SJ \qquad (6)$$

where SH – overtime per shift, hours; SJ – number of shifts per day.

Machine utilization rate shows the readiness of machine in productive work (Uusitalo, 2010) and by default this value is set to 85%. The last value differs a lot depending from working conditions and age of machines.

Productive working hours per year (SX) of each machine (except log truck and chip truck) are calculated using Eq. 7. Idle during machine movement is calculated by dividing the average machine movement distance (50 km) and average machine speed (40 km h^{-1}). Time for loading and unloading belongs to work time and is excluded from productive time. On average, machines are moved 50 times per year.

$$SX = (SV + SZ) \cdot 85\% - \left(\frac{50}{40}\right) \cdot 50 \qquad (7)$$

where SV – working overtime, hours per year.

In the calculations it is assumed that one unit of machinery is serviced by 2 to 3 operators working on average 8 hours per shift for 11 months a year (on average, 20 working days per month).

Operators' driving distance per year (on average 30 km in shift (SL)) to access felling site and to return home (SY) of each machine operator (except log truck and chip truck) is calculated using Eq. 8.

$$SY = SL \cdot 2 \cdot SJ \cdot \left((11 \cdot 20) \cdot 80\%\right) \qquad (8)$$

where SL – trip to work (on average), km in shift; SJ – number of shifts, pieces per day.

In calculation it is assumed that the average compensation for each machine operator (except log truck and chip truck) for a trip to work is 0.2 € per km but daily allowance is 6 € per person per day. Annually 186 € per person are spent for training. Also other labour costs (approximately 1,500 € per person annually) are included in cost calculation (except operators of log truck, chip truck and biomass chipper). The cost calculation includes personal insurance, 357 € per person per year.

Operational costs are variable costs and they are closely related to the work load. These costs include fuel, lubricants, hydraulic oil, repairs, regular maintenance, relocations and other variable costs not listed above. Price of item included in calculation of operating costs is variable and depends on the situation on the market.

Working hours (E_0) in calculations corresponds to engine hours. Productive working time (E_{15}) is obtained by subtracting non-productive delay time from engine hours. Yearly operational costs are calculated according to number of engine hours per year.

Table 2 shows examples of consumption of items included in operational cost calculation.

Table 2. Consumption of items included in operational cost calculation

	Harvester	Forwarder of round wood	Log truck	Forwarder of harvesting residues	Chipper	Chip truck
Fuel, L LV m^{-3}	-	-	-	-	0.7	-
Fuel, L E_{15}^{-1}	12	12	18	12	68	18
Fuel, L 100 km^{-1}	-	-	45	-	45	45
Fuel of trailer, L 100 km^{-1}	45	45	-	45	-	-
Lubricant, g E_{15}^{-1}	60	18	15	45	15	
Lubricant for chain, g E_{15}^{-1}	170	-	-	-	-	-
Fungicides, g E_{15}^{-1}	3	-	-	-	-	-
Hydraulic oil, ml E_{15}^{-1}	100	47	25	100	10	-

In order to make the prime cost calculation more accurate and adaptable to different conditions, specific productivity indicators and equations are used, like average size of extracted tree, harvester productivity, forwarder and truck load volume.

The indicators of the forest stands affecting productivity, like diameter or volume of an average extracted tree, average off-road transport distance, driving speed and other parameters can be set in the calculation.

Driving time (min) of roundwood forwarder and forwarder of harvesting residues (RI') is calculated using Eq. 9.

$$RI' = \frac{RH}{RE} + \frac{RH}{RF} \tag{9}$$

where *RH* – driving distance (one way), m; *RE* – average speed of forwarder (loaded), m min^{-1}; RF – average speed of forwarder (unloaded), m min^{-1}.

Calculation of log and chip transport (*RI''*, min) is done using Eq. 10. In calculation it is assumed that average speed of log and chip truck is 40 km h^{-1}.

$$RI'' = \frac{(2 \cdot RG)}{40} \cdot 60 \tag{10}$$

where RG – driving distance (one way), km.

Time spent (*RJ*, min or min of E_{15}) for transportation of one load with roundwood or harvesting residues forwarder, or truck of log or chip is calculated using Eq. 11.

$$RJ = RA + RB + RI \tag{11}$$

where *RA* – loading time of forwarder, minE_{15} per load; *RB* – unloading time of forwarder, min E_{15} per load; *RI* – driving time, min.

Productivity (*RM*, expressed in m^3 per productive hour or *RN*, loose volume (LV) m^3 per productive hour) and load size (*RL*) can be set as fixed values or calculated using Eq. 13 or 14 (in case if the sensitivity analysis should be done).

$$RM = \frac{RL}{RK} \tag{12}$$

where RL – average load, m^3; RK – time per load, hours. E_{15} per load.

$$RN = \frac{RL}{RK \cdot 2.4} \tag{13}$$

To transfer solid cubic meter into loose volume (LV), the density coefficient 2.4 has been used by default. The default value for load size is based on results of productivity study.

The model calculates the hourly cost (productive, engine and proposed working hours) and the unit price for each phase of the harvesting process.

Sensitivity analysis includes a range of certain input data, from minimum to maximum value obtained during the studies, national statistics or the data provided by the contractors, for instance fuel consumption for the same type of machine, average forwarding or road transport distance, or applicable range of dimensions of extracted trees (usually obtained from time studies). These values are used to determine range of costs depending from value of the parameter. The model is validated against actual harvesting contracts in state forests and hourly costs of rental machines.

RESULTS AND DISCUSSION

Harvesting costs consist of forwarding, logging and road transport of roundwood, as well as the costs of biofuel extraction where applicable. Different models are used for prime cost calculation by researchers and enterprises (FAO, 1992; Väätäinen, et al., 2006; Ackerman et al., 2014), but there is still unfulfilled demand in a model giving detailed view of the prime cost of different forest operations, integrating productivity and costing parameters in dynamic calculation system.

In different cost calculation models various factors affecting costs are taken into account (FAO, 1992; Väätäinen et al., 2006; Spinelli et al., 2009; Harrill & Han, 2012; Ackerman et al., 2014). Logging, forwarding and roundwood delivery costs are heavily affected by dimensions of the average extracted tree, which needs to be represented in sensitivity analysis to see threshold values in expected range of the work conditions. The average productivity of logging, forwarding and road transport (the last 2 values are determined by load volume) are calculated for each diameter class and used in the calculation.

The cost calculation model allows to vary the factors affecting prime costs of several machines, choosing the type of preparation and delivery of roundwood and harvesting residues, planning work hours of forest machines, changing working conditions and forest machines (Fig. 1).

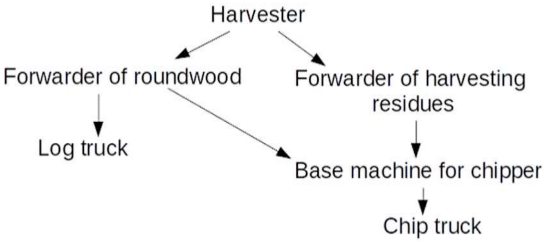

Figure 1. Modeling of harvesting system in forest operations.

Most of the cost calculation models predict calculate the cost of each separate forest machine, which do not represent how interaction of the machines and changing logging conditions can affect the cost of production and how to achieve higher economic efficiency (Ackerman et al., 2014). The following example (Table 3) shows how costs are analyzed in the proposed model.

Table 3. Example of output of cost calculation

Calculation items	Harvester	Forwarder of round wood	Log truck	Forwarder of harvesting residues	Chipper	Chip truck
Summary of costs, € per year						
Investment costs	51,725	39,058	15,206	41,246	71,194	15,212
Labour costs	62,637	62,637	72,692	62,637	60,765	72,692
Operational costs	103,896	53,056	31,207	51,102	172,673	39,150
Profit margin	10,913	7,738	5,955	7,749	15,232	6,353
Total	229,171	162,488	125,060	162,734	319,864	133,406
Productivity						
Roundwood with bark, m^3 E$_{15}$ h^{-1}	6.7	10.0	10.6	-	-	-
Biofuel, LV m^3 E$_{15}$ h^{-1}	-	-	-	37.5	96.5	23.9
Amount of roundwood and biofuel produced per each unit of machinery per year						
Total roundwood, m^3 per year	19,144	26,778	14,658	108,793	90,318	35,753
Logs, m^3 under bark	15,955	24,125	13,205	-	-	-
Biofuel (stem residues), m^3 per year	1,434	-	-	-	-	-
Biofuel (logging residues), m^3 per year	-	-	-	108,793	-	-
Bark and other residues, m^3 per year	1,755	2,654	1,453	-	-	-
Biofuel (wood chips), LV m^3 per year	3,443	-	-	261,103	216,762	85,807
Output						
Logs under bark, € per m^3	14.4	6.7	9.5			
Biofuel, € per LV m^3				0.6	1.5	1.6

Basic model version can be used to calculate if it is cheaper to deliver forest biofuel as logs or chips (Table 3); however, it can be easily adapted to different comparisons including system analysis.

According to the sensitivity analysis implemented in the model, the diameter of the average extracted tree significantly affects productivity. Similar or simplified approach can be used to determine, how the forwarding and road transport distance affects costs of production and to find threshold values for these parameters. Built in spreadsheet linear optimization functions can be used to determine the threshold values. Similar conclusions are also available in other studies (Väätäinen et al., 2006; Harrill & Han, 2012).

The model can be used to identify the factors affecting total harvesting and delivery cost under theoretical or real life conditions based assumptions (Figs 1 and 2).

Any other parameter considered in the cost calculation can be added to the sensitivity analysis. Where applicable, the sensitivity analysis should be combined with productivity models or equations. For example, change of dimensions of extracted trees should reflect in productivity of harvester, as well as on load size in off-road and road transport, reflecting in productivity of forwarder and log truck.

Sensitivity analysis of forwarder driving distance (Fig. 2) shows that increase of forwarding distance by 150 m in the conditions used for verification of the model increases the total production cost by 0.5 EUR per m^3. Fuel consumption can also be differentiated in the model, for instance, different values of fuel consumption can be applied for driving loaded and empty, as well as for loading and unloading operations.

Sensitivity analysis of utilization rate (Fig. 3.) demonstrates that increase of the utilization of harvester significantly reduces total production cost. Similar effect is observed for all machines due to increase of indirect cost per working hour.

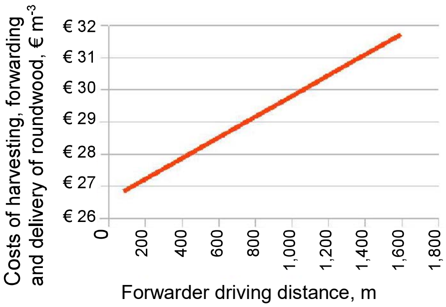

Figure 2. Sensitivity analysis of forwarder driving distance.

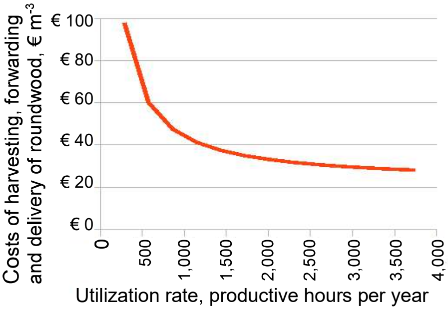

Figure 3. Sensitivity analysis of the utilization rate.

Comparison of the calculation results with actual harvesting costs in 2017 provided by the Joint stock Company 'Latvia state forests' and Central statistical bureau approves that the modeled values are within the uncertainty range of available statistical data; however there is still considerable potential for underestimation of harvesting costs by utilization of the study data due to overestimation of the utilization rate of forest machines. This parameter was estimated using expert judgments in contrast to other parameters, where dealers' centers or contractors' information is available. Therefore, the calculation was tuned to conform to the real harvesting prices by changing the utilization rate. Other parameter significantly affecting cost of production is salary rate; some companies are paying fixed monthly salaries, some are paying per produced unit, some are combining these 2 methods. As a result, provided monthly or hourly salary rates differ a lot between companies, in spite the average annual income has no tendency of such a big variation. The model uses average hourly rate assuming full-time employment as a basic assumption, which can lead to overestimation of personnel costs in case of combined or per piecework payment scheme.

CONCLUSIONS

The elaborated model is simple in use, easily extensible with additional parameters, machines and equipment. It can be used in practice, at a company level to analyze and to predict machine costs, as well as in research for system and sensitivity analysis.

One of the largest benefits of the model is using of engine hour as a reference time unit providing opportunity to use machine service data in cost calculations without adaptation of the applied data.

The model contains internal system of quality assurance, like calculation of the net income of operators and a company, and the hourly cost of machine, which can be validated against the service data.

The model is supplied with the default input data, which are already validated in Latvia and can be easily adapted to other conditions providing at the same time opportunity to avoid logical mistakes in data entering, like use of non-realistic values for consumption lubricants or fuel.

The model allows to get an overview of the cost of the machine system in dynamic conditions, which, accordingly, allows to choose the most efficient combination of machines, threshold values for certain operations, like off-road transport distance, and stand parameters, like minimum dimensions of trees.

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SOIL COMPACTION IN YOUNG STANDS DURING MECHANIZED LOGGING OF BIOFUEL AND ROUNDWOOD ASSORTMENTS

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Abstract

Impact of a variety of forestry machine types on soil compaction is evaluated in this study according to the measurement of soil penetration resistance at 0 to 80 cm depth. It is concluded in the study that soils with poor bearing capacity (PBC), comparably small penetration resistance and organic layer thicker than 5 cm are less vulnerable to soil compaction. The use of small-size forwarder Vimek 610 allows to reduce soil compaction to an insignificant level in comparison to the control sites, and most or ruts disappear within a few days in PBC conditions. Whereas John Deere 810E, which belongs to the middle-size class of forwarders, significantly compacts soil through the whole measured depth in similar conditions. Rottne F10B and John Deere 810E forwarders represent the same weight category, and soil compaction due to the use of these machines on soils with moderate bearing capacity (MBC) is similar too; however, on soils with weak (WBC) and good (GBC) conditions results are different, mostly due to a different amount of extracted roundwood in both trials. Tracked forwarder was used only in GBC conditions and the results demonstrated significant compaction only down to 22 cm depth. The trials confirm that the depth of the intensity of impact depends on the weight of the machine and amount of material extracted; however, additional measurement data are necessary to characterize the impact quantitatively in different conditions.

Key words: soil compaction, forwarding, penetration resistance.

Introduction

The demand for woody biomass as renewable material, including small dimension logs and solid biofuel is expected to rise in future. The growing demand can be met both, by increasing of planted areas of fast-growing trees and their hybrids (Jansons *et al*., 2013, 2014), as well use agroforestry systems (Rancane *et al*., 2014) and by more efficient extraction of wood during forest thinning operations, especially on soils with low bearing capacity which represents high bioenergy potential, but also considerable risk of harmful impact on the remaining stand during intensified extraction of biomass (Lazdiņš & Thor, 2009; Lazdiņš *et al*., 2013; Liepiņš *et al*., 2015). Specialized forest machinery including small forwarders is of crucial importance to increase the output of biomass from small size tree harvesting operations (Spinelli *et al*., 2010; Spinelli & Magagnotti, 2010).

The Vimek 610 forwarder is not unique in its 'small size' class, however, it is one of the few machines of this kind produced serially. The forwarder is equipped with the same engine as the Vimek harvester, front tires of the forwarder are slightly bigger and rear tires are smaller than those of the harvester. Clearance of the machine is 40 cm. Reach length 5 m, weight of fully loaded machine is about 10 tonnes (Lundberg, 2013).

Soil compaction during logging process has been studied since early 1970s. During the first trials it was proposed that soil compaction can have a negative impact on future stand development and health (Eriksson, 1981). Since that time many new studies have appeared; however, till nowadays there is no common vision about all processes interacting with the soil compaction and relationships between the stand growth and soil compaction. The studies in Latvia demonstrate that soil compaction has a long lasting effect and there is a considerable difference depending on the type of the machines. The most important is the type of forwarder used in the operations. The use of tracked forwarders results in a considerably smaller impact appearing only at a topsoil layer, but wheeled machines in the same conditions can compact soil down to 80 cm depth, even without visually identifiable signs of rutting (Lupiķis *et al*., 2014; Lupikis *et al*., 2015).

Knowing that tree roots are distributed mainly in the topsoil layer and the range of the distribution of roots considerably exceeds tree crown projection (Perry, 1982), it is obvious that not only the roots of trees growing near technological corridors (further in text – TC) have been damaged during forwarding, but also roots of those trees which are located more than 3 metres from TC. Damages of roots can cause tree infection. The most common infection of this type in Latvia is root rot, which is a well-known follower of the forest management activities, especially in coniferous forests (Kļaviņa *et al*., 2013).

Early studies on the soil compaction consider that it can improve soil water permeability (Barden & Pavlakis, 1971); more recent studies demonstrate considerable decrease of water movement speed in soil in compacted areas (Batey, 2009; Taghavifar & Mardani, 2014) approving the potentially harmful impact of the compaction on the hydrological properties of soil. Soil compaction also is a threat for plants and trees, because if soil penetration resistance is higher than 3 MPa then roots cannot or it is hard for them to penetrate those layers of soil (Lazdiņš, 2015) and in previous studies (Bassett *et al*., 2005; Cubera *et al*., 2009), the length of the main root system was constrained by soil compaction.

Soil compaction during mechanized logging is a result of direct and indirect impact of different factors. Some of them have been mentioned by Cambi M. *et al*., 2016, like soil texture and moisture; as well as content of organic matter, terrain, characteristics of wheels (type, size, shape and air pressure), weight of machine and the number of trips (DeJong-Hughes, 2003; Duiker, 2004; Wolkowski & Lowery, 2008; Cambi *et al*., 2015).

Different technical solutions are developed to reduce mechanical impact on soil. Constructors of forest machines are working on solutions to make logging machines more optimized for thinning operation, so to minimize the impact on soil and secure high productivity of the machines. The most commonly addressed solution is customization of chassis (increased size of wheels or replacement of wheels with tracks) to increase support surface and reduce maximum pressure on soil. Alternate trend is the increase of machine capacity to reduce cumulative pressure on soil due to bigger loads, as well as the opposite trend – development of small machines and optimization of forwarding process to move machines to a different category, where the key for reduction of the negative impact is planning of the forwarding trials (Sutherland, 2003; Sakai *et al*., 2008).

Freezing and thawing significantly decrease the penetration resistance in the upper layers of compacted soils according to several studies. Studies in the United States confirmed that after one winter containing several cycles of freezing and thawing the penetration resistance of farm soils was reduced by 73, 68, and 59% at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively (Jabro *et al*., 2012, 2014). Similar results have been described by European authors (Özgan *et al*., 2015). Studies in Latvia have demonstrated that in deeper soil layers (below 40 cm) soil compaction can persist for decades (Liepiņa *et al*., 2014).

The aim of this study is to compare influence of different types of forwarders (conventional, small and tracked) on soil compaction in young forest stands with different soil bearing capacity, as well as to evaluate if the initial soil penetration resistance can be used to compare forwarding conditions.

Materials and Methods

Data collected from 34 forest stands from different regions of Latvia (Skriveri, Koknese, Vecumnieki and Talsi) are evaluated in this study. The main criteria for selection of stands was the height of an average tree (below 12 m) and management history (no pre-commercial thinning done before). Some of dry and wet forest site types Oxalidosa, Hylocomiosa, Caricoso–phragmitosa and Myrtillosa (Liepa *et al*., 2014) were represented with broadleaved dominant tree species (birch, black alder, grey alder). The age of those experimental objects varies from 10 to 16 years in inventory data.

Thinning and biomass extraction was done in summer and autumn, 2013. Impact of meteorological conditions, like precipitation on soil bearing capacity during forwarding was considered by measurement of soil penetration resistance at 0-80 cm depth. The penetration resistance was measured after forwarding on technological corridors and in untouched stand area using digital penetrologger, directly after forwarding. Measurements were done in pairs of plots, where 3...5 measurements (sub-plots) are done on technological corridor (TC and 3…5 measurements were repeated 3...5 m from a side of TC in similar conditions. The measurements of the penetration resistance in each TC was repeated at every 50 m. If the TC was shorter than 200 m, the sub-plots were located in denser network. In total, 5353 measurements were used in the study, respectively, in the group where soil bearing capacity is poor (PBC) it is 457; in the group of week soil bearing capacity (WBC) – 1351; in the group where soil bearing capacity is medium (MBC) – 2032, but in the group with a good soil

Table 1

Data classification for analysis

Soil bearing capacity	In text	Average penetration resistance at 0...80 cm depth (MPa)	Biomass forwarder			
			John Deere	Rottne	Timbear	Vimek
poor	PBC	0.5...1.0	X	-	-	-
weak	WBC	1.0...1.5	X	X	-	X
moderate	MBC	1.5...2.0	X	X	-	X
good	GBC	2.0...2.5	X	X	X	-

Table 2

Technical specifications of forwarders

Producer	Model	Power of engine (kW)	Drive	Own weight (tonnes)	Load capacity (tonnes)
John Deere	810 E	95	8 tyres	12.9	9.9
Timbear	Light logg C	97	4+2 caterpillar trucks	12.0	10
Rottne	F10B	116	8 tyres	12.9	9
Vimek	610	44	6 tyres	4.9	5

bearing capacity (GBC) - 1513. All measurement data from the control sites were split into 4 groups depending on the machine used for biomass transportation. Then the average soil penetration resistance at 0...80 cm depth was calculated for every control sub-plot to characterize soil bearing capacity and different forwarding conditions. Depending on the average values of the soil penetration resistance, all sub-plots were split into 4 soil bearing capacity groups (Table 1). The marking 'X' in Table 1 marks the conditions, where the specified forwarder is used. Further data analysis is done by comparison of the difference between the soils penetration resistance in the control and TC sub-plots.

The average extracted biomass from each TC in the trials was between 15 and 25 m^3. The influence of type of forwarder on soil compaction in different conditions (initial soil bearing capacity) was evaluated in the study. Considering the conclusion of several researchers on dominating role of forwarders in compaction of soil, the type of harvester is not evaluated in the study (Lazdāns, 2004; Eliasson, 2005; Gebauer *et al*., 2012). Technical specifications of forwarders are shown in Table 2.

Significance level was calculated with $p<0.05$; $\alpha = 0.05$, and descriptive statistics were carried out with the Microsoft Excel 2013 statistical software package.

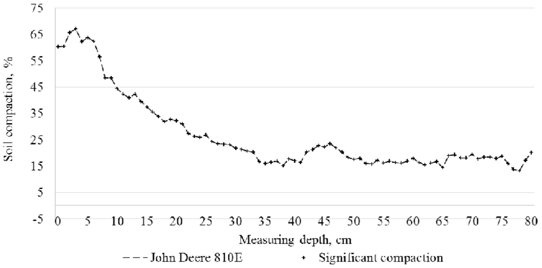

Figure 1. Soil compaction in comparison to control on soils with poor bearing capacity (PBC).

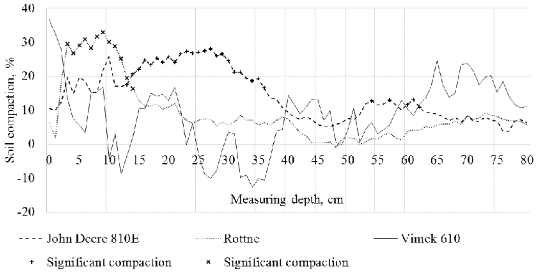

Figure 2. Soil compaction in comparison to control on soils with weak bearing capacity (WBC).

Results and Discussion

The results of the study demonstrate a different impact of the evaluated forwarders on the soil compaction in four groups of soil bearing capacity. In the first group of the soil bearing capacity (PBC) only John Deere 810E forwarder was used. Results in Fig. 1 demonstrate that average-class forwarder significantly compacted soil through the whole measured layer. Significant differences ($p<0.05$) have been detected down to 80 cm depth (marked with '+' in fig. 1). Soil compaction in the upper layers down to 18 cm depth exceed the control by 30%.

Fig. 2 summarizes results from the WBC group of soils. In this group forwarding was done with 3 forwarders – John Deere 810E, Rottne F10B and Vimek 610. Significantly compacted soil was found in areas where John Deere 810E forwarder was used (significant difference at 13...37 cm and 54...63 cm depth). In areas extracted by the Rottne forwarder significant difference between control and TC was detected only at 3...15 cm depth. Using the small Vimek 610 forwarder, no significant differences of the soil penetration resistance were found between the control and TC in WBC sites.

Fig. 3 demonstrates summary of the results in the MBC group of soils. Forwarding was done with 3 types of forwarders – John Deere 810E, Rottne F10B and Vimek 610. Significant compaction of soils is detected in all cases, but the most visible difference is found at a topsoil level. Significant compaction ($p<0.05$) of soil using John Deere 810 forwarder is found at 0...50 cm depth, using Rottne forwarder – at 0...38 cm depth, but in areas where roundwood is extracted using Vimek 610 – at 0...26 cm depth. The highest rate of compaction of topsoil within this group is found in sub-plots, where small-size Vimek 610 forwarder is used; however, the impact is relatively shallow. The reason for similar impact by the Vimek 610 can be due to a smaller surface area of tyres resulting in an increased pressure on soil. At the same time Vimek is affecting mostly the topsoil layer – below 26 cm depth the difference is insignificant. It means that soil can return to the initial condition during freezing in winter.

Figure 4 displays summary of the results in the GBC group of soils. In the GBC group forwarding of roundwood was done by three machines – John Deere, Rottne and Timbear. Significant compacted layers of soil are not detected deeper than 22 cm in sub-plots where Timbear was used. In case of John Deere, considerable compaction was found down to 18 cm depth, whereas in case of Rottne the soil was

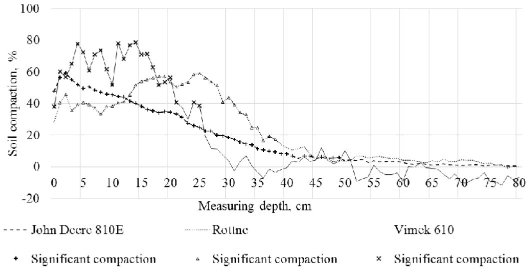

Figure 3. Soil compaction in comparison to control on soils with moderate bearing capacity (MBC).

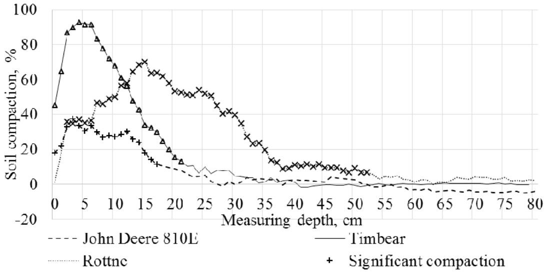

Figure 4. Soil compaction in comparison to control on soil with good bearing capacity (GBC).

significantly compacted down to 52 cm depth. John Deere and Rottne are very similar by the technical specification, but in stands where Rottne was used significant soil compaction is detected more than twice deeper in comparison to areas extracted by John Deere. Subsequent investigation explained this by considerably longer TC in stands extracted by Rottne, respectively more roundwood (25 m^3 in each corridor) was transported in these TC; respectively 10 passes instead of 6 passes with John Deere. In case of Timbear, significantly compacted soil layer is comparably shallow, because this machine is on tracked chassis, therefore has a larger contacting surface area resulting in smaller pressure. The result conforms with some of earlier studies, for instance by Bredberg, 1976, who compared machines on wheels with bogie-track and machine on tracks chassis with larger contacting surface area. However, he also concluded that the number of passes is an important factor to consider when comparing different types of the machines. While the number of forwarding passes is growing, the difference between tracked and wheeled machines is decreasing. The study results highlight the potential risk of soil damages while working in areas characterized by good bearing capacity, where no visible soil damages (ruts) (Sutherland, 2003) usually can be detected and, therefore, operators and foresters are not concerned about soil protection measures during forwarding. To avoid potentially harmful impact on soil, it is especially important in moderate and good conditions to establish strip-roads in a direction, which does not intercept with horizontal flow of groundwater to avoid accumulation of exceeding water, and to leave harvesting residues on TC to reduce the machine pressure on soil.

Figure 5 demonstrates soil compaction on TC in comparison with the control depending on the forwarder and a group of the soil bearing capacity at different soil layers. In case of John Deere 810E, the soil compaction and depth of compaction has reduced with an increase of the initial soil penetration resistance (bearing capacity). The level of compaction exceeding 20% in comparison to the control in soils with an average initial (control) penetration resistance of 0.5...1.0, 1.0...1.5 and 1.5...2.0 MPa is found down to 30 cm depth, whereas in the group of soils with initial soil penetration resistance of 2.0...2.5 MPa (GBC) it is observed only down to 10 cm depth. Although Rottne and John Deere forwarders are similar according to the technical specification, the results show a considerable difference between these machines. It is observed that soil compaction is decreasing with an increase of depth of the penetration on soils with smaller initial soil penetration resistance (0.5...1.0 MPa, WBC group of soils). Whereas if the initial soil penetration resistance is increasing (MBC and GBC group of soils), the tendency is different and down to a depth of 20 cm the level of soil

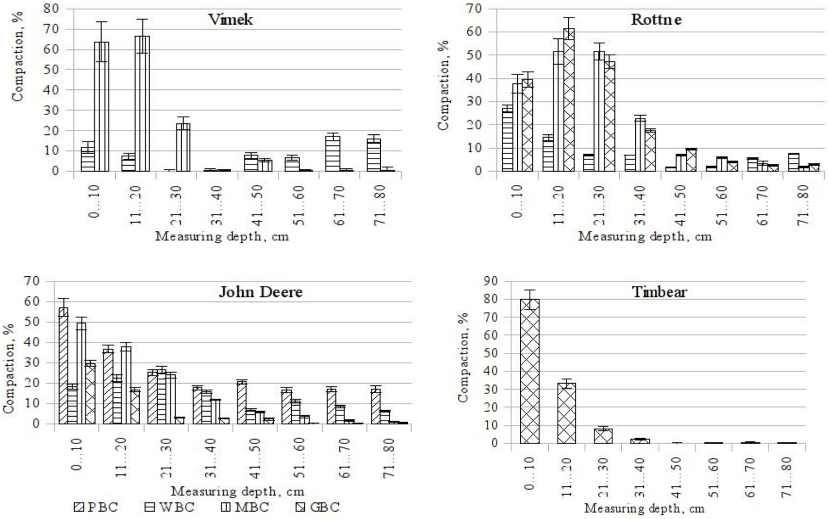

Figure 5. Soil compaction in comparison to control split by the forwarder and group of bearing capacity with standard error of mean.

compaction on TC increases, but in deeper soil layers it is decreasing. The soil compaction exceeding 20% in comparison to the control is observed down to 30 cm depth in the MBC group of soils and down to 10 cm depth in the WBC group.

In case of small-size forwarder Vimek 610, the most significant soil compaction is found in soils representing the MBC and WBC groups. Soil compaction exceeding the level of 20% in comparison to the control is found only in the MBC group of soils, while in the WBC group of soils it is not exceeding the level of 20 % throughout the whole depth of the measured soil layer.

There is relatively little data on Timbear forwarder. Only one type of conditions (GBC) is covered by the study. It is found that compaction exceeding the level of 20% in comparison to the control is not deeper than 20 cm and in contrast to other middle-size forwarders (John Deere and Rottne) the soil compaction is decreasing rapidly with an increase of depth of the measurement.

Soil compaction can be considered as a critical if the penetration resistance reaches 3 MPa. If the penetration resistance reaches this value, it means that roots of trees cannot penetrate the soil. However, the most important threat to future forest development, according to the recent studies, is not compaction itself, but the negative impact on horizontal flows of groundwater in soil (Lazdiņš, 2015). The level of soil compaction overreaching the critical value is found only in study sub-plots in the GBC group of soils, but it is found in both, the control and TC sub-plots. It should be noted that soil compaction due to off-road forwarding of roundwood usually has not significant influence on the development of roots in temperate climatic conditions. Researchers from different countries conclude that the main threat is disturbed horizontal flows of groundwater due to the soil compaction resulting in paludification of forests (Lousier, 1990; Malmer & Grip, 1990; Jim, 1993; Gebauer, 2012); however, empirical data on the influence in Latvia is limited.

Conclusions

1. Statistically significant soil compaction ($p<0.05$) down to 20 cm depth is found in the moderate bearing capacity and good bearing capacity groups of soils for all types of forwarders, whereas in the weak bearing capacity group of soils compaction exceeding 20% in comparison to the control is found for John Deere and Rottne forwarders down to 30 and 10 cm depth, respectively, but in case of Vimek the compaction of the weak bearing capacity group of soils is not detected.
2. Comparison of John Deere and Rottne forwarders highlights relationship between the number of passes and depth of compaction of soil and depth of significantly affected areas, but the study does not provide sufficient amount of data to evaluate this relationship for small-size forwarder and tracked forwarder.
3. Soil compaction due to the off-road forwarding of roundwood is found in all groups of soils, but areas with bigger soil penetration resistance are subjected to higher risk of the soil compaction than soils with smaller soil penetration resistance.
4. Tracked forwarder generates a relatively small impact located at a topsoil level, but the average impact at topsoil level is bigger in comparison to middle-size wheeled forwarders. The compaction of topsoil, which does not affect the growth of roots, should not be considered as negative impact, because according to the results of other studies it returns to initial status during several cycles of freezing.
5. The number of studies should be increased to evaluate the impact of compaction on horizontal groundwater flows; however, available information on the potential threats highlights need for careful planning of direction of technological corridors to avoid clogging of water flows in soil, and harvesting residues should be placed in TC to avoid compaction if there is risk of negative impact on water flows.

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IMPACT OF ASSORTIMENTS' STRUCTURE ON HARVESTING PRODUCTIVITY AND COSTS OF PRE-COMMERCIAL THINNING

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Abstract

The study aims to find productivity of biofuel production in pre-commercial thinning, depending on the structure of assortments and to identify factors that influence the cost of mechanized tending of young stands. Five work methods were compared in the study, starting from standard thinning (production of sawn timber, pulpwood and firewood) with no use of accumulating device and finalizing with the biofuel method – no other assortments except biofuel are produced and the most intense use of accumulating device is considered. Accumulating device is not used for production of standard round-wood assortments. The experiments were implemented in February – March, 2013. The material produced in the study was used by 'Graanul Pellets' company to evaluate possibilities to use timber extracted in pre-commercial thinning of coniferous stands in production of premium class pellets. The average productivity in different stands is statistically different. The study shows that productivity of harvesting is 3.7 … 5.1 $m^3 h^{-1}$, which can be increased by more intensive use of accumulation. No difference found between work methods in forwarding trials, but productivity grows with increase of share of firewood. Average loading time 26 min, unloading 3.6 min, average load 6.0 m^3. Prime-cost calculation shows that harvesting costs depending on the working method is in the range of 22.4 … 26.5 EUR m^{-3}. Comparison of potential expenses and incomes demonstrates that economically the most efficient is production of traditional assortments (sawn wood, small size sawn wood, pulp wood and firewood) with an active use of accumulating function.

Key words: biofuel, work methods, young stands.

Introduction

Yong stand tending or per-commercial thinning is a measure required in forestry. It is performed mainly with manual cutting without collecting of small diameter wood (Lazdāns, 2006; Meža enciklopēdija, 2003). Studies of efficiency of young stand tending technologies in 2012 showed that the young stand manual cutting still is the most cost-efficient way of young stand tending, followed by young stand tending with harvester equipped with special additional accumulating device for head (Lazdiņš et al., 2012). However, with growing demand for biofuel, the mechanized tending of young stands becomes an urgent issue. It is possible to perform qualitative young stand tending by using harvesters and produce round-wood assortments and biofuel.

Technology of young stand tending can be divided into four groups: harvesting with a harvester, with a harwarder, combined harvesting and chipping equipments, or manual cutting (Lazdiņš, 2013c). Studies on the young stand tending in Scandinavia and Latvia confirm, that mostly medium-sized harvesters with accumulating device are suitable for young stand tending (Lazdāns et al., 2008; Sirén and Aaltio, 2003). A head with an accumulating device allows multiple gripping of trees and cutting (Lazdiņš, 2013c). Such harvesters are maneuverable in young stands and are suitable for cutting and processing of small diameter trees.

Studies of usage of the mid-class harvesters in mechanized tending of young stands are carried out by Joint Stock Company 'Latvia's State Forests' commissioned project 'Industrial research of renewable energy production, processing and logistics'.

The study evaluated the impact of the structure of assortment gained by young stand tending on productivity and costs (Kalēja et al., 2014; Lazdiņš, 2013a; Lazdiņš, 2013b; Lazdiņš, 2013c). In addition to the traditional round timber assortment groups (sawn timber, pulpwood and firewood), an assortment of biofuel can be prepared from treetops and trunks that couldn't be used for traditional assortment (Lazdiņš, 2013c).

Studies in Latvian and Scandinavian countries have shown that the usage of accumulating device for preparation of non-traditional assortment greatly increases productivity and reduces the cost of mechanized tending of young stands (Lazdiņš, 2013a; Lazdiņš, 2013c; Sirena and Aaltio, 2003). Assuming that an average distance of forwarding is constant, the main factors affecting the productivity are average tree size of the stand, removal per hectare and number of timber assortments (Sirena and Aaltio, 2003). The structure of produced assortment, in turn, is determined by the chosen method of working. The studies confirmed the hypothesis that the highest productivity (amount of trees that are harvested in certain amount of time) of each machine could be achieved by reducing modifications of produced assortment (Lazdiņš, 2013c).

Studies of deciduous stands show that the cost of manual tending of young stands in harsh conditions, depending on tree's dimensions and tree stands thickness, ranges from 343 EUR ha^{-1} to 488 EUR ha^{-1}. Actual costs are up to 3 times smaller, as service providers have to tend a variety of stands, including those where the cost of 1 ha is significantly below average (Lazdiņš, 2013b). Costs of mechanic young stand tending, depending on the harvester's type, ranged on average from 800 EUR ha^{-1} to 1 113 EUR ha^{-1} (Lazdiņš, 2013b; Lazdiņš, 2013c). Although mechanized tending of young stands requires a significantly higher cost, realization of produced assortment provides some revenue. Earnings are determined by current market situation as well as the chosen supply chain model (Laina et al., 2013; Lazdiņš, 2013c; Walsh and Strandgard, 2014). The aim of the study was to find productivity of biofuel production in pre-commercial thinning, depending on the structure of assortments and to identify factors that influence the cost of mechanized tending of young stands.

Materials and Methods

The study was implemented in 4 coniferous stands representing fertile *Myrtillosa* and *Hylocomiosa* site types in the central part of Latvia nearby Koknese. The stands were specially selected for proper density (at least 1500 trees per ha^{-1}) and dimensions of trees (height of trees 9 … 12 m). The experiments (harvesting and forwarding operations) were implemented in February – March, 2013. The average temperature during the study was 1.6 degrees lower than the temperature in the given historical period. The strip-roads were marked before thinning at 20 m distance between each other. The main characteristics of stands are provided in Table 1.

For production of different assortments (work methods 1 … 4) stands 503-479-12 and 503-481-6 were selected and biofuel method (work method 5) was implemented in stands 503-455-13 and 503-455-14. Biomass expansion factors elaborated for afforested lands are borrowed for calculations (Lazdiņš, 2011d). Five work methods were compared in the study:

1. Production of traditional assortments (sawn wood 14 X 18 mm, small size sawn wood 10 X 14 mm, pulp wood and firewood), min. diameter of firewood at top 50 mm, residues left in stand, accumulating function is not used.
2. Production of traditional assortments (sawn wood, small size sawn wood, pulp wood and firewood), min. diameter of firewood at top 30 mm, residues left in stand, active use of accumulating function.
3. Production of limited number of assortments (sawn wood, small size sawn wood and firewood), min. diameter of firewood at top 30 mm, residues left in stand, active use of accumulating function.
4. Production of limited number of assortments (sawn wood and firewood), min. diameter of firewood at top 30 mm, residues left in stand, active use of accumulating function.
5. Production of firewood with min. diameter at top 30 mm, residues left in stand, active use of accumulating function.

John Deere 1070 E with H754 head equipped with special additional holders and boom length 10 m was used in the study. Two experienced operators drove the machine; however, none of the operators had previous experience with small dimension biofuel assortments and accumulating felling heads.

Standard Timberjack 810B forwarder was used in the study. All loads were weighed during forwarding, and after each fifth load or after changing position of scales empty loads were weighed.

The material with a truck was delivered to LLC 'Graanul Pellets' storage yard using standard 68 m^3 truck Delivery distance 150 km in one direction.

The material (biofuel assortment as well as sawn timber and pulp-wood produced in trials) was chipped with stationary chipper Jenz HE 700 after debarking in LLC 'Graanul Pellets' storage yard. Proportion of bark according to information provided by LLC 'Graanul Pellets' was 10% by mass (naturally wet). In order to perform recalculation to dry matter tons,

Table 1

Characteristic of stands

Object code	Area, ha	Dominant species	Average diameter of trees, cm	Average height of trees, m	Average basal area, m^3 ha^{-1}
503-455-13	3.6	spruce (*Picea abies*)	9.7	7.7	12.1
503-455-14	4.3	spruce (*Picea abies*)	9.6	9.2	19.3
503-479-12	2.4	pine (*Pinus sylvestris*)	12.0	11.7	29.5
503-481-6	1.2	spruce (*Picea abies*)	8.2	10.0	13.1

a conversion factor (1 ton of naturally wet material (average moisture content 60%) corresponds to 0.4 dry tons) was used.

Prim-cost calculation and potential income and expenses of mechanized young stand tending calculations are done according to calculation models that are used in similar studies carried out previously (Lazdiņš^{c}, 2013).

To determine the level of significance of data, the t-test is used.

Results and Discussion

Basal area before thinning on average in all stands was 18 m^{2} ha^{-1}; the average number of trees 2360 per ha^{-1}; diameter 10 cm; tree height 10 m; growing stock 62 m^{3} ha^{-1}. After thinning the average basal area reduced to 13 m^{2} h^{-1}; number of trees – to 1154 per ha^{-1}; diameter of trees increased to 12 cm. Proportion of extracted trees is 26 … 61% from initial number of trees. In 3 of 4 objects the number of extracted trees exceeds permitted value by 9 … 21% (if the area of strip-roads is considered). If the area of strip-roads (20%) is not considered, intensity of thinning could be increased.

The distribution of trees after thinning is even (Figure 1).

In total, 10722 trees were extracted in the experiment. Extracted biomass according to weighing of forwarder and analyses of moisture of fresh wood was 133 tons of dry matter (60 MWh ha^{-1} of primary energy); harvested stock with bark – 351 m^{3} (31 m^{3} ha^{-1} or 152 LV m^{3} ha^{-1} of chips). According to round-wood measured data, the amount of delivered wood was 316 m^{3} under-bark (about 354 m^{3} with bark) or about 147 tons of dry mass. The study approved that harvester measurement data cannot be used to account the amount of biomass produced by simultaneous extraction of multiple trees, because they are considerably underestimating the amount of produced material. The volume of average extracted tree is 0.03 m^{3}; the diameter of average extracted tree – 10 cm; the average number of trees per cycle – 1.3 pieces (max. 8 … 10 trees per cycle, in firewood method – 1.4 trees per cycle). On average, 30 trees have to be processed to produce 1 m^{3} of round-wood assortments.

The average distribution of productive work time in all work methods is shown in Figure 2. Bucking is the most time consuming work element (28%), the second is reaching tree (24%). Both work elements can be considerably reduced, if accumulating function is used more often, respectively.

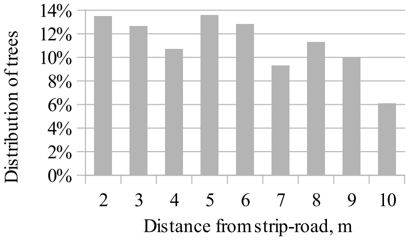

Figure 1. Distance of remaining trees from center of strip-road.

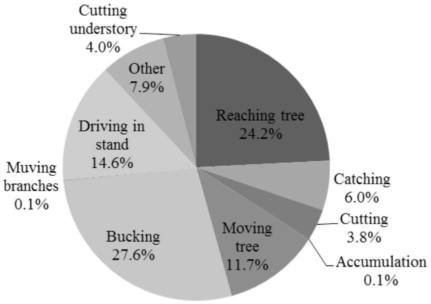

Figure 2. Average distribution of work elements in harvesting.

The production of less assortments reduces bucking time, and this value correlates with the number of crane cycles with more than one tree. In work method 4 the duration of bucking is twice less than in work method 1. This means that broader use of accumulating function may increase productivity considerably. In stands for biofuel (only) production average productivity was:

- 503-455-13 – 4.5 m^3 or 151 trees per productive hour;
- 503-455-14 – 5.0 m^3 or 159 trees per productive hour;

In stands used for comparison of impact of assortments' structure average productivity was:

- 503-479-12 – 5.0 m^3 or 133 trees per productive hour;
- 503-481-6 – 4.4 m^3 or 137 trees per productive hour.

Average productivity in all stands was 4.9 m^3 or 148 trees per productive hour. The provided productive figures exclude driving in and out of the stand.

Comparison of work methods demonstrates an increase of productivity of harvesting with reduction of the number of assortments, except work method 5, where the average diameter of trees was considerably smaller than in other stands. The productivity figures for different methods are:

1. work method – 4.7 m^3 or 114 trees per productive hour;
2. work method – 5.1 m^3 or 126 trees per productive hour;
3. work method – 5.0 m^3 or 141 trees per productive hour;
4. work method – 5.7 m^3 or 156 trees per productive hour;
5. work method – 3.7 m^3 or 136 trees per productive hour.

Production of biofuel assortments from pulp-wood and small dimensions saw logs increase harvesting productivity significantly. The study approves that the potential of accumulating device is not fully utilized.

In total, 58 loads were extracted, the average load of 2.3 tons dry mass or 6.1 m^3. Weight of pure biofuel loads equals to the weight of average load – 2.3 tons of dry mass or 6.0 m^3.

Work elements in forwarding are shown in Figure 3. The forwarding time during trials was considerably increased by snow-fall that took place some days after harvesting. Most of productive time was spent to find assortments below snow and to identify different categories of assortments; therefore, the most time consuming work element in these forwarding studies was unpredicted operations. Considering that such a situation might take place in reality, especially in winter this work element was not excluded from productive work time.

Structure of forwarding work elements depending on work method is shown in Figure 4. The highest productivity figures are characteristic to work methods with a larger share of biofuel. Less productive is work method 1, because of smaller concentration of assortments (more driving from pile to pile).

Productive forwarding time (min. per load) for different work methods is:

1. work method – loading 36 min., unloading 4 min., average load 6.6 m^{3,}
2. work method – loading 38 min., unloading 4 min., average load 7.3 m^3,
3. work method – loading 19 min., unloading 3.4 min., average load 5.6 m^3,
4. work method – loading 16 min., unloading 2.9 min., average load 5.0 m^3,
5. work method – loading 23 min., unloading 3.5 min., average load 6.0 m^3.

Average loading time 26 min, unloading 3.6 min, average load 6.0 m^3. Average driving speed 68 m min^{-1}.

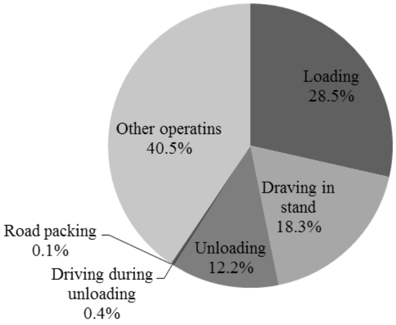

Figure 3. Average distribution of work elements in forwarding.

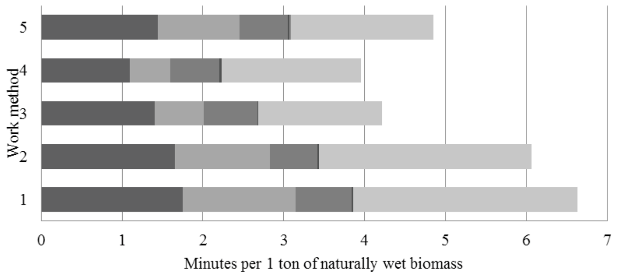

Figure 4. Structure of forwardig work elemets depending from work method.

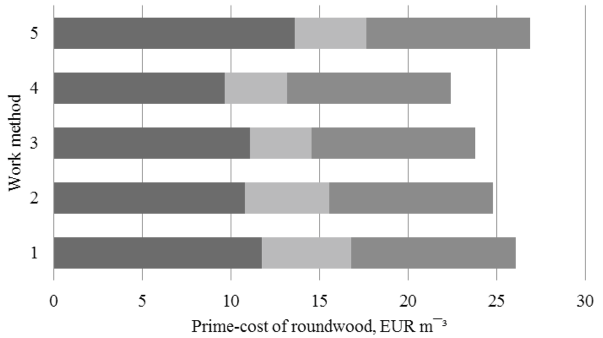

Figure 5. Structure of prime-cost of production and delivery of round-wood matherial.

The structure of prime-costs of production and delivery of round-wood material depending on work method is shown in Figure 5. If work method 5 is not considered (because of smaller dimensions of extracted trees and, respectively, higher production cost), the most efficient is the 4th method. Although the cost of production and delivery of round-wood materials depending on work method ranges from 22 (work method No.1) to 27 (work method No. 2) EUR m^{-3} and differences from the economical point of view are considerable, differences between work methods are not statistically significant ($p<0.05$).

Prime-cost of round-wood considerably drops if a part of cost equal to standard motor-manual thinning is excluded (Figure 6). In spite of that, the production cost is still too high to produce only biofuel assortment in pre-commercial thinning. Market price of firewood utilized in pellet production (respectively, accounted under bark) is 23 EUR m^{-3} on average; therefore, the risk of failure (economic losses) is very high for all methods. There are no statistically significant differences ($p<0.05$) between work methods.

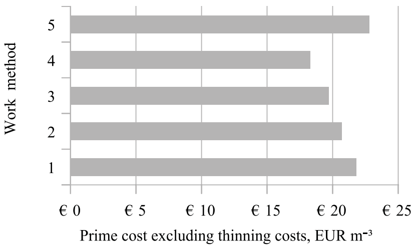

Figure 6. Prime-cost of round-wood excluding thinning cost.

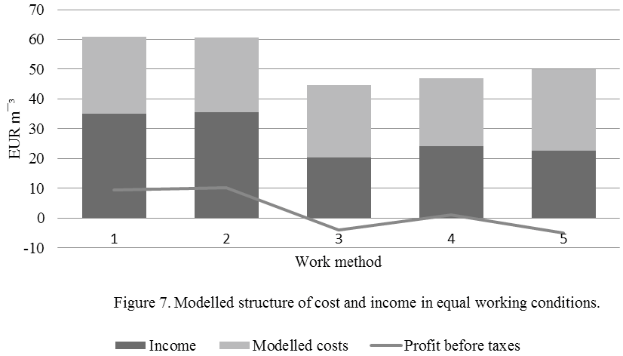

Figure 7. Modelled structure of cost and income in equal working conditions.

Potential income from selling round-wood is considered in a separate calculation of modelled structure of cost and income in equal working conditions. According to Figure 7, working methods 3 … 5 are related to high risk of negative net income; but the most profitable method is No 2 – production of standard assortments and biofuel from undergrowth trees considering reduced min. top diameter of biofuel logs (30 mm).

There are no statistically significant differences ($p<0.05$) between work methods.

Conclusions

1. Average amount of round-wood (under bark) produced in thinning is 28 m^3 ha^{-1}. Share of firewood is 20 – 100%.
2. The average productivity in different stands is statistically different. In stands where only biofuel is prepared, the average productivity was 155 trees per productive hour, but in stands where also other assortments are prepared, the average productivity was 135 trees per productive hour.
3. Comparison of work methods demonstrates an increase in productivity of harvesting with reduction of the number of assortments, except work method 5, where the average diameter of trees was considerably smaller than in other stands. Productivity of harvesting is 3.7 … 5.1 m^3 h^{-1}. Productivity can be increased by more intensive use of accumulation (only 20% working cycles in the study contained more than 1 tree).
4. No difference was found between work methods in forwarding trials, but productivity grows with increase of share of firewood. An average loading time is 26 min, unloading is 3.6 min., but an average load - 6.0 m^3. An average driving speed is 68 m min^{-1}.

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ECONOMIC VALUE OF WOOD CHIPS PREPARED FROM YOUNG STAND TENDING

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Abstract

Small diameter wood obtained from young stand tending, with average $d_{1.3} > 4$ cm, is suitable for the production of biofuel. So far mainly hand motorized tools have been used in young stand tending, to gather the small -diameter wood is costly and unprofitable. As the technology evolves and labor costs rise studies are carried out on how to increase the profitability of the young stand tending, by applying mechanized tending and production of biofuel from small-diameter wood. The study analyzed indicators, which directly affect the profitability of biofuel production from small-diameter wood produced by harvester tending. The biofuel production costs are analyzed using average purchase price of woodchips production service paid by JSC ‘Latvijas valsts meži’ (further JSC LVM). Revenue related to sales of chips is analyzed on the basis of JSC LVM average sales price for woodchips. The price of the preparation of the small-diameter wood is high and the proportions of the full cost price of wood chips make up 38%. The price of forwarding service impact on the full cost price comprises up to 25% and depends on the forwarding distance. The profitability calculation shows, that production of woodchips from the harvester tended young stands has to be regarded as unprofitable.

Key words: energy wood, small diameter wood, young stand, profitability.

Introduction

Young stand tending is very important for the forest industry. The main objective is to establish consistent, appropriate to circumstances, economically viable forest stand with the desired species composition and number of trees, by providing them with adequate growing space (Meža enciklopēdija, 2003; Lazdāns, 2006). Young stand tending is one of the basic tasks in the forest economy and so far has been associated only with expenses. Although tending can be repeated one to three times within one forest growth cycle, the frequency of tending has been reduced for economic reasons, while searching for the most optimal efficiency (Lazdāns, 2006).

As the technology evolves, it is likely that small-diameter wood from young stand tending in future could be used for biofuel production. The income from the sale of biofuel would increase the total income from the stand, but such practices are not used in Latvian. The young stand tending is done mainly by hand motorized tools. Cultivated small-diameter wood is left to decay in tend because, despite the variety of new technical solutions, the cost of harvesting and processing of small-diameter wood are high (Lazdāns, 2006; Lazdāns et al., 2008; Lazdiņš, 2012). Biofuel extraction from the young stand tending is seen as a great opportunity to increase the economic value of forests in Scandinavia and is supported at the national level through subsidies. Due to the increasing expenses of hand labor, the young stands are tended in a mechanized way. Small-diameter wood is used in production of the energy wood chips (Lazdāns, 2006; Ehring et al., 2010; Lazdiņš, 2012). In order to help the young stand tending, the Latvian private forest owners are given an opportunity to gain support from the European Agricultural Fund for Rural Development (EAFRD) activity of Rural Development Programme 2007 - 2013 ‘Improving the economic value of forest’. The aim is to increase the economic value of forests by tending young stands, which has an area of at least 2 hectares and the average stand height of 10 or less meters. So far 2.3 million LVL has been acquired from this activity (Lazdiņš, 2012; Rural Support Service…, 2013).

Biofuel extraction from young stand is not affected by fluctuations in logging amount (Lazdiņš, 2012). Three potentials should be considered when evaluating the possibilities to produce wood chips form small-diameter wood. The theoretical potential is built on all the theoretically and physically available small diameter wood resources, which can be used in production of energy wood chips, regardless of the technical, environmental, legal and administrative constraints. Theoretical potential is calculated from forest auditing data of a particular young stand during a specified period of time. The technical potential of biofuel is derived from theoretical potential, by taking into account technical, ecological and legal constraints. Economically based biofuel potential is based on technically available potential of biofuels, the realization of which, according to the current market situation, is economically profitable. Analysis of potential production costs and revenue from woodchips is carried out to evaluate economic profitability (Hepperle, 2010; Straube, 2010; Lazdiņš, 2012). The data are used to calculate the cost-effectiveness or economic efficiency in this analysis. Profitability or yield from the production process is denoted by term cost-effectiveness. Results from the profitability calculation show whether the profitability is sufficient or it is necessary to increase it by improving the production process (Pelšs, 2001). The objective of this study was to analyze the profitability of wood chips produced from small-diameter wood obtained from harvester tended young stands.

Materials and Methods

Average purchase price of wood chips production service paid by JSC 'Latvijas valsts meži' (JSC LVM) are analyzed as well as the average sales value of wood chips as of February 2013. The volume of wood chips sales is analyzed for the period from 2006 to 2013. The overall cost-effectiveness formula is used to calculate the profitability of wood chips production from the energy wood obtined from young forest tending (Formula 1).

$$R = \frac{P}{A} \times 100, \tag{1}$$

where: R is turnover profitability, %; P is profit or loss, LVL bulk m^{-3}; A is turnover, LVL bulk m^{-3} (Pelšs, 2001; Ahtikoski et al., 2008).

Turnover for one bulk m^3 of produced wood chips is sales price LVL bulk m^{-3}. JSC LVM forecasted average sales price of chips in 2013, from which the full cost price of wood chips will be deducted, is used for the calculation of profit or loss (Formula 2).

$$P = C_{sale} - I_{full}, \tag{2}$$

where: C_{sale} is sales price of wood chips, LVL bulk m^{-3}; I_{full} is full cost price of wood chips, LVL bulk m^{-3} (Pelšs, 2001).

The full cost price of wood chips from young stand small diameter wood is calculated by classical model of full cost price (Formula 3):

$$I_{full} = I_{cut.} + I_{forw.} + I_{chipp.} + I_{trans.} + I_{adm.} + I_{sell.} + I_{overh.}, \tag{3}$$

where: $I_{cut.}$ is the price of the small diameter wood cutting service, LVL bulk m^{-3}; $I_{forw.}$ is the price of forwarding service, LVL bulk m^{-3}; $I_{chipp.}$ is the price of chipping service, LVL bulk m^{-3}; $I_{trans.}$ is the price of road transportation service, LVL bulk m^{-3}; $I_{adm.}$ is the administration costs, LVL bulk m^{-3}; $I_{sell.}$ is selling costs, LVL bulk m^{-3}; $I_{overh.}$ is overheads, LVL bulk m^{-3} (Pelšs, 2001; Petty and Kärhä, 2011).

The cost of small-diameter wood preparing service is affected by the chosen technical solution. The current study analyzed the preparing of small-diameter wood by harvester. The price of the forwarding service as well as the price of road transportation service depends on the distance. The general linear regression model is used to describe the relationship between the factorial sign, which in this case is the distance of forwarding or road transportation, and the resulting feature, which in both cases is the price of services (Formula 4):

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, \quad i = 1 \dots N, \tag{4}$$

where: β_0 is the free member of the general group regression line; β_1 is the directional coefficient of the general group regression line; ε_i is the random error; N is the number of general group elements.

The chipping service price was taken as a constant value and, according to the average JSC LVM prices of wood chips production service for February of 2013, is 1.87 LVL bulk m^{-3}.

It is assumed that the administrative costs, which should be included in full cost price of wood chips, comprise 3% of the production cost of wood chips, but the cost of sales is 2%.

The overhead, includable in the full cost price of wood chips, could be special paper coverage for drying small diameter wood. It increase full cost price of wood chips by 0.04 LVL bulk m^{-3}

Results and Discussion

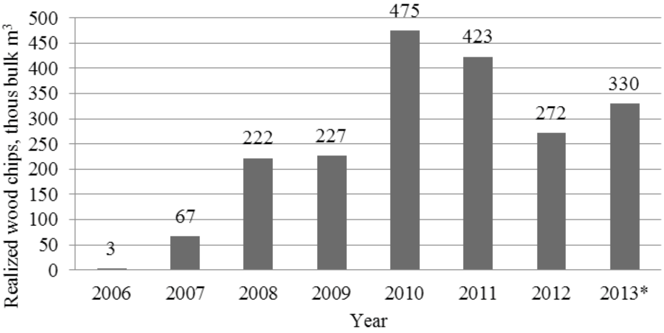
Monitoring data about wood biomass usage for energy purposes have shown that from 2005 to 2011 in Latvia we can observe an upward trend in wood chip consumption. Monitoring data also show that in 2008 Latvia experienced a little decrease in wood chip consumption, that can be explained with the onset of the economic crisis. In 2009 the consumption of wood chips returned to the level of 2007 and continued to grow (Koksnes biomasas izmantošanas…, 2012).

JSC LVM is one of the largest wood chip producers in this country. Analyzing JSC LVM wood chip sales (Fig. 1) it can be concluded that from 2006, when JSC LVM started to produce the wood chips, till 2010 there was a sharp rise in wood chip sales. The volume sold in 2007 increased 22 times in comparison with that of 2006. The rapid sales growth was observed in 2008, when, compared to 2007, it increased 3 times. The sales growth in 2009 was low compared to 2008, while in 2010, compared to 2009, wood chip sales increased 2 times, reaching 475 thousand bulk m^3. These sales growth trends can be explained by the increase in wood chip consumption in Latvia. The fall in consumption in 2008, associated with the onset of economic crisis, did not affect the JSC LVM wood chip sales volume as it accounted for only 11% of total national consumption of wood chips (Koksnes biomasas izmantošanas…, 2012). The slight decline in sales happened in 2011 and this tendency continued also throughout 2012. The above situation can be explained by economic constrains associated with the implementation of the forest certification system and reorganization of the production. In the 2011 the consumption of wood chips decreased by about 4.4%. Sales of wood chips in 2012, compared to 2010, decreased 1.7 times and got closer to the amount of wood chip sales of 2009.

Sales of wood chips in 2013 will increase 1.2 times in comparison to 2012. The production of wood chips has also increased in other Baltic and Nordic countries (Koksnes biomasas izmantošanas.., 2012).

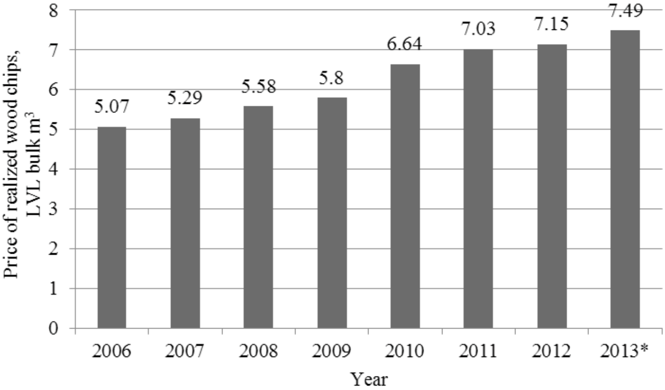
The average price at which the JSC LVM sold the wood chips has increased (Fig. 2.).

The price growth in 2007 when the JSC LVM launched the sale of wood chips was 4% compared to 2006. In 2008 compared with 2007, the sales price increased by another 5%. Such increases can be observed in 2009, when the sales price, compared to 2008, rose by 4%. In 2010, compared to 2009, the sales price of wood chips increased by 13%. This



* predicted sales volume

Figure 1. Volume of wood chips sold by JSC LVM during the years 2006 to 2013, thousand bulk m^3.



* predicted sales price

Figure 2. Price changes of realized wood chips by JSC LVM during the years 2006 to 2013, LVL bulk m^{-3}.

tendency continued in 2011, when, compared with 2010, the price rose by 6%, while in 2012, compared with 2011, by 2%. The price of wood chips increased 1.4 times or by 29% in 2012, compared to 2006, when LVM began marketing the wood chips. Increase in sales price is expected to continue in future. This is due to the growing demand for energy wood chips that is associated with the rise in consumption (Koksnes biomasas izmantošanas…, 2012).

Previous studies have confirmed that harvesting of small-diameter wood for production of wood chips should be started only if the average height of the felled small-diameter wood is from 4 to 9 meters, and the number per hectare, depending on the species, ranges from 5,000 to 6,000 units. It is possible to harvest 30 to 110 m3 small-diameter wood per hectare from young stands that meet these conditions. Young stands, from which the cultivated small-diameter wood will be used in the production of wood chips, should be at least 2 to 3 hectares, so that small-diameter wood chipping material would form at least 100 m^3 of small-diameter wood in the upper stack. When a young stand is chosen for the biofuel production, sustainability of the soil plays an essential role, in order to allow tending of young stands, forwarding of small diameter wood and construction of stowage (Lazdāns, 2006). The average diameter of trees at breast height ranges from 4 to 30 cm.

Several combinations of technology and machines can be used in the wood chip production. Traditional scheme of wood chip production begins with a small-diameter wood preparation, transportation, chipping and further transport.

When the service rates of young stand tending by the harvester are analyzed, cost of production of biofuel derived from young stands can be calculated.

Small-diameter wood cutover preparation costs range from 2.12 to 2.39 LVL bulk m^{-3} depending on the selected logging equipment (Lazdāns et al., 2008). Since so far the harvester has not been used in tending of young stands with a volume of average tree $d_{1.3} < 8$ cm, no information on pricing is available. Scientific studies show that the smaller the average diameter of the tree stands the higher the production costs of small-diameter wood. Based on this information assumption is made that the service average price for harvester used tending of young stand with an average tree $d_{1.3} < 8$ cm would exceed the average price of small-diameter wood production from young stands with an average tree $d_{1.3} > 8$ cm. The price for harvester service has been analyzed for a young stand with an average tree $d_{1.3} > 8$ cm (Fig. 3.). It appears that the forwarding price is affected not just by average volume of timber, but also by tree species.

The lowest thinning service prices are for pine (*Pinus sylvestris*) stands. They are l ower than prices for the rest of the stands by average 0.5%; consequently, it can be considered that the differences are not statistically essential (Fig. 3.). Spruce (*Picea abies*) tending prices are on average 4% higher than prices for pine stands and other stands.

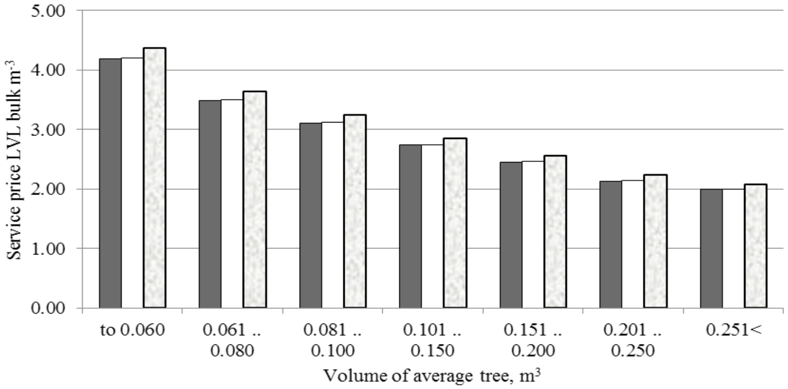


Figure 3. Price of harvester thinning service depending on the tree species and average tree volume, LVL bulk m^{-3}.

Another significant issue for analysis of wood chip production costs is the price of small-diameter wood forwarding service, depending on the distance. Small-diameter wood forwarding prices are equalized to prices of logging residues forwarding service in selective cutting (Fig. 4.).

There is a strong linear relationship between forwarding distance (l) and average price of service (c), as indicated by the coefficient of determination $R^2 = 0.9995$, i.e. if the forwarding distance increases by 100 metres, service price increases by 0.19 LVL bulk m^{-3}.

Road transportation service prices for produced wood chips also have a significant impact on the wood chip production costs. The price of service (c) increases if the transportation distance (l) increases. This correlation can be explained by a linear regression model (Fig. 5.).

Price for every 10 km increases by 0.16 LVL bulk m^{-3}, if the wood chips are transported to the final consumer in Latvia. Price for every 10 km increases by 0.19 LVL bulk m^{-3} if the wood chips are transported outside the Latvian border.

The selected manufacturing technology greatly affects efficiency of the wood chip production. Technology and tending methods are chosen by the above mentioned criteria - the soil bearing capacity, stand density and average diameter of the tree (Vilkriste, 2012).

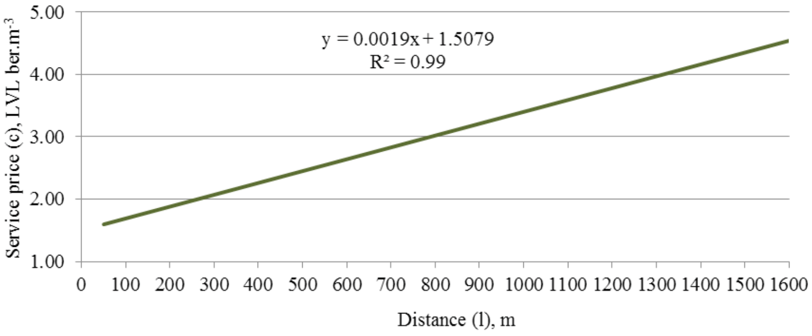


Figure 4. Price of thinning residual forwarding service depending on the forwarding distance, LVL bulk m^{-3}.

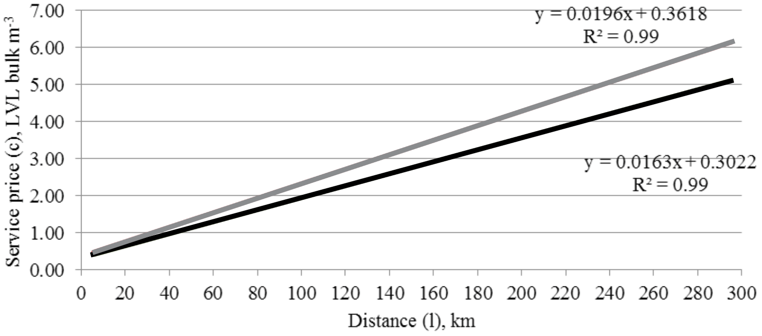


Figure 5. Price of wood chips road transportation service depending on the distance , LVL bulk m^{-3}.

Table 1

Full cost price calculation for wood chips

Indicators	Volume of average tree (to 0.060 m^3)	Full cost price structure, %	Volume of average tree (more than 0.251 m^3)	Full cost price structure, %
Price of cutting service	4.19	38.4	1.99	23.2
Price of forwarding service (601 … 700 m)	2.74	25.1	2.74	31.9
Price of chipping service	1.87	17.2	1.87	21.8
Price of road transportation (71 … 80 km)	1.54	14.1	1.54	17.9
Overheads	0.04	0.4	0.04	0.5
Cost of production	**10.38**	**95.2**	**8.18**	**95.2**
Costs of administration	0.31	2.9	0.25	2.9
Costs of sales	0.21	1.9	0.16	1.9
Full cost price	**10.90**	**100**	**8.59**	**100**

To calculate the full cost price of wood chips, two full cost price calculating models were created. In the first model it was assumed that young stand tending is carried out by harvester with the average tree volume of up to 0.060 m^3. The second model of tending stand average tree volume is greater - 0.251 m^3 (Table 1).

In calculations we used JSC LVM average service purchase price for chipping as of February 2013. Assuming that the average forwarding distance of small-diameter wood from the young stand tending for JSC LVM is within the range of 601…700 m and the average road transportation distance is from 71…80 km, in calculations we used the average price of service purchase. The estimated overheads were 0.04 LVL bulk m^{-3}.Results of the first calculation model show that the production cost of wood chips is 10.38 LVL bulk m^{-3}, while the full cost price is 10.90 LVL bulk m^{-3}. Results of the second calculation model show that the production cost of wood chips is 8.18 LVL bulk m^{-3}, so the full cost price is 8.59 LVL bulk m^{-3} respectively.

From the analysis of the full cost price and cost structure of wood chips we can conclude that in the first calculation model the biggest part of total costs comprise harvesting service costs, followed by forwarding and chipping service costs. Road transportation service costs are also relatively high. Administration and marketing costs as well as overheads account for only 5.2% of the full cost price of wood chips. Cost structure of the second calculation model differs from the first model. With the increase of average tree volume obtained from young stand, the service costs of small-diameter wood harvesting will decrease. The biggest part of costs consists of forwarding costs of small-diameter wood, followed by harvesting, chipping and road transportation service costs.

Assuming that the sales price of wood chips is 7.49 LVL bulk m^{-3}, in the first calculation model full cost price of wood chips is higher than the sales price, thus production of wood chips under certain conditions result in loss – 3.41 LVL bulk m^{-3}. The calculation results show that the profitability level of turnover is negative (- 46% bulk m^{-3}). In the second calculation model the full cost of wood chips is higher than the sales price of wood chips (loss – 1.10 LVL bulk m^{-3}). Consequently, the profitability level remains negative (- 15% bulk m^{-3}).

Production of wood chips from harvester tended young stands has to be regarded as unprofitable due to the current average price which JSC LVM pays the contractors for the production services. Possibilities to reduce the cost of production have to be explored to make more profitable production of small-diameter wood biofuel. Particular emphasis should be put on small-diameter wood preparation costs, which account for the greatest proportion of the total cost. Small-diameter wood preparation cost reductions can be achieved by boosting workers' productivity. It could be done by using the multi-operation machines in the preparation process (Lazdāns, 2006). Cost-benefit ratio of wood chip production could be increased if the market price of wood chips increased.

Conclusions

1. The prices for the preparation of small-diameter wood produced from harvester tending young stand are high and depending on average tree volume of stand represent about 24 to 38% of the full cost price of wood chips.
2. Forwarding service prices depend on forwarding distance. The price for every 100 m increases by 0.16 LVL bulk m^{-3}. It creates substantial full cost price increase in the form of wood chips.

3. Transportation prices are different, depending on the final consumer - whether it is in Latvia or abroad. The price for every 10 km increases by 0.16 LVL bulk m^{-3} in Latvia and 0.19 LVL bulk m^{-3} if the wood chips are transported outside.
4. Production of wood chips from harvester tended young stands has to be regarded as unprofitable due to the current average price which JSC LVM pays to the contractors for wood chip production services.

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THEORETICAL EVALUATION OF WOOD FOR BIOENERGY RESOURCES IN PRE-COMMERCIAL THINNING IN LATVIA

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Abstract

The study represents results of theoretical evaluation of forest biomass available for solid biofuel production in pre-commercial thinning in Latvia. The study is based on the National forest inventory (NFI) data; calculations are done for each NFI plot separately. The calculation is done in three steps – selection of the NFI sample plots, which fulfils criteria for the pre-commercial thinning, development of the diameter distribution table, setting the criteria of the thinning intensity, calculation of extractable biomass. Thinning from below (removal of the smallest trees) is considered in calculation. Two types of biomass are accounted – full tree (aboveground biomass) and stem-wood (stem biomass). The study demonstrates that pre-commercial thinning could become an important source of forest biomass in Latvia (15400 GWh of primary energy according to current situation in forests); however, dimensions of trees and harvesting conditions might be challenging for production. The most of the potential biofuel resources are located in stands with average tree higher than 8 m; therefore, it is reasonably to develop and introduce technologies applicable for production of partially delimbed trees.

Key words: pre-commercial thinning, solid biofuel, resource assessment.

Introduction

Up to 40 years old coniferous, ash and oak stands, up to 10 years old grey alder as well as up to 20 years old stands of other deciduous species are considered young stands (Latvijas Republikas Saeima, 2000). Pre-commercial thinning is done to improve stand structure and secure growth of tree species and populations, which are more adopted to a particular place, to increase productivity of the forest stand and increase value of remaining trees in future. Properly done pre-commercial thinning secures that target trees reach commercially valuable dimensions 10...20 years earlier (Bisenieks, 2005). Pre-commercial thinning in Latvia is usually done with bush-saws before trees reach 6 m height, in pine stands – even sooner. Restrictions for thinning intensity are set by the Regulations of Cabinet of Ministers No. 935 (Ministru Kabinets, 2012). No solid biofuel has been collected in pre-commercial thinning in Latvia up to now, in spite of the fact that this is one of the most important potential sources of high quality solid biofuel in forest operations.

Recent studies on the solid biofuel production in pre-commercial thinning in Latvia are concentrated on increase of productivity and selection of stand for more efficient extraction; however, knowledge about resources and accounting methods are poorly developed (Lazdiņš and Thor, 2009). Due to the fact that there were no alternative solutions, motor-manual pre-cmmercial thinning was also out of the scope of researchers during last decades. Recent studies by the LSFRI Silava about productivity of the motor-manual thinning shows that average productivity varies between 0.14 and 0.03 ha hour^{-1} (7...33 hours ha^{-1}), depending on initial number of trees in the stand, if the average tree height is 6...7 m (Zimelis et al., 2012). This means that mechanized extraction of biomass for energy can be feasible in delayed pre-commercial thinning in forest stands with larger trees, where motor manual operations are loosing their efficiency.

Modern harvesting machines can be used in pre-commercial thinning to produce traditional roundwood assortments as well as forest biofuel from small size stems and tops of trees. Extraction technologies applicable in the pre-commercial thinning can be organized into 4 groups: harvesters or harvarders with accumulating felling heads, combined extraction and comminution machines and motor-manual operations. Combined machines have practical meaning in short rotation plantations, because in normal forest stands relief, dead wood, stumps and other obstacles are considerably hampering productivity (Skogforsk, 2011).

Importance of the resource assessment in the light of productivity of harvesting machinery and adaptation of harvesting methods is highlighted, for instance, in Sweden, where young stands with average tree height less than 12 m covers 12.3% of the forest area and stands with average tree height between 12 and 15 m – 18.4% of the forest area. The first group of stands can contribute to bioenergy production with 149 mill. tons of wood (50 dry tons ha^{-1}); the second group of stands can contribute with 258 mill. tons of wood (62 dry tons ha^{-1}). Studies in Sweden approves that biofuel production in pre-commercial thinning is not feasible, if breast height diameter of average tree in a stand is below 8 cm. For smaller trees the new „Boom corridors” technology and new type of accumulating felling head is invented, securing by 16% higher productivity in comparison to traditional methods (Bergström, 2009; Bergström et al., 2010).

The aim of the study is to estimate potential solid biofuel resources in pre-commercial thinning following to legal and technical restrictions of the forest management.

Materials and Methods

Theoretical assessment of the solid biofuel resources in pre-commercial thinning is done based on the results of the first round (2004...2008) of the National forest inventory (NFI). All sample plots and their compartments, which correspond to the land use categories forest or afforested land are used in calculation. The NFI data utilized in calculation are land use category, area of the plot or its compartment (in recalculation to forest area 1 m^2 = 0.69 ha), stand type, stand age, soil (organic or mineral), dominant tree species, number of trees in the dominant stand, diameter and height of average tree, basal area and growing stock of the dominant stand. Additional parameters calculated on the base of the NFI data are volume of average tree, minimal number of trees in respect to height of average tree and dominant tree species according to national legislation (a correction of + 10% was applied in calculation). Open street map data (Geofabrik GmbH and OpenStreetMap Contributors, 2013) was used to determine average distance between centre of the particular NFI plot and the nearest road. The State forest register database was used to identify those NFI sample plots, which overlaps with forest compartments, where forest management is restricted by law. The areas, where forest thinning is forbidden, were excluded from the calculation of resources.

The NFI plots and sectors suitable for solid biofuel production in pre-commercial thinning were selected by separation of areas on poor soils (*Cladinoso-callunosa, Callunoso-sphagnosa, Callunosa mel.* and *Callunosa turf. mel.*) as well as in stand types, where pre-commercial thinning is not a common forestry practice (*Sphagnosa, Caricoso-phragmitosa, Dryopterioso-caricosa* and *Filipendulosa*). Remaining plots were split into 2 groups – on wet and organic soils (suitable for extraction on frozen soil) and on dry or drained mineral soils (can be extracted at any time). Then the plots and compartments with average tree height of 4...12 m were selected for further evaluation – selection of areas, where basal area (number of trees) would be above minimal allowed value after extraction of 20% of trees (cleaning of 4 m wide strip-roads). For species, which do not have legal requirements for minimal basal area, the values of birch are used in calculation (Ministru Kabinets, 2012).

Due to lack of reliable biomass expansion factors for small trees in forest lands, biomass expansion factors elaborated in afforested lands were used in the resource assessment (Lazdins, 2011). Stem and aboveground biomass of trees is estimated using equation 1, species specific coefficients are provided in Table 1. Biomass calculations are done according to the dominant tree species.

$$Y_i = b_0 * x_i^{b_1}, \textit{where}$$

Y_i – *biomass* (*stem or above ground biomass, kg*);
x_i – *factorial value* (*diameter at breast height, cm*);
b_0; b_1 – *coefficients*.
(1)

Growing volume is calculated by multiplying stem biomass and relative wood density (Table 2). For other species that are mentioned in Table 2 density of birch was applied.

Extractable biomass is calculated in two steps. At the first step, the number and biomass of trees extractable on strip-roads was estimated, assuming that strip-roads cover 20% of stands; at the second step, the number and biomass of trees to be harvested in the remaining stand to reach minimum basal area were estimated. Stem volume extractable on strip-roads was calculated using proportion – 20% of growing stock, stem biomass was calculated according to relative

Table 1

Coefficients for calculation of biomass of trees (Lazdiņš et al., 2011)

Species	Stem biomass		Above ground biomass	
	b_0	b_1	b_0	b_1
Aspen	0.17	1.78	0.27	1.61
Birch	0.17	1.95	0.29	1.76
Grey alder	0.16	1.77	0.2	1.78
Spruce	0.36	1.37	1.16	1.21
Black alder	0.1	2.27	0.12	2.24
Pine	0.14	1.88	0.23	1.91

wood density (Table 2), above ground biomass was calculated using biomass expansion factors (Table 3). Average tree volume on strip-roads was calculated using equation 2, number of extractable trees – equation 3.

$$v = \frac{V}{n}, \text{ where}$$

v – stem volume of average tree, m^3,
V – given growing stock, $m^3 ha^{-1}$,
n – given number of trees per ha^{-1}. (2)

$$n_1 = \frac{V * 20}{v}, \text{ where}$$

n_1 – number of extractable trees per ha^{-1}. (3)

Table 2

Relative wood density (Penman, 2003)

No.	Species	Relative wood density, tons m^{-3}
1.	Aspen	0.35
2.	Grey alder	0.45
3.	Birch	0.5
4.	Spruce	0.4
5.	Black alder	0.45
6.	Ash	0.58
7.	Oak	0.58
8.	Pine	0.42

Table 3

Biomass expansion factors (Penman, 2003)

No.	Species	Biomass expansion factors (stem to above ground biomass)
1.	Coniferous species	1.35
2.	Deciduous species	1.30

Estimation of biomass of extractable trees in the remaining stand starts with calculation of diameter distribution of the stand using *Beta* distribution equation (Arlinger, 1997). The general Beta function is provided in equation 4.

$$B_{(m,n)} = \int X^{m-1} * (1 - X)^{n-1} * d * x \quad m, n > 0 \tag{4}$$

Minimal diameter of trees $a = 0.4 \cdot d$, maximal diameter $b = 1.7 \cdot d$, where d is diameter of average tree in the plot. The equation is approved in stands with average diameter of trees in the range of 6...60 cm (Arlinger, 1997); therefore, there is a risk that estimation of the solid biofuel resources in this study may have high level of uncertainty.

Coefficient *m* for pine, birch and other species is calculated by equation 5, for spruce – with equation 6. Coefficient *n* is calculated by equation 7 for all species.

$$m = 0.5 + 0.1 * (d - 6) \tag{5}$$

$$m = 0.3 + 0.08 * (d - 6) \tag{6}$$

$$n = m * \left(\frac{b - a}{d - a} - 1 \right) \tag{7}$$

Number of trees in each diameter class is calculated using equation 8. Distribution of trees is calculated within the range of 2...30 cm with 1 cm step. It the sum of trees in distribution differed from actual number of trees, remaining trees were added or removed equally from all presented diameter classes.

$n = (x - a)^{m-1} * (b - x)^{n-1}$, where
x – *diameter of tree* (*cm*) (8)

Extractable trees were accounted in smaller diameter classes until the number of trees to be removed is reached. Respectively, all trees in larger diameter classes are set for retaining until the sum of trees in a particular diameter class reaches the minimal number of trees calculated earlier; the rest of trees in remaining diameter classes are marked for extraction. The last stage of calculation is estimation of average diameter of extractable trees and above ground and stem biomass using equation 1, stem volume by multiplying of stem biomass and relative wood density, calculation of total extractable biomass and stem volume (in strip-roads and a stand), number of extractable trees and average volume, and other characteristics of extractable trees.

The intermediate results (extractable above-ground biomass per ha^{-1}) were filtered to select outliers (values exceeding range of 3 standard deviations), which were replaced with average values except outliers (extractable above-ground biomass, stem biomass and stem volume per ha^{-1}) for particular tree species.

Results and Discussion

According to the study results, extraction of biofuel in pre-commercial thinning is possible in 161 kha area (4.5% of the forest area in Latvia and about 20% of the forest stands, which fits the height criteria for pre-commercial thinning). Total extractable aboveground biomass is 2962 ktons (15400 GWh of primary energy), stem biomass – 2231 ktons, stem-wood – 4.9 mill. m^3. Average extractable aboveground

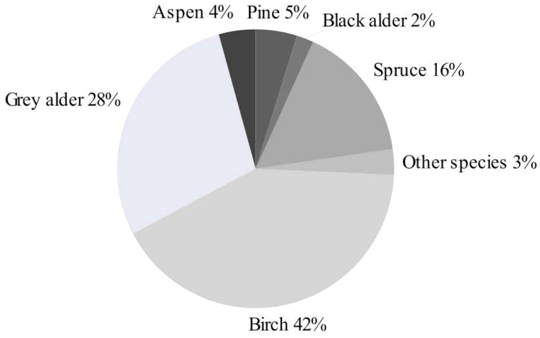

Figure 1. Distribution of stem biomass available for biofuel production in pre-commercial thinning.

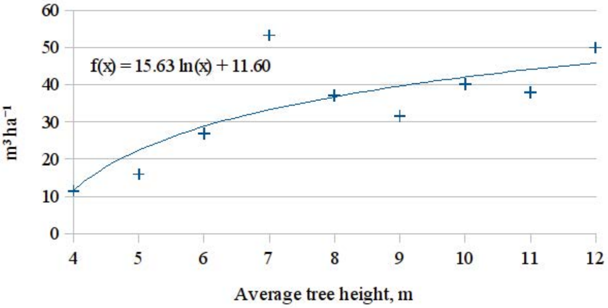

Figure 2. Average extractable stock depending on height of average tree.

biomass is 25 tons ha^{-1}, stem biomass – 19 tons ha^{-1}, stem volume – 41 m^3 ha^{-1}. Stem volume of average extractable tree is 0.01 m^3; this includes trees with diameter of less than 4 cm, which are not used for biofuel production, respectively actual stem volume of average tree is larger. Average age of stand suitable for biofuel production is 18 years.

The most of the resources are concentrated in birch dominant areas (42%, Figure 1), coniferous contributes to 21% of the resources, which means that potential deliveries of biomass to pellet factories using mainly coniferous wood is limited (462 ktons of stem-wood).

If selecting only stands with average breast height diameter of at least 8 cm, the biofuel extraction in pre-commercial thinning can be done in 53 kha (33% of the potentially accessible areas), including 13 kha accessible only in winter. Total extractable aboveground biomass in these areas is 1065 ktons, extractable stemwood – 2.4 mill. m^3 (49% of stem-wood accessible in pre-commercial thinning according to this study), stem volume of average extractable tree is 0.03 m^3.

Extractable stock of stem-wood varies from 12 m^3 ha^{-1} in areas with average tree height of 4 m to 50 m^3 ha^{-1} in areas with average tree height of 12 m (Figure 2). The largest average extractable stock is in birch stands (66 m^3 ha^{-1}). Average estimated intensity of thinning is 41% of the growing stock.

Stem volume of average extractable tree follows to exponential regression determined by the initial height of average tree (Figure 3). The stem volume of average extractable tree is 15 times bigger in areas, where height of average tree is 12 m in comparison to areas with 4 m long trees and 6 times larger in comparison to areas with 6 m long trees. This means that delaying of pre-commercial thinning is important factor to increase feasibility of the biofuel extraction.

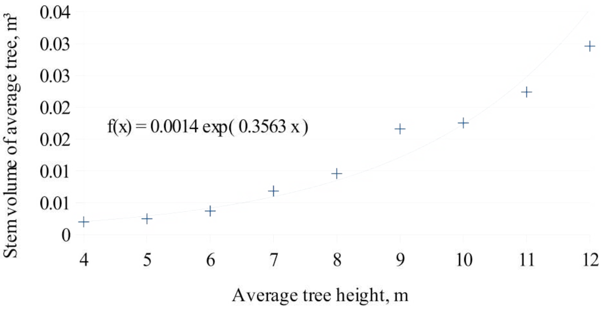

Figure 3. Average extractable stock depending on height of average tree.

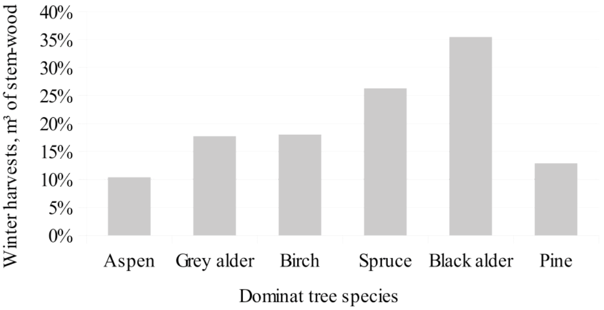

Figure 4. Proportion of solid biofuel to be extracted in winter time.

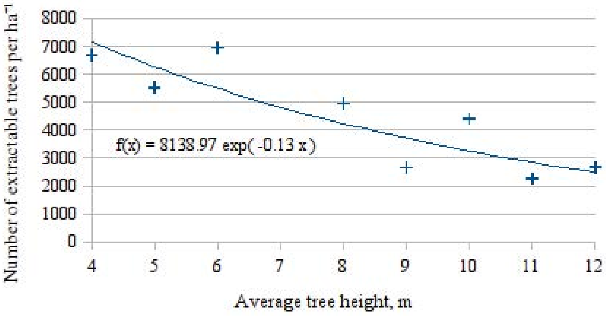

Figure 5. Average number of extractable trees depending from height of average tree.

The average proportion of solid biofuel, that can be extracted in winter time only is 19%; the highest (35%) this proportion is areas, where black alder is dominating, the smallest (respectively, 10% and 13%) in aspen and pine dominant areas (Figure 4).

The average number of extractable trees varies from 7 thousand to 2 thousand per ha; it has a tendency to decrease with the increase of height of average tree (Figure 5). The average distance from the centres of the NFI plots to the nearest to the road is 279 m; there is no linear correlation between height of average tree in the area and distance to the road; which means that all resources are equally accessible. However, the distance to average road and actual forwarding distance is not calibrated in Latvia, therefore, the actual distance to the road might be longer.

Conclusions

1. Extraction of biofuel in pre-commercial thinning is possible in 161 kha area. Total extractable aboveground biomass is 2962 ktons, stem-wood – 4.9 mill. m^3, including 21% of resources located in coniferous dominant stands. Considering that the calculation includes biomass of trees being thinner than 4 cm, the results of the study can slightly overestimate the biofuel resources.
2. Biomass expansion factors as well as the coefficients used in calculation of the diameter distribution of trees are not evaluated in young stands; therefore, the resource assessment in this study should be considered as preliminary and further improvements are necessary, especially elaboration of equation for calculation the diameter distribution of trees.
3. Economically efficient biofuel extraction (according to Swedish assumptions) can be done in Latvia in 53 kha with total extractable aboveground biomass of about 1065 ktons (36% of the total potential in pre-commercial thinning).
4. The delaying of pre-commercial thinning is an important factor to increase feasibility of the biofuel extraction, because the stem volume of extractable trees is 6 times bigger in areas where an average tree is 12 m in comparison to areas with 6 m long trees; therefore, silvicultural studies should be concentrated on evaluation of delayed thinning to find synergies between forest management and biofuel production.
5. Accessibility of the biofuel seems not to be a problem (only 19% of biofuel can be extracted only in winter time); however, average harvesting conditions may be much worse than in the study, because they are determined by the worst place in a stand and not the average conditions.

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