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

SKUJU KOKU CELMU IEGUVES UN TRANSPORTĒŠANAS TEHNOLOĢISKS RISINĀJUMS

Agris Zimelis

TECHNOLOGY FOR EXTRACTION AND TRANSPORTATION OF CONIFEROUS STUMPS

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.sc.ing. **AGRIS ZIMELIS**

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ANOTĀCIJA

Celmu izstrāde plašāk zināma Skandināvijas valstīs. Plašāki pētījumi par šo atjaunojamo koksnes energoresursu ieguvi tiek veikti, sākot ar 1970. gadu. Sākotnēji šī resursa izmantošana saistīta ar plānoto celulozes rūpnīcu izejvielu nodrošinājumu. Tagad Somijā celmu koksnes ieguve jau vairākus gadus tiek realizēta ražošanā kā biodegvielas avots. Piemēram, 2005. gadā šī izejmateriāla izmantošana koģenerācijas ciklā sastādīja 0.4 milj. m^3. Pirmie pētījumi šajā virzienā 21. gadsimtā Latvijā veikti 2006. gadā. Celmu raušana eksperimentāli ir veikta AS "Latvijas valsts meži" (LVM) un SIA "Rīgas meži". Agrāk šo resursu pielietoja arī ķīmiskā rūpniecībā, iegūstot kolofoniju, terpentīnu un to tālākas pārstrādes produktus.

Darbā, balstoties uz Meža valsts reģistra (MVR) un Meža resursu monitoringa datiem, novērtēti kopējie pieejamie celmu koksnes energoresursi. Kopējais celmu resursu daudzums skuju koku izcirtumos atbilst 103 tūkst. GWh primārās enerģijas izteiksmē, no kuriem tehniski iegūstamais ikgadējais apjoms atbilst 349 GWh primārās enerģijas. Lielākā daļa iegūstamās biomasas ir damakšņa un vēra tipos. Analizējot kopējos pieejamos resursus, lielākā daļa jeb 62% ir iegūstami LVM apsaimniekotajos mežos un 38% pārējos mežos.

Celmu izstrādes energoefektivitātes raksturošanai kopējā tehnoloģiskajā procesā izmantoti līdz šim visi pētījumu objekti Latvijā, kuros veikta celmu izstrāde biokurināmā sagatavošanai. Datu analīzē ietverti dati par 3022 celmu izstrādi.

Modelējot energoefektivitātes rādītājus, identificēta nepieciešamība ietvert aprēķinos datus par augsnes sagatavošanu, veicot to vienlaicīgi ar celmu izstrādi. Līdz ar to tika uzsākti teorētiski aprēķini, lai modelētu celma rāvēja darbību pie dažādiem scenārijiem. Aprēķini balstās uz teorētiskās mehānikas likumiem, pēc kuriem nosakāma tehnikas stabilitāte, ko ietekmē galvenokārt izraujamā celma caurmērs un atrašanās vieta. Tieši šie faktori maina nepieciešamos tehniskos parametrus – ekskavatora pašmasu, nepieciešamo hidraulikas caurplūdi un citus svarīgus rādītājus. Balstoties uz šiem aprēķiniem, pētījumā izstrādātas un aprobētas darba metodes celmu raušanai-plēšanai.

Kā efektīvākais pielietojamais tehnoloģiskais variants celmu koksnes ieguvei darbā ieteikts: celmu izstrādi veikt ar Latvijā uzbūvēto celmu rāvēju-plēsēju MCR 500 II, pievešanu veicot ar vidējās klases forvarderu (analīzē iekļauts John Deere 810D forvarders), celmu drupināšanai starpkrautuvē izmantojot jaudīgu biomasas drupinātāju, piemēram, CBI Magnum Force 6800P un drupināto koksni gala patērētājam piegādāt, izmantojot autovilcienu ar vismaz 90 m^3 ietilpību (analīzei izmantots Volvo FM autovilciens). Izmantojot šo tehnoloģisko shēmu, kopējais enerģijas izmantošanas lietderības koeficients ir 3.9. Tas nozīmē, ka celmu koksnes tālākā izmantošanā iegūstamais enerģijas daudzums būs lielāks salīdzinājumā pret pievadāmo enerģijas daudzumu ieguves procesā.

Pētījuma rezultāti apkopoti 11 zinātniskos rakstos un, balstoties uz pētījuma rezultātiem, sagatavoti un saņemti 2 Latvijas patenti celmu raušanas-plēšanas un augsnes gatavošanas iekārtām.

ABSTRACT

Stump harvesting has been well studied in Scandinavian countries. More detailed studies on stumps as a renewable wood energy resource have been carried out since 1970ies. From the beginning this type of wood resource was linked with planned supply materials for pulp mills. For instance, in Finland for the last couple of decades the extraction of stump wood is carried out as a source for biofuel where in 2005 more than 0.4 mil m^3 of raw material was used in the cogeneration cycle. First extensive studies in Latvia were done in 2006 where experimental stump harvesting have been performed in JSC "Latvian State Forests" and LLC "Rīgas Meži". In the past this raw material was used in chemical industry for extraction of rosin, turpentine and their further refined products.

In this thesis the assessment of available stump wood energy resources was made using the data from State forest register (SFR) and National forest inventory (NFI). After summarizing abovementioned data, more than 103 thousand GWh of primary energy resource from stumps in clear-cuts of coniferous have been detected. Technically extracted annual amount of primary energy corresponds to 349 GWh. According to the Latvian forest typology largest amount of biomass was detected in *Hylocomiosa* and *Oxalidosa* forest types. The majority of available resources 62% can be obtained in state forests and 38% in other forests.

To characterize the efficiency of stump extraction in common technological process, in this study all previous studied sites where stump harvesting for biofuel purposes was performed in the territory of Latvia. In total data from 3022 stumps were included.

During the modelling process, in which energy efficiency parameters were detected, a need for additional information on soil preparation and stump harvesting was detected. Furthermore, theoretical calculations were started to model the stump operational process under different scenarios. These calculations were based on theoretical mechanical rules where technical stability is detectable, which is mainly depended on diameter on removable stump and site-specific location. Mostly, these two factors are crucial, where technical parameters such as excavator unladen weight, required hydraulic flow and other important parameters should be changed. Based on abovementioned calculation, in this study the elaboration and approbation of particular methods for stump pulling and crushing was done.

In the result of this study, it is suggested that the most effective technological approach of stump extraction using MCR 500 II stump lifting head (in additional, this feature is made in Latvia) with medium class forwarder (in this particular study John Deere 810D forwarder is included). Furthermore, for stump grinder it is suggested to use, for instance, CBI Magnum Force 6800P where delivery of grinded wood to the final consumer would be performed by the truck with a capacity at

least 90 m^3 (in this study the Volvo FM truck is included). The use of this technology scheme, the total amount of energy efficiency factor is 3.9. This explains the fact that the amount of energy obtained from further use of the wood extracted from stumps will be higher compared to the amount of energy supplied in the extraction process.

The main results of the thesis are published in 11 scientific papers and based on research results two Latvian patents have been developed and approved for stump pull and crush, and soil preparation as a part of forestry technology.

SATURS / *CONTENTS*

1. DARBA VISPĀRĪGAIS RAKSTUROJUMS

1.1. Tēmas aktualitāte

Enerģētikas sektors cieši mijiedarbojas ar citiem sektoriem, tajā skaitā mežsaimniecību, un energoresursu cena var būtiski ietekmēt kopējo valsts ekonomisko izaugsmi. Politiskā līmenī ir svarīga bioenerģētikas prioritātes noteikšana (Pavļuts, 2013), tādējādi palielinot atjaunojamo energoresursu (AER) pašnodrošinājumu. Lielāko daļu no elektroenerģijas ražošanai patērētās dabasgāzes iespējams aizstāt ar AER, tostarp koksni. Koksnes izmantošanai enerģētikā ir priekšrocības – tā ir vietējas izcelsmes atjaunojams produkts. Kurināmās koksnes īpatsvars kopējā energoresursu patēriņā Latvijā ir 31%. Šo resursu izmantošanai Latvijā vērojams stabils pieaugums no 46 tūkst. TJ 2008. gadā līdz 59.5 tūkst. TJ 2017. gadā.

Nepietiekoši pētīta ir celmu koksnes ražošanas energoefektivitāte, t.i. enerģijas daudzums, kas jāpatērē, lai šo maz apgūto izejmateriālu varētu izmantot enerģijas ieguvei. Pakalpojuma potenciālajiem sniedzējiem, mežizstrādātājiem, kā arī politikas veidotājiem un nevalstiskajām organizācijām, kas iesaistījušās dažādās biokurināmā ilgtspējas sertificēšanas shēmās, ir nepieciešams apzināt iekārtu specifiskos parametrus un izstrādes tehnoloģiju raksturojumu, lai resursa ieguvi veiktu maksimāli efektīvi un sniegtu visiem interesentiem objektīvu informāciju par dažādiem celmu biokurināmā ieguves aspektiem.

2011. gadā pētījuma ietvaros izstrādāts celmu raušanas-plēšanas kauss MCR 500, ar kura palīdzību vienlaikus var veikt celmu raušanu-plēšanu, kā arī augsnes sagatavošanu ar pacilu veidošanas vai skarificēšanas metodi, tādējādi veicinot mērķtiecīgu meža atjaunošanu stādot vai sējot.

1.2. Promocijas darba mērķis, uzdevumi

Promocijas darba mērķis. Izstrādāt pamatojumu tehnoloģijai, kas ļauj skuju koku izcirtumos sagatavot un nogādāt līdz nokraušanas laukumiem celmu biokurināmo ar minimālu kopējā tehnoloģiskā procesā izmantoto enerģijas daudzumu. Atbilstoši pētījuma mērķim izvirzīti četri pētnieciskie uzdevumi:

1. potenciālo celmu koksnes resursu novērtējums skuju koku izcirtumos;
2. tehnisko prasību pamatojums celmu rāvēja efektīvu darbu nodrošinošas tehnoloģiskā mezgla konstrukcijas izveidei;
3. celmu izstrādes energobilances uzlabošanas iespēju analīze, apvienojot celmu izstrādi un augsnes sagatavošanu pirms meža atjaunošanas;
4. enerģijas patēriņu samazinošas tehnoloģijas izstrāde celmu biokurināmā sagatavošanai un pievešanai līdz nokraušanas laukumiem.

<u>Promocijas darba tēze.</u> Atjaunojamo koksnes energoresursu palielināšanai ir efektīvi izmantot celmu koksni, jo visa tehnoloģiskā procesa energobilance ir pozitīva.

1.3. Darba zinātniskā novitāte un praktiskā nozīme

Promocijas darba ietvaros izstrādāts celmu raušanas-plēšanas tehnoloģiskais risinājums, kurš ietver iekārtas projektēšanu un izgatavošanu, aprobāciju un darba metodes izstrādāšanu celmu plēšanā. Pirmoreiz Latvijā izstrādāta un patentēta celmu raušanas-plēšanas iekārta un veikta tehnoloģiskā procesa energoefektivitātes izvērtēšana.

1.4. Zinātniskā darba aprobācija

Publikācijas zinātniskos žurnālos un konferenču rakstu krājumos:

I Zimelis, A., Ariko, S., Saveļjevs, A. (2018). Исследовние влияния разлицных факторов на поперечную устойчивостъ корцевателя, Труды БГТУ, 174– 181.

II Zimelis, A., Lazdiņš, A. Sarmulis, Z. (2014). Productivity of stump extraction with MCR 500 bucket in Latvia. Arsa-Advanced Research in Scientific Areas Dec. 1. - 5. 2014, 310–313.

III Lazdiņš, A., Lazdāns, V., Kalēja, S., Zimelis, A., Prindulis, U., Kļaviņa, D., Rozītis, G. (2014). Celmu biokurināmā resursu un to pieejamības apskats egļu audzēs valsts mežos. Mežzinātne, 28, 166–179.

IV Zimelis, A., Lazdiņš, A., Sarmulis, Z. (2013). Comparison of productivity of CBI and MCR-500 stump lifting buckets in Latvia. Proceedings of Research for Rural Development 2013. Jelgava, pp. 59–65.

V Lazdiņš, A., Zimelis, A. (2012). System analysis of productivity and cost of stump extraction for biofuel using MCR 500 excavator head. Proceedings of Research for Rural Development 2012. Jelgava, pp. 62–68.

VI Zimelis, A., Lazdāns, V., Lazdiņa, D. (2012). Evaluation of forest regeneration results after stump extraction in joint stock company "Latvian state forests". Proceedings of Research for Rural Development 2012. Jelgava, pp. 69–72.

VII Lazdiņš, A., Zimelis, A. (2012). Productivity of stump lifting head MCR-500. Mežzinātne, 25, 42–44.

Publikācijas koferenču tēžu krājumos:

1. Makovskis, K., Lazdiņš, A., Zimelis, A., Gaitnieks, T. (2015). Productivity and cost of stump extraction in forest stands heavily affected by root rot. Book of abstracts of International Scientific Conference of the Forest Sector "Knowledge Based Forest Sector". Riga, LSFRI Silava, pp. 31–33.
2. Lazdiņa, D., Lazdiņš, A., Zimelis, A. (2012). Comparison of productivity of soil scarification with conventional excavator bucket and mounder MPV-600. Proceedings of OSCAR 2012. Riga, LSFRI Silava, pp. 131–134.

3. Lazdiņš, A., Zimelis, A., Gusarevs, I. (2012). Preliminary data on productivity of stump lifting head MCR-500. Proceedings of Renewable Energy and Energy Efficiency. Jelgava, Latvia University of Agriculture, pp. 150–155.

Pētījumā rezultātā sagatavoti divi patenti.

1. Lazdiņš, A., Lazdāns, V., Gusarevs, I., Zimelis, A., Kurmis, E., Dmitrijenko, V., Lazdiņa, D. (2013). Multifunkcionāla iekārta celmu raušanai-plēšanai ar pacilveida stādvietu veidošanu. LR patents Nr. 14769. Latvijas Republikas Patentu valde.
2. Lazdiņš, A., Lazdiņa, D., Lazdāns, V., Gusarevs, I., Zimelis, A., Kurmis, E., Dimitrijenko, V. (2013). Iekārta pacilveida stādvietu veidošanai meža augsnēs. Latvijas patents Nr. 14692. Latvijas Republikas Patentu valde.

Pētījuma rezultāti prezentēti četrās konferencēs.

1. Zimelis, A. (2018). Technology and energy balance in stump harvesting with MCR 500. 17th International Scientific Conference "Engineering for Rural Development", Latvia University of Life Sciences and Technologies, Jelgava, Latvia, 23–25.05.2018.
2. Zimelis, A. (2015). Productivity and cost of stump extraction in forest stands heavily affected by root rot. International Scientific Conference of the Forest Sector "Knowledge Based Forest Sector", LSFRI Silava, Riga, Latvia, 04– 06.11.2015.
3. Zimelis, A. (2013). Comparison of Productivity of two stump lifting heads CBI and MCR-500 in Latvia. Annual 18th International Scientific Conference "Research for Rural Development 2013", Latvia University of Life Sciences and Technologies, Jelgava, Latvia, May 2013.
4. Zimelis, A. (2012). Evaluation of Forest Regeneration Results After Stump Extraction in 2008 in Zemgales Forestry District of Joint Stock Company "Latvia State Forest". Annual 18th International Scientific Conference "Research for Rural Development 2012", Latvia University of Life Sciences and Technologies, Jelgava, Latvia, 16–18.04.2012.

1.5. Promocijas darba struktūra un apjoms

Promocijas darba struktūra veidota atbilstoši izvirzītajiem uzdevumiem. Darbs sastāv no trijām nodaļām. Pirmajā nodaļā sagatavots koksnes biomasas izmantošanas iespēju un celmu ieguves paņēmienu izzinātības apskats. Otrajā nodaļā aprakstīta celmu koksnes resursu novērtēšanas un izstrādes metodika, kur pētījuma rezultātā izstrādātas darba metodes un paņēmieni celmu raušanai-plēšanai, kombinējot ar augsnes gatavošanu. Trešajā nodaļā analizēti pētījuma rezultāti atbilstoši promocijas darbā izvirzītajam mērķim un pētnieciskajiem uzdevumiem.

Promocijas darba apjoms 76 lpp., pētījumā informācija apkopota 19 tabulās un 29 attēlos, promocijas darba izstrādē izmantoti 94 literatūras avoti. Darba noslēgumā formulēti 7 secinājumi.

2. MATERIĀLS UN METODES

2.1. Empīriskā materiāla raksturojums

Pirmā uzdevuma risināšanai potenciālā un tehnoloģiski pieejamā celmu koksnes apjoma notikšana balstīta uz Meža statistiskās inventarizācijas (MSI) datiem, pēc kuriem aprēķināta celmu biomasa, pielietojot J. Liepiņa izstrādātos vienādojumus.

Otrā uzdevuma izpilde saistīta ar celmu raušanas-plēšanas konstrukcijas, darba metožu un tehnisko prasību izveidi un aprobāciju. Celmu raušanas-plēšanas iekārtas specifikācijas projektēšanas uzdevumā balstītas uz teorētiskās mehānikas aprēķiniem, bet aprobācija – uz mērījumiem lauka izmēģinājumos.

Pirms celmu raušanas būtiski visus celmus marķēt, savukārt pašu raušanas-plēšanas procesu nodrošināt atbilstoši plānotajām darba metodēm. Iekārtas, resp., tehnoloģiskā mezgla uzlabojumi atspoguļojas kā ražīguma izmaiņas sadalījumā pa darba elementiem, kur rādītāju salīdzināšanai pielieto aprakstošo un secinošo statistiku.

Trešā uzdevuma (celmu izstrādes energobilances uzlabošanas iespēju analīze, apvienojot celmu izstrādi un augsnes sagatavošanu pirms meža atjaunošanas) izpildei nepieciešamas atbilstošas cirsmas, kurās var salīdzināt dažādus augsnes gatavošanas paņēmienus. Vērtēšanas kritēriji ir sagatavotais stādvietu skaits un kvalitāte, ražīgums un patērētā degviela. Datu kopu salīdzināšanai pielieto aprakstošo statistiku.

Ceturtā uzdevuma izpilde balstīta uz kopējo celmu izstrādes un transportēšanas tehnoloģiju, kurā kā rezultējošie rādītāji ir ražīgums (sadalījumā pa darba elementiem) un fosilo energoresursu patēriņš ražošanas procesā. Datu analīzei pielietota aprakstošā un secinošā statistika.

Izmēģinājumiem izraudzītas platības, kurās atjaunošanas cirte veikta 3 gadus pirms plānotās celmu izstrādes, bet kā papildus kritēriji objektu atlasei ir sugu sastāvs un meža tips – valdošā suga egle (vismaz 70%), damakšņa, vēra vai šaurlapju āreņa meža tipam atbilstošas audzes. Tālākais datu ievākšanas process saistīts ar lauku darbiem, kuros darba laika uzskaite un citi būtiski rādītāji uzskaitīti atsevišķi sadalījumā pa darba operācijām.

2.2. Celmu koksnes resursu novērtējuma metodika

Aprēķini veikti, izmantojot MSI, atbilstoši iepriekš izstrādātajai metodei celmu biokurināmā novērtēšanai audzes līmenī (Lazdiņš et al., 2014) parastajai priedei (*Pinus sylvestris* L.), parastajai eglei (*Picea abies* (L.) H. Karst), bērzam (*Betula pendula* Roth) un apsei (*Populus tremula* L.). Celmu biomasas aprēķināšanai sākotnēji identificētas mežaudzes pēc vecuma – valdošās sugas koku vecums ir vienāds vai lielāks par Meža likuma 9. pantā definētajām robežvērtībām galvenās izmantošanas cirtei (Ministru Kabinets, 2010). Papildus atlases kritēriji saistīti ar meža zemju ilgtspējīgu izmantošanu – nenoplicināšanu, proti, celmu ieguve iespējama auglīgās augsnēs, kas atbilst mētrāja (*Vacciniosa*), lāna (*Myrtillosa*), damakšņa (*Hylocomiosa*), vēra (*Oxalidosa*), gāršas (*Aegopodiosa*), slapjā damakšņa (*Myrtilloso-sphagnosa*), slapjā vēra (*Myrtilloso-polytrichosa*), slapjās gāršas (*Dryopteriosa*), mētru āreņa (*Vacciniosa mel.*), šaurlapju āreņa (*Myrtillosa mel.*), platlapju āreņa (*Mercurialiosa mel.*), mētru kūdreņa (*Vacciniosa turf. mel.*), šaurlapju kūdreņa (*Myrtillosa turf. mel.*) un platlapju kūdreņa (*Oxalidosa turf. mel.*) tipiem (Lazdiņš et al., 2014). Papildus no datu atlases izslēgtas platības ar galvenās cirtes ierobežojumiem – aizliegta mežsaimnieciskā darbība: galvenā cirte, kopšanas cirte un kailcirte. Celmu resursu novērtēšanai, balstoties uz MSI datiem. Biomasas aprēķini veikti, izmantojot J. Liepiņa izstrādātos vienādojumus, ekstrapolējot atsevišķu koku pazemes biomasu uz parauglaukuma līmeni.

$$y = a \cdot x^b \quad , \qquad (2.1)$$

kur:
y – iegūstamā sakņu biomasa, $t_{sausnas}$;
a, *b* – koeficienti;
x – koksnes krāja, $m^3\ ha^{-1}$.

Celmu biomasas aprēķini ražīguma rādītāju analīzē balstīti uz Marklunda un Repola izstrādātajiem algoritmiem, kas ir saistīts ar nepieciešamību nodrošināt datu salīdzināmību ar Ziemeļvalstīs un iepriekš Latvijā veiktiem pētījumiem. Saskaņā ar celmu biomasas aprēķiniem, izmantojot līdz šim aprobētus vienādojumus, ir iespējams salīdzināt iegūtos rādītājus ar līdzīgos pētījumos iegūtiem datiem, kas pieejami zinātniskās publikācijās.

2.3. Celmu raušanas darba paņēmieni un tehnisko prasību sagatavošana

Celmu izstrādes pētījumā izmantotas 3 darba metodes. Pirmā metode paredzēta darbam ar CBI celmu raušanas iekārtu. Otrā un trešā darba metode paredzētas MCR 500 iekārtai, kas izstrādāta, ņemot vērā mežsaimnieciskās vajadzības saistībā ar augsnes gatavošanu. Otrās un trešās metožu atšķirība ir saistīta ar iekārtu tehniskiem un tehnoloģiskiem uzlabojumiem, lai nodrošinātu augstāku ražīgumu un kvalitatīvāku augsnes sagatavošanu.

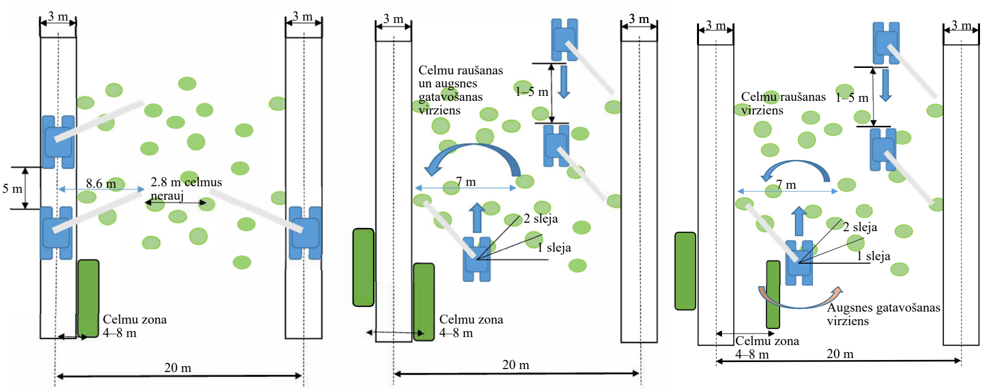
Veicot celmu raušanu ar CBI iekārtu, ekskavators pārvietojas pa tehnoloģiskajām brauktuvēm, veicot celmu raušanu un to nokraušanu, veidojot celmu kaudzes paralēli brauktuvei. Celmu raušanu veic no labās puses, perpendikulāri pārvietošanās virzienam (2.1. att., pa kreisi). Celmu raušanu sāk ar tuvāk esošajiem celmiem un turpina ar tālāk esošajiem celmiem. Celmu raušana joslā tiek pārtraukta, ja tehnika pēdējo celmu izrāvusi ar maksimālo izlici. Tālāk pārvieto manipulatoru pa kreisi uz nākamo joslu, raušanu uzsākot ar celmiem, kuri ir tuvāk mašīnai.

Veicot celmu raušanu ar MCR 500 iekārtu, ekskavators pārvietojas starp tehnoloģiskajām brauktuvēm (2.1. att., vidū). Celmu raušanu veic no labās uz kreiso pusi. Celmu raušanu uzsāk perpendikulāri tehnikas pārvietošanās virzienam, veidojot 1. joslu. Pirmos celmus rauj tālāk no tehnikas ar maksimālo izlici un nokrauj paralēli brauktuvei, pēc tam celmus rauj virzienā uz tehnikas pusi un nokrauj paralēli brauktuvei. Vienlaikus ar celmu raušanu veic augsnes sagatavošanu, veidojot pacilas. Lielākas dimensijas celmiem, kuru caurmērs pārsniedz 25 cm, veic to pārplēšanu vairākās daļās. Savukārt, lai samazinātu minerālaugsnes īpatsvaru, pēc celmu izraušanas tos vairākas reizes ar manipulatoru paceļ un nomet zemē, to darot līdz brīdim, kad minerālaugsne vairs neatdalās no celma, bet ne vairāk kā 3 reizes. Pēc celmu izraušanas tehnika pārvietojas 5 m uz priekšu.

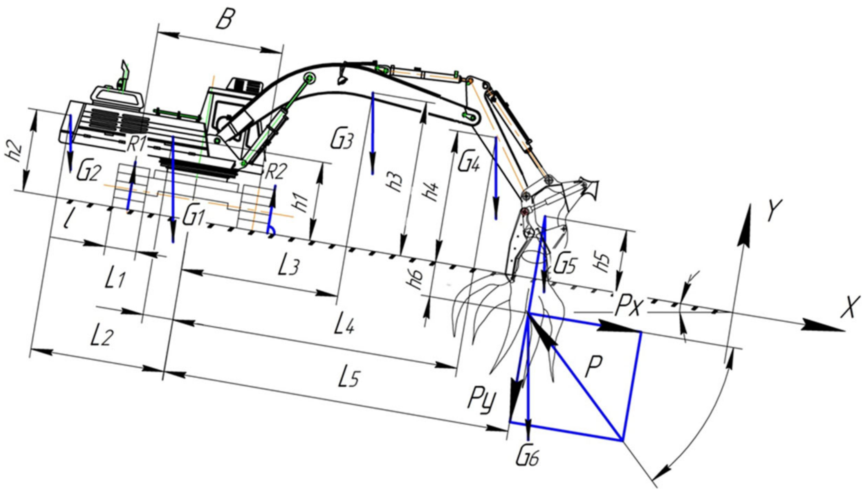
Veicot celmu raušana ar uzlabotu MCR 500 iekārtu, ekskavators pārvietojas starp tehnoloģiskajām brauktuvēm (2.1. att., pa labi). Celmu raušanu veic no labās uz kreiso pusi perpendikulāri pārvietošanās virzienam. Celmus rauj no tālākās joslas punkta virzienā uz tehnikas pusi. Celmus nokrauj paralēli pārvietošanās virzienam, veidojot nelielas kaudzes 4–8 m attālumā no tehnoloģiskās brauktuves ass. Kad celmi tehnikas pārvietošanās virzienā ir izrauti, tehnika pārvietojas 1–5 m uz priekšu un sagatavo augsni aiz sevis. Ja izrautā celma caurmērs ir > 25 cm, veic tā sadalīšanu vairākās daļās, izmantojot plēšanas nazi, vienlaicīgi veicot celma nomešanu vai purināšanu, lai samazinātu minerālaugsnes daudzumu.

MCR 500 projektēšanas uzdevums:

- iekārtai jābūt jaunam multifunkcionālām produktam, kuram ir būtiski uzlabotas un papildinātas tehniskās īpašības (masa, gabarītizmēri, konstrukcija u.c.) un ar to vienlaicīgi ir iespējama kā celmu izstrāde, tā augsnes sagatavošana, no celmiem atbrīvotajā platībā veidojot pacilas;
- kopējā masa ≥ 1600 kg, kas panākta, balstoties uz teorētiskās mehānikas aprēķiniem, kā arī modelējot iekārtas konstrukcijas elementus atbilstoši plānotajām slodzēm;
- iekārtai jābūt oriģinālai konstrukcijai pacilu ar plakanu virsmu veidošanai;
- jānodrošina izveidoto pacilu sablīvēšana ar darba galvas pamata plāksnes daļu (LV 14769 B, 2014).



2.1. att. **Darba metodes celmu raušanā**
(pa kreisi CBI, vidū MCR 500 un pa labi uzlabota metodika MCR 500).



2.2. att. **Celmu raušanas spēka aprēķināšana**

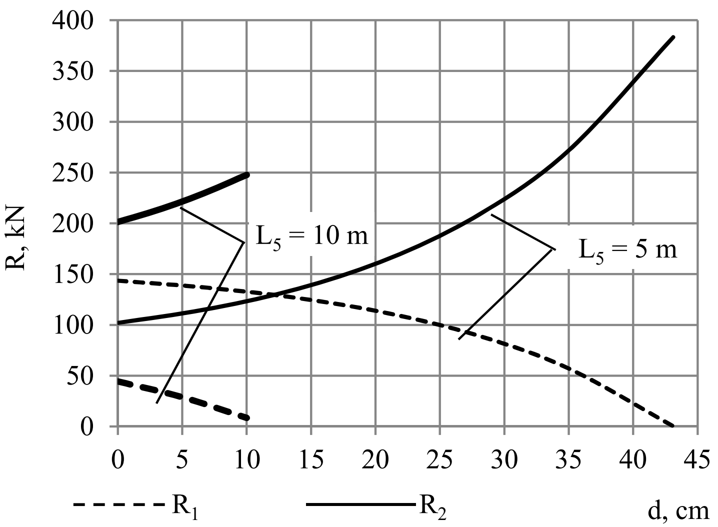
G_1–G_6 – bāzes šasijas, atsvara, hidromanipulatora sastāvdaļu, tehnoloģiskās iekārtas un celma pašmasai atbilstošs smaguma spēks N; L_1–L_6 – attālums no bāzes šasijas, atsvars, hidromanipulatora sastāvdaļas, tehnoloģiskā iekārta, celma pašmasas smaguma centrs līdz ekskavatora ass līnijai, m; h_1–h_5 – augstums, kādā atrodas sastāvdaļu smaguma centri, m; h_6 – celma augstums horizontālā plaknē, m; B – ekskavatora bāze, m; l – kāpurķēdes platums, m; Px, Py – celma raušanas komponentes, N; P – celma raušanas pamatspēks, N; α – zemes virsmas slīpums, grādi; φ – leņķis starp celmu raušanas virsmu un atbalsta virsmu, grādi; A – apgāšanās punkts, R_1, R_2 – augsnes reakcijas spēks zem kāpurķēdēm, N.

Celmu raušanas iekārtas aprēķiniem izveidota pamatshēma (2.2. att.). Izmantojot izstrādāto shēmu, var vērtēt ekskavatora tipa celmu rāvēja stabilitāti, veicot celmu raušanu, un noteikt darbības efektivitāti, izmantojot dažādus darba paņēmienus, atkarībā no atbalsta virsmas slīpuma, celma caurmēra, celma novietojuma un augstuma, ņemot vērā arī bāzes šasijas tehniskos parametrus.

Pētījumā vērtēti dažādu rādītāju ietekme uz ražīgumu un slodzēm, piemēram, celma caurmērs, celma smaguma spēka atkarība no augsnes līmeņa, celma smaguma spēka darbības virziens, hidromanipulatora izlices attālums, kāpurķēdes platums. Konstatēts, ka hidromanipulatora izlices lielāks rādītājs ievērojami samazina celmu rāvēja ekspluatācijas iespējas. Piemēram, pie hidromanipulatora minimālas izlices (L_{min} = 4 m), ar vertikālo celmu raušanas spēku nesamazinot šķērsstabilitāti, var raut celmus ar caurmēru 43 cm, bet, palielinot hidromanipulatora izlici 2.5 reizes, maksimāli izraujamā celma caurmērs samazinās līdz 11.7 cm (2.3. att.).

Papildus augšminētiem rādītājiem apskatīts šāds celmu raušanas paņēmiens:

- tehnoloģiskās iekārtas vertikālā kustība (φ = 90°);
- hidromanipulators ir pozīcijā, kurā φ = 0° vai φ = 180°;
- tehnoloģiskās iekārtas kombinētā kustība (0° < φ < 90°), ja kustība notiek no ekskavatora virzienā uz darba iekārtas pusi (prom no ekskavatora, 90° < φ < 180°).



2.3. att. **Celma caurmēra (d) un hidromanipulatora (L_5) izlices ietekme uz atbalsta kāpurķēžu reakciju**

Konstatēts, ka celmu raušanā ar vertikālo kustību ir vismazākā reakcija, bet tāds darba paņēmiens nav efektīvs ražošanas apstākļos. Šādā veidā raujot celmus un kustinot tehnoloģisko aprīkojumu horizontālajā virsmā 30° leņķī pret bāzes mašīnas atbalsta virsmu, tiek panākts, ka reakcija R zem kāpurķēdes palielinās 2.16–6.25 reizes, celma caurmēram palielinoties no 5 līdz 10 cm. Tajā pašā aprēķinā konstatēts, ka pie noteiktās manipulatora izlices maksimālā celma caurmērs ir līdz 25 cm.

Pētījumā konstatēts, ka visdrošākā šķērsstabilitāte panākta uz horizontālas virsmas, un celmu raušanas iekārtai uz ekskavatora bāzes ir iespējams raut celmus ar caurmēru līdz 50 cm un vairāk. Limitējošais rādītājs ir visas mašīnas saķeres spēja ar grunti.

2.4. Energoefektivitātes uzlabošanas tehnoloģijas izstrādes metodika

Darba laika uzskaite sadalījumā pa elementiem visā izstrādes procesā balstās uz katra darba elementa pabeigšanas laika fiksēšanu katram darba ciklam. Uzsākot darba laika uzskaiti, hronometrētājs nospiež pogu “Sākt” (palaiž laika uzskaiti) un darba procesā fiksē katra izdalītā darba elementa pabeigšanu.

Kopējā drupinātās koksnes izstrādes tehnoloģiskajā procesā energopatēriņa uzskaite un analīze veikta sadalījumā pa darba operācijām, no kurām tālākā procesā izvēlēta visefektīvākā, to pamatojot ar pētījumā veiktajiem aprēķiniem. Katra no daļām analizēta atsevišķi, to sadalot pa darba operācijām un tehnikas vienībām; modelējot enerģijas izlietojumu celmu raušanā un pievešanā līdz augšgala krautuvei (AGK), kopumā izdalot 6 variantus, noskaidrots variants, kurā enerģijas izlietojums ir vismazākais.

Lai aprēķinātu kopējo energoresursu ietilpību un kopējo iespējamo enerģijas atdevi, pētījumā izmantots vienādojums, kur kopējā energobilance norāda uz atgūstamo enerģiju, salīdzinot ar ražošanas procesā patērējamo enerģiju (Wasiak, 2018).

Lietderības koeficientu aprēķina, salīdzinot enerģiju, kuru iespējams iegūt, sadedzinot kurināmo, to attiecinot pret kopējo patērējamās enerģijas daudzumu. Ja mazākā vērtība ir vienāda ar 0, tad lietderības koeficients arī ir 0.

3. REZULTĀTI UN DISKUSIJA

3.1. Celmu resursu pieejamība Latvijā

Kopējie teorētiski pieejamie celmu koksnes energoresursi atbilst 142 TWh primārās enerģijas, no kuriem daļa, atbilstoši saimnieciskās darbības ierobežojumu pazīmēm, ir saimnieciski nepieejamos mežos. Lielāko daļu teorētiski pieejamo celmu biomasas resursu veido priede (45%), egle (36%), bērzs (15%) un apse (4%). Summējot meža tipus, kuros celmu koksnes ieguve nav rekomendējama, kā arī mežus, kuros ir sezonāli izstrādes ierobežojumi, 35% platību celmu raušanu nevar veikt.

Potenciāli pieejamais celmu koksnes apjoms atbilst 103 TWh primārās enerģijas, kur lielākā iegūstamā biomasa (55%) ir sausieņu meža tipos. Lielākā daļa potenciāli pieejamo resursu ir valsts mežos – 68%. Privātpersonu un uzņēmumu īpašumā ir 32% platību. Tehniski pieejamais ikgadējais celmu koksnes apjoms līdzinās 349 GWh primārās enerģijas. Atbilstoši CSP datiem apkopojumā "Katlumājās patērētais kurināmais un saražotā siltumenerģija, TJ", 2018. gadā bija nepieciešami 7690 TJ kurināmās šķeldas katlumāju darbības nodrošināšanai. Izmantojot celmu koksni enerģijas ieguvei, tā nodrošinātu 16.3% no kopējā koksnes energoresursu pieprasījuma.

3.2. Ražīguma analīze celmu koksnes sagatavošanas tehnoloģiskajā procesā

Platībās, kurās plānots veikt celmu raušanu-plēšanu, kopumā uzmērīti 3022 celmi. Vidējais celma caurmērs platībās, kur celmu izstrāde veikta ar CBI, ir 33.5 ± 0.4 cm, vidējais augstums 26.5 ± 0.4 cm. Savukārt platībās, kur darbojās MCR 500, vidējais celma caurmērs bija 33.6 ± 0.2 cm, bet vidējais augstums – 33.1 ± 0.4 cm. Marķēto celmu raksturojums sagatavots, balstoties uz mērījuma datiem, kuri ievākti pirms celmu izstrādes. No visiem uzmērītajiem celmiem skuju koki ir 75% no kopējā biomasas (egle 59% un priede 16%).

Kopā pētījuma laikā izrauti 2720 celmi. Vidējā izrautā celma caurmērs, strādājot ar CBI raušanas iekārtu, ir 33 ± 11 cm, ar MCR 500 – 33 ± 9 un ar MCR 500 II – 38 ± 10 cm. Vidējais laika patēriņš vienas $t_{sausnas}$ sagatavošanai ir 0.3 h efektīvā darba laika. Celmu raušanas procesā lielākais laika patēriņš ir celmu izraušanai no augsnes. Tam jāpatērē 33% no kopējā laika. Mazāk laika aizņem griešanās ar ekskavatoru (12%), ekskavatora pārvietošanās (11%), celma saplēšana (11%), minerālaugsnes nopurināšana (11%) un celma satveršana (10%).

Atbilstoši produktīvā darba laika patēriņam izmēģinājumos, aprēķinātie rādītāji būtiski atšķiras ($p = 0.01$) atkarībā no izstrādes metodes. Tas skaidrojams ar efektivitātes uzlabošanu darba procesā, tādējādi samazinot nepieciešamo laika patēriņu tāda daudzuma celmu izraušanai, no kura var iegūt vienu $t_{sausnas}$. Strādājot ar CBI, 1 $t_{sausnas}$ sagatavošana aizņem 0.19 h, savukārt, strādājot ar MCR 500 – 0.34 h. Iegūtajiem datiem piešķirt vispārinošu nozīmi nebūtu korekti, jo MCR 500 I pirmajā izmēģinājumu posmā (2. darba metode) ekskavatora hidrosūknis nenodrošināja nepieciešamo eļļas plūsmu un pretnazis faktiski nebija izmantojams celmu plēšanai. Pēc tehniskiem uzlabojumiem un 2. metodes pilnveidošanas ražīguma rādītāji palielinājās līdz 0.19 $t_{sausnas}$ h^{-1}, kas atbilst ar CBI iegūtajiem rādītājiem. Jāņem vērā arī tas, ka šī pētījuma laikā tehnikai tika veikti remonti, lai nodrošinātu nominālo eļļas plūsmu. Tālākos aprēķinos darba ražīgums netiek modelēts pie dažādiem tehniskās gatavības līmeņiem.

Izmēģinājumu laikā sasniegtais vidējais ražīgums, strādājot ar CBI iekārtu, ir 13.6 m^3 h^{-1}, savukārt ar MCR 500 – 7.8 m^3 h^{-1}. Salīdzinot darba laika patēriņu sadalījumā pa darba elementiem, sliktāki rādītāji (darba laika patēriņa pieaugums ar negatīvu zīmi), salīdzinot abas iekārtas, ir celmu izcelšanai –69%, saplēšanai –533%, celma purināšanai –67%, celmu nomešanai –137%. Lai uzlabotu ražīguma rādītājus, celmu raušanas-plēšanas tehnoloģiskajā risinājumā veikta virkne uzlabojumu:

1. pazemināts cilindra stiprinājums; kā rezultātā, samazinot pleca garumu, saskaņā ar teorētiskās mehāniskas aprēķiniem uzlabojas pretnaža efektivitāte un ātrdarbība, kas būtiski ietekmē ražīguma rādītājus;
2. palielināta konstrukcijas izturība pret sānspiedi, kā rezultātā uzlabojas iekārtas tehniskā gatavība, tādējādi samazinot dīkstāves remontu laikā, mainot pretnaža pirksta bukses;
3. palielināts hidropievadu šķērsgriezums, kā rezultātā iekārtu var pieslēgt lieljaudas hidropievadam, samazinot eļļas plūsmas pretestību sistēmā, kā rezultātā cilindrs var darboties ātrāk;
4. virkne uzlabojumu saistīta ar augsnes gatavošanas moduli, palielinot tā virsmas laukumu un sānu malu liekumu, kā rezultātā uzlabojas produktivitāte un darba izpildes kvalitāte.

Pēc iekārtas tehniskiem un tehnoloģiskiem uzlabojumiem izmēģinājumos konstatēts, ka, MCR 500 I, salīdzinot ar MCR 500 II būtiski samazinājies darba laika patēriņš, pārrēķinot uz saražotās produkcijas vienību. Vidējais ražīgums, strādājot ar MCR 500 II iekārtu bez augsnes gatavošanas, ir 13.1 m^3 h^{-1}, bet papildus gatavojot augsni – 11.1 m^3 h^{-1}.

Strādājot ar CBI un MCR 500 II, sasniegtie ražīguma rādītāji ir līdzīgi ($p = 0.16$). Salīdzinot celmu raušanas ražīguma rādītājus ar līdzīgiem pētījumiem Ziemeļvalstīs, kuros salīdzinātas dažādus celmu raušanas kausus, konstatēts, ka Latvijā iegūti būtiski labāki ražīguma rādītāji. Ziemeļvalstīs dažādos pētījumos ražība bija vidēji 7–10 m^3 h^{-1} (Laitila et al., 2008; Athanassiadis et al., 2011; Moffat et al., 2011; Palander et al., 2015; Kärhä & Mutikainen, n.d.). Jāņem vērā, ka salīdzinātie rādītāji ir indikatīvi, jo pastāv būtiskas atšķirības, ko nosaka augsnes tips un raujamo celmu dimensijas. Latvijā veiktajos izmēģinājumos celmi ir būtiski lielāki un izstrāde veikta galvenokārt minerālaugsnēs, bet salīdzinājumā ietvertajos Ziemeļvalstu pētījumos informācija ir par kūdras augsnēm.

Darba laika uzskaite, lai aprēķinātu ražīguma rādītājus pievešanā, veikta 7 cirsmās, kopumā uz augšgala krautuvi pievedot 107 kravas. Pievešanas attālums ir no 140 m līdz 850 m.

Pētījumā konstatēts, ka forvardera produktīvais laiks celmu pievešanas operācijās ir no 88% līdz 100%, salīdzinot ar pievešanas darbiem Latvijā, kur šis rādītājs ir zemāks. Izmantojot ekvivalentas tehnikas vienības, produktīvās stundas darba laika īpatsvars ir no 77% līdz 94% (Rozītis et al., 2017). Pētījuma ietvaros neproduktīvo laiku veido tehnikas remonti, apkopes un meža mašīnu operatoru atpūta darba laikā. Teorētiski produktīvajam darba laikam nevajadzētu būt lielākam par 67%, ja maiņas ilgums ir 8 un vairāk stundas. Tas skaidrojams ar operatoru atpūtu darba laikā, pieņemot, ka operatori 45 min. strādā un 15 min. atpūšas. Šāda atpūta tiek pieņemta un iekļauta tālākos aprēķinos, rēķinot ražīguma rādītājus. Publikācijās tas minēts kā rādītājs G15 (Talbot et al., 2003) vai E15 (Sirén and Aaltio, 2003), kas raksturo atpūtas ilgumu vienā stundā.

Sasniegtie ražīguma rādītāji izmēģinājumu cirsmās celmu pievešanā ir no 3 līdz 12 m^3 h^{-1} produktīvajā darba laikā. Salīdzinoši nelieli ražīguma rādītāji saistīti ar forvardera kravas tilpnes neefektīvu izmantošanu, pieredzes trūkumu un ekskavatora operatora izvairīšanos no celmu plēšanas izstrādes laikā.

Celmu koksnes biomasas transportēšanas laikā uz starpkrautuvi ir jārēķinās ar daļēji piepildītām kravām, jo celmu koksni teju neiespējami sakraut konteinera tipa puspiekabē. Izmēģinājumu objektos tilpīguma koeficients celmu koksnes izvešanā ir 0.4, pētījumā sasniegtie ražīguma rādītāji – 3.5 $t_{sausnas}$ h^{-1}. Celmu koksnes transportēšanas attālums līdz starpkrautuvei pētījumā ir 7 km. Līdz šim publicētajā informācijā par efektīvu transportēšanas attālumu minēts, ka līdz 10 km lielam attālumam ir vismazākās izmaksas uz vienu km. Pētījumā secināts, ka celmu pārvešana uz starpkrautuvi būtiski palielina biokurināmā ražošanas izmaksas, padarot šo biokurināmā veidu nekonkurētspējīgu, ja ir pieejamas mežizstrādes atliekas galvenajā cirtē vai sīkkoksne no kopšanas cirtēm, tāpēc no šī ražošanas posma ir jāizvairās, veicot drupināšanu jau AGK.

Celmu smalcināšana izmēģinājumos veikta ar vairākām iekārtām. Magnum Force 6800P drupinātāja ražīgums izmēģinājumos bija 110 tonnas h^{-1}. Strādājot ar drupinātāju Doppstadt 441SM, ražīgums bija 26 t h^{-1}. Pētījumā sasniegtie rādītāji ir mazāki, salīdzinājumā ar literatūrā minētajiem (Irdla et al., 2017), un tas skaidrojams lielā mērā ar smalcināšanai nepiemērotu celmu izstrādes metodi – parasti celmi nebija pārplēsti un to ievadīšana drupinātājā prasīja papildus darba laika patēriņu. Lai sasniegtu labākus ražīgums rādītājus, vidēja izmēra un lielākos celmus nepieciešams sadalīt vismaz 4 daļās (Anerud, 2012).

3.3. Augsnes sagatavošanas izvērtējums

Pētījumā izmantotais augsnes sagatavošanas kvalitātes kritērijs, izmantojot pacilu metodi, ir sagatavoto stādvietu skaits (Zimelis et al., 2012). Izmēģinājumu platībās, kurās augsni sagatavoja disku frēze (kontrole), izveidotas 1352 ± 50 pietiekoši lielas stādvietas uz vienu hektāru, bet, izmantojot celmu raušanas iekārtu – 1250 ± 72 stādvietas uz vienu hektāru.

Augsnes gatavošanai ar disku frēzi patērētas 89 ± 18 min. ha^{-1}, bet, izmantojot celmu raušanas-plēšanas iekārtu, 229 ± 21 min. ha^{-1}. Salīdzinot ražīguma izmaiņas, raujot celmus ar MCR 500 II un papildus gatavojot augsni, konstatēts ražīguma samazinājums par 15%, sasniedzot 11.1 $m^3 h^{-1}$. Degvielas patēriņš, strādājot ar disku frēzi, ir 18 L ha^{-1} (neskaitot tehnikas pārvadāšanas starp objektiem, papildus vēl 38 L 100 km^{-1} katrā virzienā), bet, izmantojot ekskavatoru, degvielas patēriņš augsnes sagatavošanai ir 49 L ha^{-1}.

3.4. Celmu izstrādes energoresursu patēriņa bilance

Energoresursu patēriņa aprēķināšanai dažādiem meža darbiem noteikts kopējais energopatēriņš un identificēts efektīvākais celmu raušanas un pievešanas variants.

Strādājot ar Komatsu PC210LC, kurš aprīkots ar CBI raušanas iekārtu, atbilstoši koksnes drupināšanas tehnoloģijai un resursu ieguvei no meža, pievadāmais energoresursu apjoms strauji sāk samazinās, ja izraujamo celma caurmērs sasniedz 20 cm. Salīdzinot ar MCR 500 II, energoresursu patēriņa straujš samazinājums novērojams tajās pašās celmu caurmēra grupās. Salīdzinot degvielas patēriņu pie vienāda vidējā izstrādājamā celma caurmēra (42 cm), strādājot ar CBI celmu raušanas iekārtu, tas ir 0.91 L m^{-3}, savukārt, strādājot ar MCR 500 II, degvielas patēriņš ir 1.05 L m^{-3}. Jāatzīmē, ka tehniskā mašīnu gatavība nav vienāda abām salīdzinātajām iekārtām, tāpēc MCR 500 II prototipam degvielas patēriņš var samazināties, pilnveidojot darba metodi.

Forvardera ražīguma ietekme uz kopējo enerogoefektivitāti celmu biokurināmā ražošanā pētījumā nebija būtiska, ja ražīgumu pārsniedza 5 $m^3 h^{-1}$. Pētījumā konstatētais degvielas patēriņš, strādājot ar John Deere 810D, ir 14.3 L h^{-1}. Logset forvardera degvielas patēriņš aprēķināts pēc Lofflera formulas, un, ņemot vērā tā dzinēja jaudu (170 hp), aprēķinātais patēriņš ir 18.5 L h^{-1}. Veicot celmu pievešanu ar Ponsse Bufallo, uzskaitītais degvielas patēriņš ir 16.8 L h^{-1}; līdzīgos pētījumos Latvijā, testējot dažādas atbalstķēdes, konstatētais degvielas patēriņš kokmateriālu pievešanā var sasniegt 17.7 L h^{-1} (Lazdiņš, 2017).

Salīdzinot degvielas patēriņu pie vienāda ražīguma (7 $m^3 h^{-1}$) un pievedot ar John Deere 810D, aprēķinātais patēriņa patēriņš ir 2.05 L m^{-3}, strādājot ar Ponsse Gazelle – 2.40 L m^{-3} un ar Logset 4F – 2.65 L m^{-3}. Degvielas patēriņš samazinās zem 1 L m^{-3}, sasniedzot ražīgumu 15 $m^3 h^{-1}$. Svarīgākie tehnikas parametri ir dzinēja jauda un kravnesība.

Celmu koksni pārvedot no AGK uz starpkrautuvi, kas atrodas 7 km attālumā, Scania R480 patērēja 1.29 L m^{-3}, bet Scania R500 – 1.52 L m^{-3}. Aprēķinātās atšķirības saistītas ar to, ka Scania R500 degvielas patēriņš ir vidēji par 19% lielāks nekā otrai mašīnai.

Celmu drupināšanai, izmantojot CBI Magnum Force 6800P un atbilstoši vidējiem ražīguma rādītājiem, pētījumā bija patērēti 0.69 L m^{-3}, bet, izmantojot drupinātāju Shredder DW2060, degvielas patēriņš bija mazāks – 0.56 L m^{-3}. Jāņem vērā, ka 2. gadījumā izmantots arī sijātājs Doppstadt 441SM, kura degvielas patēriņš ir 1.31 L m^{-3}. Līdz ar to kopējais degvielas patēriņš šim mašīnu komplektam ir 1.87 L m^{-3}.

Salīdzinot enerģijas patēriņu autovilcieniem Scania 380 un Scania 420, konstatēts, ka abām mašīnām ir līdzīgs degvielas patēriņš – vidēji 1.87 L m^{-3}; savukārt Scania R500 un Volvo FM tas ir nedaudz mazāks, attiecīgi, 1.52 L m^{-3}, bet – 1.40 L m^{-3}, aprēķinātā patēriņa atšķirības saistītas ar dzinēja jaudu.

Saskaņā ar pētījuma rezultātiem efektīvākais celmu koksnes izstrādes tehnoloģiskais risinājums ir plānot izstrādi ar MCR 500 II un pievešanu veikt ar John Deere 810D vai ekvivalentu vidējās klases forvarderu. Ja nepieciešama celmu pārvešana uz starpkrautuvi, jāizvēlas transports ar mazāko degvielas patēriņu. Neatkarīgi no tā, vai celmus plānots drupināt AGK vai starpkrautuvē, būtiski veidot šauras un augstas celmu krautnes, lai visus celmus varētu aizsniegt ar drupinātāja vai autovilciena manipulatoru. Būtiskākie celmu transportēšanas mašīnu atlases kritēriji ir no metāla izgatavota kravas tilpne (tas saistīts ar ilgmūžību, jo, metot kravas tilpnē līdz 2 tonnas smagus celmus, var tikt bojāts konteiners). Transportam jābūt aprīkotam ar manipulatoru celmu iekraušanai vai arī iekraušanu jāveic ar forvarderu.

Kopējais degvielas patēriņš drupinātās koksnes izstrādei un piegādei (neierēķinot augsnes sagatavošanu) ir 6.82 L m^{-3}. Aprēķinātais kopējās lietderības koeficients ir 3.9. Tas nozīmē, ka, sadedzinot celmu šķeldas, iegūstāmais enerģijas daudzums, ir 3.9 reizes lielāks, nekā energoresursu patēriņš ražošanas un piegādes procesā. Pētījumā identificēti arī vairāki risinājumi energoresursu patēriņa samazināšanai ražošanas procesā, piemēram, veicot drupināšanu AGK un iepildot šķeldas tieši autovilcienā, kā arī celmu raušanas-plēšanas kvalitātes uzlabošana, lai palielinātu pievešanas un drupināšanas procesu efektivitāti.

SECINĀJUMI UN PRIEKŠLIKUMI

1. Potenciāli pieejamo celmu koksnes resursu novērtēšanai precīzākā aprēķinu metode ir balstīta uz meža ekosistēmu iedalījumu, atkarībā no šī resursa ieguves iespējamības. Saskaņā ar MSI datiem potenciāli pieejamais celmu koksnes apjoms, kas Latvijas teritorijā atbilst 103 TWh primārās enerģijas. Balstoties uz aprēķiniem un ievērojot pētījumā izvirzītos pieņēmumus, ik gadu pieejamas 349 GWh primārās enerģijas, kas var aizstāt 16% no kopējās valstī patērētās kurināmās koksnes. Precīzākiem aprēķiniem nepieciešams noskaidrot celmu koksnes vidējo reducēto blīvumu sadalījumā pa koku sugām.

2. Izmantojot multifunkcionālas iekārtas prototipu MCR 500, darba procesā konstatētas nepilnības, kas ietekmē kopējo tehnikas noslodzi. Atsevišķas tehnoloģiskas darbības tiešā veidā negatīvi ietekmē celmu izcelšanas, saplēšanas un purināšanas ražīgumu. Pēc izmēģinājumiem ar MCR 500 pirmo prototipu veikta virkne uzlabojumu – cilindra stiprinājuma pazemināšana, konstrukcijas izturības palielināšana, hidropievadu šķērsgriezuma palielināšanas un augsnes gatavošanas agregāta virsmas palielināšana. Pēc uzlabojumiem MCR 500 otra prototipa ražīguma pieauguma par 59%, sasniedzot CBI ražīgumu, papildus nodrošinot iespēju kvalitatīvi veikt augsnes sagatavošanu.

3. Celmu raušanas-plēšanas procesā negatavojot augsni, konstatēts: strādājot ar prototipu MCR 500 II, lietderības koeficients ir 19.9 (pie ražīguma 13.1 $m^3\ h^{-1}$); savukārt, strādājot ar CBI iekārtu, lietderības koeficients ir 22.2 (pie ražīguma 13.6 $m^3\ h^{-1}$). Ar izstrādāto prototipu var veikt celmu raušanu un augsnes sagatavošanu, jo pacilu gatavošanas procesā ir svarīgi apgriezto velēnu piespiest, nodrošinot 0.4 m^2 liela mineralizēta laukuma izveidošanu. Raujot celmus ar MCR 500 II un papildus gatavojot augsni, ražīgums samazinās par 15%, sasniedzot tikai 11.1 $m^3\ h^{-1}$ (lietderības koeficients celmu raušanai un augsnes gatavošanai ir 16.9).

4. Saskaņā ar pētījuma rezultātiem, efektīvākais risinājums celmu koksnes izstrādei ir celmu raušana-plēšana ar MCR 500 II iekārtu, celmu pievešana ar vidējas klases forvarderu, piemēram, John Deere 810D, drupināšana starpkrautuvē, izmantojot lieljaudas drupinātāju CBI Magnum Force 6800P vai ekvivalentu, un drupinātās koksnes nogādāšana patērētājam ar autovilcienu, kas aprīkots ar puspiekabi, piemēram, Volvo FM. Pētījumā kopējais degvielas patēriņš celmu ražošana bija 6.82 $L\ m^{-3}$, kas veido pozitīvu lietderības koeficientu 3.9, t.i., enerģijas patēriņš kurināmā ražošanai ir 3.9 reizes mazāks, nekā patērētājiem piegādātās enerģijas daudzums.

5. Būtisku degvielas patēriņa samazinājumu kurināmā ražošanā var panākt, uzlabojot celmu raušanas-plēšanas darba metodi (saplēšot vidēja un liela izmēra celmus vismaz 2 daļās, ko var ērtāk novietot gan forvardera kravas telpā, gan celmu krautnē). Celmu plēšana uzlabo arī celmu krautņu kvalitāti (pamatnes platums ne lielāks par 3 m). Izmantojot drupinātāju AGK, var nodrošināt šķeldu iekraušanu tieši autovilcienā. Šie risinājumi teorētiski ļauj samazināt degvielas patēriņu vismaz par 35%, kā arī ļauj būtiski samazināt celmu kurināmā ražošanas izmaksas.

6. Celmu raušanas-plēšanas procesa nodrošināšanai ieteicama darba metode, kura paredz tehnikas pārvietošanos starp tehnoloģiskajām brauktuvēm, celmu raušanu veikt no labās uz kreiso pusi attiecībā pret pārvietošanās virzienu, tādējādi optimizējot laika patēriņu un paaugstinot ražīgumu. Izrautos celmus vajag nokraut nelielās kaudzēs 4–8 m attālumā no tehnoloģiskās brauktuves ass, tādējādi nodrošinot optimālus darba apstākļus arī forvarderam. Celmu rāvēja darba pozīcijas maiņa jāorganizē, pārvietojoties celmu raušanas virzienā par 1–5 m, un tādējādi maksimāli izmantojot tehnikas priekšrocības, jo ar izlici 4 m var izraut celmus ar diametru līdz 43 cm, un reizē nepasliktināt tehnikas šķērsstabilitāti. Minerālaugsnes piejaukumu nopurināšanai rekomendējama celma sadalīšana vairākās daļās augstu virs zemes tā, lai pāršķeltie celma fragmenti atsistos pret zemi.

7. Pētījumā izstrādāta tehnoloģiskā iekārta un darba metodes celmu raušanai un augsnes sagatavošanai, kā arī aprēķināta kopējā energobilance, kas norāda uz šī resursa ieguves potenciālu, bet papildus nepieciešams izvērtēt ekonomisko ieguvumu, iekļaujot aprēķinā mežsaimnieciskos ieguvumus – egļu audzēs samazināt sakņu trupes (*Heterobasidion annosum* (Fr.) Bref.) izplatības risku, atteikties no 1. agrotehniskā kopšanas, jo platībā, kur gatavotas pacilas, tā nav nepieciešama, kā arī samazināt priežu lielā smecernieka (*Hylobius abietis* L.), meža maijvaboles (*Melolontha hippocastani* Fabr.) un egļu lielā sakņgrauža (*Hylastes cunicularius* Er.) bojājumus.

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Izsaku pateicību kolēģiem, kuri mani atbalstīja.

Visbeidzot izsaku vislielāko pateicību savai ģimenei par morālo atbalstu darba izstrādes gaitā.

1. GENERAL DESCRIPTION

1.1. Topicality of theme

In general, the energy sector closely interacts with other sectors whereas the price of this resource might significantly influence the economic growth of the country. Politically, the bioenergy use has been prioritized (Pavļuts, 2013), thus increasing the self-sufficiency of renewable energy resources (RER). It is known, that it is possible to replace the use of natural gas consumption for energy with renewable energy resources, including fuelwood. The fuelwood is a local-origin renewable energy resource, and that might be considered as an advantage. The fuelwood proportion of use in Latvia reaches 31% with a positive increase from 46 thousand TJ in 2008 to 59.5 thousand TJ in 2017.

There is a lack of scientific studies which deals with an assessment of energy efficiency for stump wood production. More detailed, additional information is needed to evaluate the amount of energy that has to be consumed during the process of stump wood extraction. It is also important to known specific technical parameters and characteristics of the technical process for involved stakeholder groups, for instance, potential service providers, forest machine operators as well as policymakers and non-governmental organizations which are involved in the sustainable bioenergy certification process. This will help to deliver objective information to all stakeholders for several aspects related to different stump bioenergy extraction.

In 2011 the within the scope of this study the stump lifting head prototype, MCR 500, providing the stump-pulling and splitting function, as well as soil scarification (by making mounds and scarified furrows), thus improving the following forest regeneration quality.

1.2. Research aim, tasks and thesis

Aim of the thesis

To develop the basis for technology allowing the processing and transportation of stump bio-fuelwood to landing sites in coniferous tree felling sites with minimum total used energy in the entire technological process.

Objectives of the study:

1. to assess the potential resources of stump wood in joint stock company “Latvia’s state forests” (LVM) coniferous tree felling sites;
2. to create the basis for technical requirements for the development of efficient design of the stump lifting technology;
3. to analyze opportunities to improve the energy balance of stump extraction,

where a combination of stump extraction and soil scarification for the forest regeneration is considered;

4. to develop the technology for reducing energy consumption in stump biofuel production and transportation to a landing site.

The hypothesis of the study

The use of stump wood to increase the share of renewable resource because the energy balance of the entire technological process in positive.

1.3. Scientific novelty and applicability of the study

PhD thesis focuses on novel technological solutions for stump lifting and splitting, which includes the design and production of the stump lifting device, as well as approbation and the development of working methods. This is the first instance when stump lifting and splitting device has been developed in Latvia and the analysis of energy efficiency of the entire technological process is elaborated.

1.4. Approbation of the study

The main results of the thesis are published in 10 scientific papers and, based on research results, two Latvian patents have been elaborated and approved. In addition, results have been presented in five international conferences.

1.5. Structure and volume of thesis

The structure of the doctoral thesis is subject to the study tasks proposed in the study. The thesis contains three chapters. The first chapter deals with the analysis of the potential of the use of wood biomass and different extraction techniques of stumps. The second chapter describes the empirical material and methodology of assessment of stump wood energy resources whereas a result of the study applied methods and techniques for stump pull and crushes combined with soil preparation have been developed. The third chapter analyses the study outcome in compliance with the aim and research tasks of the doctoral thesis.

The thesis contains 75 pages, information has been summarized in 19 tables and 29 figures and 94 literature references have been used. Seven main conclusions and recommendations are elaborated on the basis of this study.

2. MATERIALS AND METHODS

2.1. The characteristics of empirical material

The first task addressed the assessment of available stump wood energy resources made using data from the National forest inventory (NFI). Further, calculation of stump biomass was performed using equations presented by J. Liepiņš.

To accomplish the second task, the approbation of approaches and technical requirements on stump pull and crush was evaluated. The elaboration of equipment for stump pull and crush is based on theoretical mechanical calculations. Also, fieldwork measurements are performed for proposed equipment approbation. However, it is important to mark all stumps before their extraction. Further, it is critical to provide all process according to planned work methods for stump-lifting and splitting. Also, improvements in equipment and technology reflect changes in productivity by elements of work, where descriptive statistics are used to compare indicators.

To accomplish the third task (improvement of the energy balance of stump extraction, where a combination of stump extraction and soil preparation before forest regeneration is considered), it is crucial to select appropriate felling areas where different soil preparation approaches can be compared. The assessment criteria are prepared planting number and quality, productivity, and consumed fuel. It is feasible to use descriptive statistics to compare data sets.

The fulfilment of the fourth task is based on the technological process on stump extraction and transport technology where the following assessment criteria are used: productivity (by work elements) and fossil energy consumption. Descriptive and inferential statistics is used to compare data sets.

Study sites were selected in areas where clear-cutting was performed three years before planned stump extraction and the following additional criteria were used: species composition (spruce dominant stands) and forest type (moderate rich mineral soils with optimal water regime). Further empirical data process is related to fieldwork studies where monitoring of working time and other relevant indicators are listed separated by work categories.

2.2. The methodology for assessment of stump wood energy resources

The assessment of available stump wood energy resources was made using the data from the National forest inventory (NFI). All calculations have been done following the previously developed method for stump biofuel assessment at the stand level (Lazdiņš et al., 2014) for the following species: Scot's pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.), birches (*Betula pendula*

Roth. and *Betula pubescens* Ehrh.) and common aspen (*Populus tremula* L.). To calculate stump biomass, initially, forest stands were categorized by age, selecting those sites already reached the regenerative felling age according Law on Forests, Section 9 (Ministru Kabinets, 2010). Other site selection parameters were related to the sustainable use of forest lands, for instance, forests with mineral soils in the *Vacciniosa*, *Myrtillosa*, *Hylocomiosa*, *Oxalidosa*, *Aegopodiosa*, *Myrtilloso-sphagnosa*, *Myrtilloso-polytrichosa*, *Dryopteriosa* stand types. Also, forest types with drained mineral and peat soils such as *Vacciniosa mel., Myrtillosa mel., Mercurialiosa mel., Vacciniosa turf. mel., Myrtillosa turf. mel.* and *Oxalidosa turf. mel.*) were considered in the selection (Lazdiņš et al., 2014). Forest stands with restrictions on thinning or final felling were excluded from the selection. The evaluation of stump resources was performed based on Latvian National forest inventory (NFI) data. Underground biomass and stump of each tree is calculated and later extrapolated to a sample plot level were calculated using the elaborated equations elaborated by J. Liepiņš.

$$y = a \cdot x^b \ , \tag{2.1}$$

where:
y – potential root biomass, $t_{\text{dry matter}}$;
a, b – parameters;
x – the volume of the stand, $m^3\ ha^{-1}$.

The calculation of stump biomass in the further analysis of productivity indicators are established on algorithms presented by Marklund and Repola to ensure data comparability between the studies.

2.3. Approaches for stump extraction and preparation of technical requirements

In total three work methods were tested in stump extraction. The first work method is related to the CBI stump extraction machine. The new prototype device MCR 500 was elaborated within the study and the following work methods are tested: conventional stump extraction method supplemented with soil preparation using mounding method. Different methods are related to technical and technological improvements of the MCR 500 device (method 2 – application of the 1st prototype and method 3 – application of the 2nd prototype) to ensure a higher productivity rate and better quality for soil preparation.

Stump extraction with CBI stump extraction machine. Stump extraction and splitting is done while excavator moves along technological trails. Thereafter, stump piles are organized in parallel to the trails. Stumps are pulled from the right side, forming a zone, perpendicular to the direction of movement (Fig. 2.1, the left side). However, stump extraction begins with the closest stumps and continues towards the furthest ones. Stump extraction in this zone is completed when the machine has extracted the last stump with maximum crane extend. Further, the excavator is moved forward and to the left side on the next zone where stump extraction begins, respectively, with the nearest one.

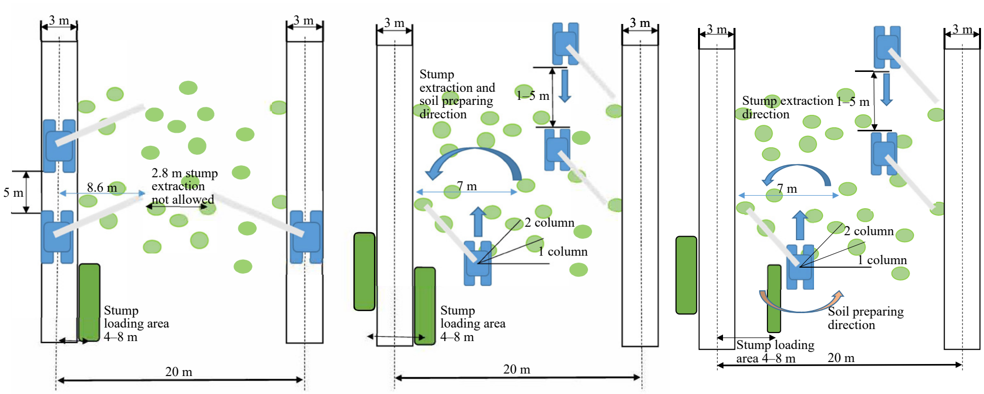

Fig. 2.1. **Work methods for stump-pulling**
(to the left CBI, in the middle MCR 500 and
to the right side advanced method with MCR 500 device).

<u>Stump extcration with MCR 500 device.</u> The excavator moves between technological trails (Fig. 2.1, in the middle). Stump extraction is done from right to left side, and perpendicular to the direction of movement. Stump extraction begins perpendicular to the direction of movement, forming the 1st zone. The first stumps are pulled out further away from the machine with the maximum crane extent and loaded parallel to the trails whereas at the same time soil preparation is done behind the excavator. The relatively small stump piles are arranged in parallel to the direction of movement, 4–8 m away from the axis of technological trails. When stumps are pulled out in the direction of movement then excavator moves 1–5 m forward and prepares soil behind it. If the pulled stump diameter is larger than 25 cm, then additional actions are needed, such as stump splitting into several parts and dropping of splitted stump parts to reduce the amount of mineral admixtures. After stump extraction the machine moves forward 5 m.

The elaborated stump extraction head fulfils following criteria:

- a new and multifunctional device with improved and advanced technical properties (mass, overall size, and dimension, construction, etc.). At the same time, it is possible to realize multiple functions, such as stump extraction and soil preparation using mounding method;
- with a total mass of up to 1600 kg, which is based on theoretical mechanical calculations and performing theoretical computing, as well as modelling construction elements by the proposed loads during stump extraction and soil scarification operations;
- the original construction permitting creation of mounds with flat surface;
- suitable to compact the created mounds using the base part of the mounding plate (LV 14769 B, 2014).

The design of work order for the different methods in stump extraction is provided in Fig. 2.2. It is possible to use this scheme for determining the stability of an excavator type stump-pulling during the stump extraction, as well as estimated

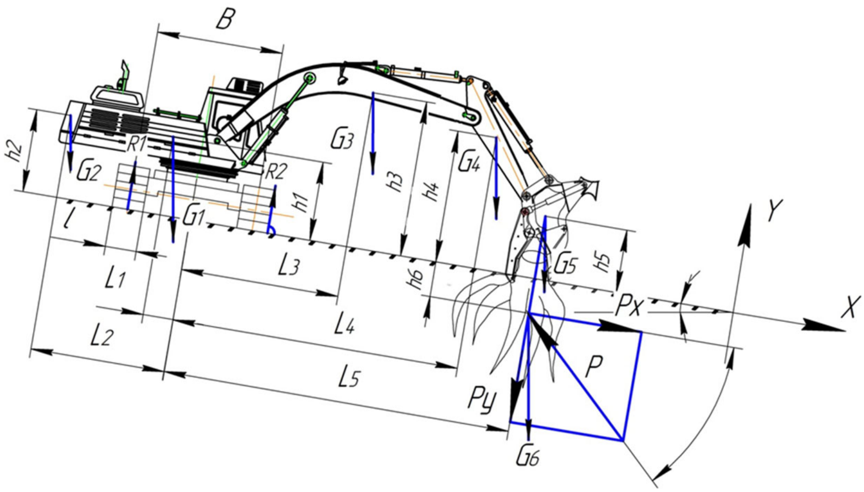

Fig. 2.2. **Force calculations for stump extraction**

G_1–G_6 – base chassis, counterweight, components of the hydraulic manipulator, technological equippment, gravitational force equal to stump's mass N; L_1–L_6 – distance from the base of chassis, counterweight, components of hydraulic manipulator, technological equipment, stump center of mass till excavator's axis line, m; h_1–h_5 – the height at which centers of gravity of components are located, m; h_6 – stump height on a horizontal surface, m; B – basis of excavator, m; l – track width, m; Px, Py – components of stump-pulling, N; P – stump-pulling force, N; α – the slope of the ground surface, degree; φ – the angle between stump-pulling surface and support surface, degree; A – tipping point, R_1, R_2 – the power of soil reaction under the track, N.

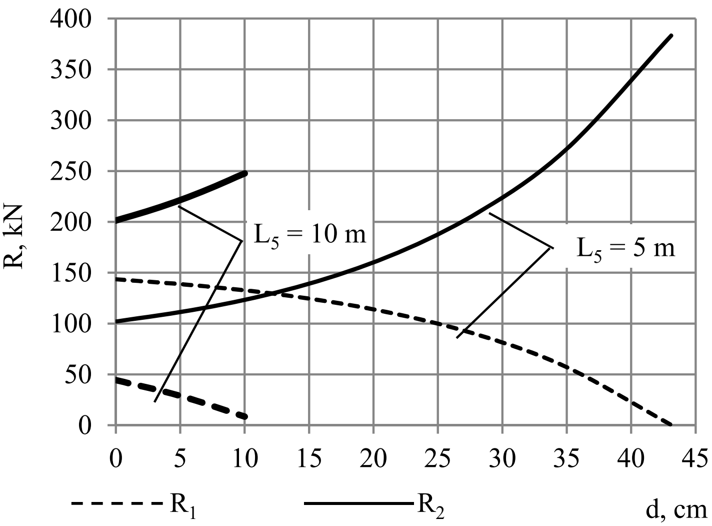

Fig. 2.3. **The diameter of stumps (d, cm) and influence of hydraulic manipulator (L_5) boom on response to support of tracks**

the productivity where use of different work methods is taken into account. For instance, support surface, a diameter of the stump, stump height and location, and technical parameters of the base chassis.

Different parameters of the stands and stump extraction operations are obtained in this thesis, for instance, the diameter of the stump, dependence on stump gravity on the soil surface, the direction of action on stump gravity, the hydraulic manipulator crane distance and track width. It has been found that a higher extend of the crane significantly reduces the operational capacity of a stump-pulling device. For instance, at the minimum crane extend (L_{min} = 4 m) with the vertical power of stump-pulling it is possible to extract stumps with a diameter of 43 cm without reducing the transverse stability. When the extend of the crane increases 2.5 times, the maximum extractable stump diameter decreases to 11.7 cm (Fig. 2.3).

In addition to the abovementioned parameters, the following stump extraction approach is considered:

- vertical movement of the technical device (φ = 90°);
- a hydraulic manipulator is in the position where φ = 0° or φ = 180°;
- combining movement of the technological device (0° < φ < 90°), if the movement is from excavator to the direction of working device (away from an excavator, 90° < φ < 180°).

It has been found that stump-pulling with the vertical movement has the lowest response, but it is not efficient under exploitation conditions. Furthermore, by pulling stumps in this way, moving the excavator on the horizontal surface at the degree of 30° toward the supporting surface of the base machine is achieved that reaction (R) under track increases 2.16–6.25 times (stump diameter increases from 5 to 10 cm). The achievements from the same computing show that the crane can work with stumps with up to 25 cm in diameter.

Results show that the safest transverse stability is achieved on a horizontal surface when on excavator base stump-pulling device might pull stumps with a diameter of up to 50 cm and more. For this, the limiting factor is the soil adhesion to the surfaces of the entire machine.

2.4. The development of methodology for the improvement of energy efficiency

The monitoring of working time by elements throughout the stump harvesting process is based on recording the end time per each working element. When starting to monitor time, the responsible person presses the “Start” button (starts the time recording) and during the work, all stages of work elements are fixed. Energy efficiency and productivity of the stump extraction was performed by work operations, from which most efficient was selected for the further interpretations, based on computing made in this study. Each operation is analyzed separately. Also modelling of the energy consumption in the extraction and forwarding of stumps to the roadside landing were estimated. Also, the variation with the lowest energy consumption has been identified.

To calculate the total energy capacity and to determine the total potential energy return, in this study, the equation, where the total energy balance indicates the recoverable energy that can be achieved from the total energy supplied is used (Wasiak, 2018). The total efficiency factor is calculated based on the energy that can be acquired in comparison to the total energy consumed.

3. THE ANALYSIS OF RESULTS AND DISCUSSION

3.1. Availability of stump resources in Latvia

The total renewable energy resources of the stumps correspond to 142 TWh of primary energy where part of it, regarding forest management restrictions, is located in forest lands where management activities are prohibited. Most of the theoretically available biomass resources of stumps consist of Scot's pine (45%), Norway spruce (36%), birch species (15%), and that for common aspen – 4%. It has been concluded that according to the calculations based on the forest site types where stump extraction theoretically is possible and other limitations 35% of the forest areas are not accessible for stump extraction, because of the forest management restrictions. The potentially available amount of stump wood is equal to 103 TWh primary energy, where the most of the biomass (55%) is located in forests with dry mineral soils. More than a half of the potentially available resources of stump wood are located in state forests – 68%. The amount of annually technically available stump wood resources is 349 GWh of primary energy. According to the data from the Central Statistical Bureau in Latvia, in the report "Fuel consumption and heat produced in heat plants, TJ" in 2018, 7690 TJ of wood chips were needed to provide the functionality of heat plants. In the case of using stumps for energy production, it would provide 16.3% of the demands of the total energy resource.

3.2. Analysis of productivity in the technological process of stump wood preparation

In total 3022 stumps have been measured in areas where it is planned to carry out stump-lifting and splitting activities. The average diameter of the stump is 33.5 ± 0.4 cm and height is 26.5 ± 0.4 cm in the areas where stump harvesting was performed with CBI. In the areas where stump extraction was done using MCR 500, the average diameter of the stump was 33.6 ± 0.2 cm and height – 33.1 ± 0.4 cm. The marked stump characterization was based on measurement data, which were collected before stump extraction. From all measured stumps, 75% corresponded to conifers (Norway spruce – 59% and Scots pine – 16%).

During the study, a total of 2720 stumps were extracted. The average diameter of stump when working with CBI stump extraction machine is 33 ± 11 cm, with MCR 500 – 33 ± 9 cm and with MCR 500 II – 38 ± 10 cm. The average time consumption for one $t_{\text{dry matter}}$ is 0.3 h of productive working time. The greatest time consumption is related to stump pulling activity out of soil. It takes approximately 33% from the total working time. Other activities take less time – turning the excavator machine (12%), the movement of excavator machine (11%), the stump crushing activity (11%), the performance of mineral soil shaking (11%) and activity of the positioning of the head (10%).

The consumption of productive working time differs significantly between the harvesting methods ($p = 0.01$). This is explained by improved efficiency of the working process, thus reducing the time required to extract 1 $t_{dry\ matter}$ of stumps. For instance, while working with CBI stump extraction machine, the preparation of 1 $t_{dry\ matter}$ takes 0.19 h, but working with MCR 500 device – 0.34 h. It would be not correct to extrapolate obtained data because during collection empirical data, the excavator's hydraulic pump of MCR 500 did not provide sufficient oil flow and the splitting knife was not able to split stumps. After technical improvements and upgrade of the method 2, the productivity rate is increased to 0.19 $t_{dry\ matter}$ per hour, similar to the rate accessed with the CBI head. In addition, it has to be taken into account that equipment was repaired to ensure the required oil flow. For further calculation the work productivity rate is modelled at different levels of technical readiness.

The achieved average productivity rate with CBI equipment is 13.6 $m^3\ h^{-1}$ and that for MCR 500 – 7.8 $m^3\ h^{-1}$. When comparing the working time consumption by work elements the lower indicators (an increase of working time consumption with negative sign), was determined by comparing both devices, such as stump extraction –69%, stump crushing –533%, stump shaking –67%, and stump dropping –137%. To increase productivity, the following improvements have been made in the stump-lifting and splitting equipment:

1. lowered cylinder mounting; according to the theoretical mechanical calculations, when reducing shoulder length then improvements in splitting knife efficiency and speed have been observed. This significantly affects productivity;
2. increased construction resistance toward side pressure. As a result, the improvements in technical conditions have been observed, thus reducing downtime during repairs due to replacement of splitting blade control arm bushes;
3. enhanced hydraulic cross-section; This allows to connect device to a high-power hydraulic drive system, thus reducing the resistance of oil flow in the system, and the cylinder can operate faster;
4. several improvements are related to the soil preparation module, which allows increased productivity and overall work performance.

After several improvements in work method and the equipment field studies demonstrated that the MCR 500 II prototype significantly decreased the consumption of working time per produced unit compared to MCR 500. The average productivity rate working with MCR 500 II device without soil preparation reaches 13.1 $m^3\ h^{-1}$, but with the addition soil preparation – 11.1 $m^3\ h^{-1}$.

The productivity rate of CBI and MCR 500 II is similar ($p = 0.16$). Comparing productivity rate for stump extraction with similar studies in Nordic countries, where comparison of different stump pulling heads is included, this study in Latvia has shown remarkably higher productivity rates. For instance, several studies in Nordic countries shows average productivity rate from 7 to 10 m^3 per hour (Laitila et al., 2008; Athanassiadis et al., 2011; Moffat et al., 2011; Palander et al., 2015; Kärhä & Mutikainen, n.d.). It has to be taken into account that abovementioned rates are indicative, because additional factors such as soil type and stump diameter significantly affects productivity rate. In Latvia, field trials are implemented in study sites on mineral soils with stump diameters significantly larger compared to the studies in Nordic countries, which are also focused mainly peat soils.

To calculate productivity rate for transportation, the monitoring of working time was extracted from seven felling areas where in transportation of 107 loads where analyzed. In general, the average transportation distance in the study sites was from 140 m to 850 m.

According to the study results the productive time of the forwarder in transportation of stumps is from 88% to 100%, compared to other transportation works in Latvia, where this rate is lower. Other studies using equivalent technical units, demonstrates the proportion of productive work time ranging from 77% to 94% (Rozītis et al., 2017). During the study, the most of the non-productive time is related to technical repairs, maintenance and resting time for machinery operators during working hours. Theoretically, productive working time should not exceed 67% if a shift lasts 8 hours or more. This can be explained by the resting time of the operators during working hours, assuming that the operators work 45 minutes following by short breaks lasting for 15 minutes. This assumption is included in further calculations of the productivity rate. In several research papers and reports above-mentioned information is specified as an indicator G15 (Talbot et al., 2003) or E15 (Sirén & Aaltio, 2003), which characterize the length of the break per hour.

Achieved productivity rates in experimental felling areas for stump transportation varies from 3 to 12 $m^3\ h^{-1}$ during productive work time. It has been found that relatively low productivity rates are related to inefficient use of the load tank of a forwarder. Also, the lack of experience by the excavator operator and avoidance of stump crushing during the operational work has been considered as a downside.

During the forwarding of stump biomass to the roadside landing, it is necessary to take into account partially filled loads because it is almost impossible to stack stumps in a container-type loading space. In the experimental study sites, the load density coefficient of stump wood is 0.4, and the forwarding productivity in this study are 3.5 $t_{dry\ matter}\ h^{-1}$. The distance of stump wood transportation to the intermediate loading pile is 7 km. Other studies have shown that the optimal transportation distance is considered up to 10 km where the lowest cost per km was observed. This study concludes that stump transportation to the intermediate landing site from the roadside landing significantly increases the total cost of biofuel production, thus making this type of biofuel uncompetitive. If logging residue and branches from regenerative felling or thinning are available, this production phase makes stump extraction incompetitive. To reduce costs stump comminution should be done in a roadside landing.

The stump comminution in the experimental fieldwork was performed with several crushers, including Magnum Force 6800P, demonstrating productivity rate of 110 tons per h, and Doppstadt 441SM, demonstrating productivity rate of 26 tons per h. This study has shown lower productivity rates compared to similar studies (Irdla et al., 2017), which is explained by the fact that the most of the stumps were not splitted and additional efforts were necessary to get them into the grinder. To ensure high performance during the whole production cycle it is necessary to split stumps with average and large diameter into at least four parts which will allow increasing productivity during forwarding and comminution (Anerud, 2012).

3.3. Assessment of soil preparation

In this study, soil preparation was performed using mounding method and the main quality criteria is number of suitable planting spots (Zimelis et al., 2012). In the control sites, where the soil was prepared with disc trencher, 1352 ± 50 planting spots per ha was produced. The stump-pulling device produced 1250 ± 72 plantings spots per ha. The scarification of the soil with disc trencher took 89 ± 18 min. ha^{-1}, but using a stump-lifting device – 229 ± 21 min. ha^{-1}. The total productivity rate of MCR 500 II decreased by 15% due to soil scarification and reached 11.1 $m^3 h^{-1}$. Estimated fuel consumption when using disc trencher is 18 L ha^{-1} (excluding the transportation of machinery between sites, in addition to 38 L of fuel is needed for each 100 km^{-1}), but in the case when using excavator, the fuel consumption for soil preparation is 49 L ha^{-1}.

3.4. The balance of development energy consumption of extraction of stumps

To calculate the consumption of energy during various operations in the stump extraction and processing, the total energy consumptions and most effective stump-pulling and transportation options was determined.

While working with Komatsu PC210LC, which is equipped with CBI stump-lifting device, the whole technology cycle including comminution and road transport, the energy consumption decrease rapidly if the diameter of the extracted stumps reaches 20 cm. Comparison of the abovementioned while using of the MCR 500 II prototype demonstrates similar decrease of energy consumption at the same diameter threshold. Comparing the fuel consumption while extracting the same size stumps (diameter 42 cm), CBI stump-lifting device demonstrates fuel consumption of 0.91 L m^{-3}, but MCR 500 II prototype – 1.05 L m^{-3}. It is important to highlight that technical readiness of the both heads is different, therefore MCR 500 II after further improvements of work method and construction might reduce fuel consumption.

The impact on forwarder productivity on the overall energy efficiency of stump biofuel production was not significant, if the productivity exceeded 5 $m^3 h^{-1}$.

In this study, the fuel consumption using the John Deere 810D is 14.3 L h^{-1}. The fuel consumption of the Logset forwarder is calculated according to the Loffler formula and, taking into account its engine power (170 hp), the fuel consumption is 18.5 L h^{-1}. For stump forwarding with Ponsse Bufallo, the recorded fuel consumption is 16.8 L h^{-1}. In similar studies in Latvia testing of various support chains the observed fuel consumption for offroad forwarding of logs can reach 17.7 L h^{-1} (Lazdiņš, 2017).

The fuel consumption at the same productivity rate (7 m^3 h^{-1}) while using John Deere 810D is 2.05 L m^{-3}, using Ponsse Gazelle – 2.40 L m^{-3} and that using Logset 4F – 2.65 L m^{-1}. Fuel consumption decreases below 1 L m^{-3}, if the productivity rate reaches 15 m^3 h^{-1}. The most important technical parameters are engine capability and load capacity.

Transportation of logs from the roadside landing site to and intermediate landing located 7 km away requires 1.29 L m^{-3} of fuel when Scania R480 was used and 1.52 L m^{-3} if Scania R500 is used. The calculations are based on the machine monitoring based assumption that the fuel consumption for Scania R500 was higher on average by 19% in comparison to other trucks.

In this study the fuel consumption of stump grinder CBI Magnum Force 6800P is 0.69 L m^{-3} on average and of the Shredder DW2060 – 0.56 L m^{-3}. It has to be taken into account that in the second case sieving machine Doppstadt 441SM is included in the calculation with the average fuel consumption of 1.31 L m^{-3}. Therefore, the total fuel consumption for the abovementioned machine set reaches 1.87 L m^{-3}.

Comparing the fuel consumption of container trucks Scania 380 and Scania 420, both trucks have similar fuel consumption – on average 1.87 L m^{-3}. However, the fuel consumption of Scania R500 and Volvo FM is lower (on average 1.52 L m^{-3} and 1.40 L m^{-3}, respectively). Differences in fuel consumption correlates with the engine power.

In accordance with study results, the most effective technological approach for stump wood harvesting is to plan stump extraction with MCR 500 II, because it provides opportunity to prepare soil in the felling sites and to improve water regime, and stump forwarding with John Deere 810D or similar middle-class forwarder. If stump transportation to the intermediate landing site is necessary, then the transport with the lowest fuel consumption might be chosen. Regardless of whether crushing is done at a roadside landing or intermediate landing site, it is important to make narrow and high piles of stumps so that they are easily accessible by a truck or forwarder crane. The most important criteria for selection of stump transportation tracks is metal cargo trailer (it is related to durability, because loading of stumps with a weight up to 2 tons in a cargo might damage the container).

The transport must be equipped with a manipulator for the loading stumps or loading might be done with a forwarder, which adds complexity to organization of works.

The overall fuel consumption for stump wood grinding and transportation (without soil preparation) is 6.82 L m^{-3}, and the total amount of energy efficiency factor is 3.9. This explains the fact that the amount of energy delivered to end users with stump biomass will be much higher compared to the amount of energy consumed during extraction, processing and transportation of stumps. In these thesis also several proposals for further reduction of energy consumption in the production process have been proposed. For instance, when stump grinding is done at roadside landing site, wood chips should be delivered directly to the truck significantly reducing fuel consumption. It is also necessary to improve the quality of stump-lifting and splitting performance which will increase the efficiency of transportation and stump grinding.

CONCLUSIONS AND SUGGESTIONS

1. The evaluation of the potentially available stump wood resources is based on the classification of forested ecosystems and legal restrictions determined availability of this resource. According to the NFI data 103 thousand TWh of primary energy resources from stumps are stored in the territory of Latvia. Technically, annually accessible amount of primary energy in stumps corresponds to 349 GWh, which can replace 16% of total fuelwood consumed in the country. It is also necessary to determine more accurate calculation where distribution by tree species and average reduced density of wood is included.
2. The study results demonstrated that several disadvantages of the first prototype of the MCR 500, which significantly influence the overall productivity and technical readiness. Numerous improvements were implemented in the 2nd prototype, for instance, lowering of the cylinder mounting, increased durability of the construction, enhancing hydraulic cross-section, and increasing the surface of the unit for soil preparation. After the abovementioned improvements, the productivity MCR 500 II prototype increased by 59% reaching the productivity rate of the CBI device. Additionally, the soil preparation is possible with MCR 500.
3. During the stump-lifting and splitting while working with MCR 500 II prototype without additional soil preparation, the amount of energy conversion efficiency is 19.9 (the productivity rate is 13.1 $m^3\ h^{-1}$). However, while working with CBI device, the energy conversion efficiency is 22.2 (the productivity rate is 13.6 $m^3\ h^{-1}$). The 2nd prototype of MCR 500 can extract and split stumps and prepare soil for the forest regeneration by making compacted mounds with surface area of 0.4 m^2. Soil scarification decreases overall productivity by 15% reaching 11.1 $m^3\ h^{-1}$ (energy efficiency factor combining stump extraction and soil preparation is 16.9).
4. As a result of this study, it is suggested that the most effective technological approach of stump extraction using MCR 500 II device and stump forwarding is ensured by medium-class forwarder (for instance, John Deere 810D used in the study). Furthermore, for stump comminution it is suggested to use CBI Magnum Force 6800P (similar option might be considered) where the delivery of grinded wood to the final consumer would be performed by the truck which is equipped by semi-trailer (in this study Volvo FM truck is used). The findings show that the total amount of fuel consumption for stump production reaches 6.82 $L\ m^{-3}$, which provides a positive energy efficiency factor, respectively, 3.9. In other words energy consumption for fuelwood production is 3.9 times lower than the amount of energy supplied to consumers.

5. To achieve a significant reduction in fuel consumption during the fuelwood production process, improving methods for stump-lifting and splitting are essential (the medium and large diameter stumps should be split at least in 2–4 parts which leads to much higher efficiency during forwarding and comminution). Also, stump splitting improves the quality of stump loading at a roadside landings ensuring that the base width of a pile is not exceeding 3 m). When stump comminution is done at a roadside landing site, wood chips should be loaded directly to the truck. Theoretically, these solutions would reduce fuel consumption by at least 35%, as well as the cost of stump fuelwood production would be much smaller.

6. In this study, the efficient working method for stump-lifting and splitting is elaborated. Specifically, the machinery movement between technological trails is essential, while stump extraction is performed from the right to the left side from the direction of movement. This allows optimizing working time and increasing productivity rate. The relatively small stump piles are arranged 4–8 m away from the axis of technological trails which provides optimal working conditions also for the forwarder. The change of the working position of the machine can be organized by moving in the direction of stump-pulling by 1–5 m while acquiring the advantages of the technical device because with lifting head 4 m it is possible to extract stumps no larger than 43 cm (diameter). Also, this provides the technical device transverse stability. Furthermore, the following actions are recommended for mineral particles removal performance: the stumps might be splitted in several parts relatively high above the ground surface where the broken fragments of the stump would hit the ground. If the result is not sufficient then stump dropping might be repeated several times.

7. The elaborated stump extraction device and working methods for stump extraction and soil preparation ensures competitive performance. However additional beneficial forest management aspects of stump extraction should be evaluated further. For instance, the reduction of the risk of spreading of root rot (*Heterobasidion annosum* (Fr.). Bref.) in spruce stands, reduction of costs of early tending in areas where mounding method is applied for soil preparation, reduction of risk of damages by *Hylobius abietis* L., *Melolontha hippocastani* Fabr. and *Hylastes cunicularius* Er.

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ РАЗЛИЧНЫХ ФАКТОРОВ НА ПОПЕРЕЧНУЮ УСТОЙЧИВОСТЬ КОРЧЕВАТЕЛЯ

В статье рассмотрены конструктивные особенности технологического оборудования, которое применяется для извлечения пней в настоящее время, и перспективные направления его развития. Приведена сравнительная оценка результатов исследований ряда ученых, посвященных определению усилий корчевки пней и изучению способов их снижения. Учитывая широкое распространение корчевателей на гусеничном шасси в Европейских странах, нами разработана расчетная схема, позволяющая исследовать влияние различных факторов на поперечную устойчивость данных машин. Расчетная схема учитывает взаимное расположение отдельных элементов базового шасси и технологического оборудования и их габаритно-массовые параметры. Для проведения теоретических исследований в качестве базового шасси был выбран экскаватор Newholland E215B с технологическим оборудованием производства SIA «ORVI» (Республика Латвия). Критическим считался случай, когда осуществляется отрыв одной из гусениц шасси. В процессе исследования варьируемыми параметрами являлись диаметр пней, способ корчевки, высота расположения пня над опорной поверхностью, угол наклона местности, массово-геометрические параметры базового шасси и его отдельных элементов в процессе выполнения технологических операций, вылет гидроманипулятора, ширина устанавливаемых на корчевателе гусениц. На основе проведенных исследований даны рекомендации по повышению эффективности эксплуатации корчевателей.

Ключевые слова: корчеватель, поперечная устойчивость, расчетная схема, параметры шасси, диаметр пня, ширина гусеницы.

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INVESTIGATION OF THE INFLUENCE OF VARIOUS FACTORS ON THE TRANSVERSE SUSTAINABILITY OF THE STUMP PROCESSOR

The article deals with the design features of the technological equipment, which is used to extract stumps at present and prospective directions for their development. A comparative evaluation of the results of studies of a number of scientists devoted to determining the efforts of stump rooting and studying methods for their reduction is given. Given the wide distribution of the stump processor on the caterpillar chassis in European countries, we will consider a calculation scheme that allows investigating the influence of various factors on the transverse stability of machines. The design scheme takes into account the relative position of the individual elements of the base chassis and technological equipment and their overall mass parameters. To carry out theoretical studies, the Newholland E215B excavator was selected as the basic chassis with technological equipment manufactured by SIA ''ORVI'' (Republic of Latvia). Critical was the case when the separation of one of the chassis tracks is carried out. In the process of the study varied the parameters: the diameter of the stumps, the way of stump processor, the height of the stump above the bearing surface, the angle of the clone of the terrain, the mass-geometric parameters of the base chassis and its individual elements in the process of performing the technological operations, the outlet of the hydromanipulator, the width of the caterpillars installed on the stump processor. On the basis of the research, recommendations are given to increase the efficiency of the operation of the stump processor.

Key words: stump processor, transverse sustainability, design scheme, chassis parameters, diameter of stumps, caterpillar width.

Введение. В настоящее время актуальным направлением является разработка и внедрение оборудования и машин для корчевки пней, что обеспечивает повышение эффективности выполнения лесохозяйственных и лесовосстановительных работ [1–4]. При небольшом объеме работ корчевка пней осуществляется с помощью ковша экскаватора, однако ведутся работы по созданию более современных машин для корчевания и подготовки лесных площадей под посадку культур [5–9]. Так шведская фирма Gremo представила радиоуправляемую машину [2, 10] с манипулятором и специальным корчевателем в виде изогнутой вилки с механизмом раскалывания (рис. 1, *а*). Для очистки лесосек от пней, камней и крупных порубочных остатков на отечественных предприятиях широкое распространение получила корчевальная машина КМ-1 (рис. 1, *в*), представляющая собой лесной трактор с передней навеской рабочего органа в виде зубьев, позволяющих осуществлять корчевку за счет тягового усилия, подъемной силы или сочетания того и другого [5–7]. Аналогичную компоновку имеют корчеватели, создаваемые на базе бульдозеров путем навешивания корчевального оборудования МП-18-6 Мозырского машиностроительного завода (рис. 1, *г*) [5].

В странах Скандинавии для корчевания пней и корней чаще всего применяются гусеничные экскаваторы со специальным оборудованием (рис. 2). При этом на стрелу экскаватора навешивается вилочный корчеватель, представляющий собой изогнутую вилку с несколькими зубьями или вилку с зубьями, копательной лопаткой и раскалывающим механизмом [2, 10].

Выбор корчевальной машины и способа корчевки зависит от применяемых технологий, количества и диаметра пней, имеющегося парка машин, их компоновочных решений и технических характеристик. При этом наименее изученными являются корчеватели, создаваемые на экскаваторном шасси.

Основная часть. При работе манипуляторных машин основным эксплуатационным параметром, ограничивающим функциональные возможности, является поперечная устойчивость [11, 12], на которую оказывают влияние кроме массово-геометрических параметров динамические процессы и компоновочные параметры технологического оборудования [12–15]. При этом отсутствуют методики, позволяющие рекомендовать режимы эксплуатации данного оборудования и базового шасси при корчевке пней. Учитывая, что эффективность применения манипуляторных корчевальных машин в значительной степени ограничена грузоподъемностью манипулятора, первоочередной задачей являлось установление зависимости влияния диаметра пня на усилие корчевки.

В данном направлении работал Савич В. Л., который установил зависимость вертикального усилия корчевки от диаметра пня, при этом погрешность результатов теоретических и экспериментальных исследований составила 8–10% [16].

Аналогичные исследования проводил Солдатенков В. И. [17], которым установлено, что при удалении пней необходимо выделить две стадии формирования сил сопротивления. Первая стадия связана с внедрением рабочего органа в земляную поверхность вокруг корчуемого пня, в результате которого происходит перерезание как грунта, так и части корневой системы; вторая – связана с вертикальным подъемом пня.

а *б* *в* *г*

Рис. 1. Компоновочные схемы корчевателей:
а – Gremo Besten; *б* – WESTTECH G1250; *в* – КМ-1; *г* – МП-18-6

а *б* *в*

Рис. 2. Рабочие органы для корчевания:
а – изогнутая вилка с несколькими зубьями; *б* – изогнутая вилка с зубьями, копательной лопаткой и раскалывающим механизмом; *в* – корчеватель с захватами и механизмом дробления

На рис. 3 представлены зависимости требуемых усилий на корчевку, установленные Савичем В. Л. (P_1) [15], Солдатенковым В. И. (P_2) [16] и Египко С. В [17].

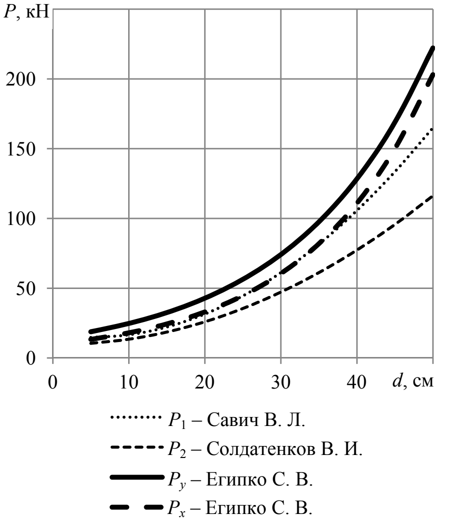

Рис. 3. Изменение усилий корчевки от диаметра пня

Для моделирования процесса работы корчевателя применялись результаты исследований Египко С. В., который установил необходимые усилия (рис. 3) на корчевку пней вертикальным (P_y) и горизонтальным (P_x) движением [17].

Для исследования влияния на эксплуатационные свойства корчевателя параметров пней, способов корчевки и массово-геометрических параметров базового шасси была разработана расчетная схема (рис. 4), учитывающая расположение отдельных элементов машины в процессе выполнения технологических операций.

Разработанная с учетом вышеперечисленных результатов модель позволяет производить оценку устойчивости базового шасси манипуляторного типа при осуществлении операций корчевки, а также осуществлять оценку эффективности применения различных приемов работы в зависимости от уклона местности, диаметра пня и высоты его расположения, а также технических характеристик базового шасси.

Для исследования в качестве базового шасси был выбран экскаватор Newholland E215B с технологическим оборудованием производства SIA «ORVI» (Республика Латвия), оценка поперечной устойчивости которого производилась на основании изменения реакций под гусеницами.

При исследовании критическим считался момент, когда происходит отрыв гусеницы от опорной поверхности. Исходя из приведенной выше схемы реакции R_1 и R_2 определяются по выражениям:

$$
\begin{aligned}
R_1 = [&G_2(L_2+0{,}5B+0{,}5l)\cos\alpha - G_2h_2\sin\alpha +\\
&+G_1(L_1+0{,}5B+0{,}5l)\cos\alpha - G_1h_1\sin\alpha -\\
&-G_3(L_3-0{,}5B-0{,}5l)\cos\alpha - G_3h_3\sin\alpha -\\
&-G_4(L_4-0{,}5B-0{,}5l)\cos\alpha - G_4h_4\sin\alpha -\\
&-(G_5+G_6)(L_5-0{,}5B-0{,}5l)\cos\alpha - G_5h_5\sin\alpha -\\
&-G_6h_6\sin\alpha - P_y(L_5-0{,}5B-0{,}5l)\sin\varphi +\\
&+P_xh_6\cos\varphi]/(B+0{,}5l),
\end{aligned}
$$

$$
\begin{aligned}
R_2 = [&-G_2(L_2-0{,}5B)\cos\alpha + G_2h_2\sin\alpha +\\
&+G_1(0{,}5B-L_1)\cos\alpha + G_1h_1\sin\alpha +\\
&+G_3(L_3+0{,}5B)\cos\alpha + G_3h_3\sin\alpha +\\
&+G_4(L_4+0{,}5B)\cos\alpha + G_4h_4\sin\alpha +\\
&+(G_5+G_6)(L_5+0{,}5B)\cos\alpha + G_5h_5\sin\alpha +\\
&+G_6h_6\sin\alpha + P_y(L_5+0{,}5B)\sin\varphi -\\
&-P_xh_6\cos\varphi]/(B+0{,}5l).
\end{aligned}
$$

В процессе исследований варьируемыми параметрами являлись: диаметр пня, высота его расположения над поверхностью земли, направление действия корчующего усилия, вылет гидроманипулятора и ширина гусеницы.

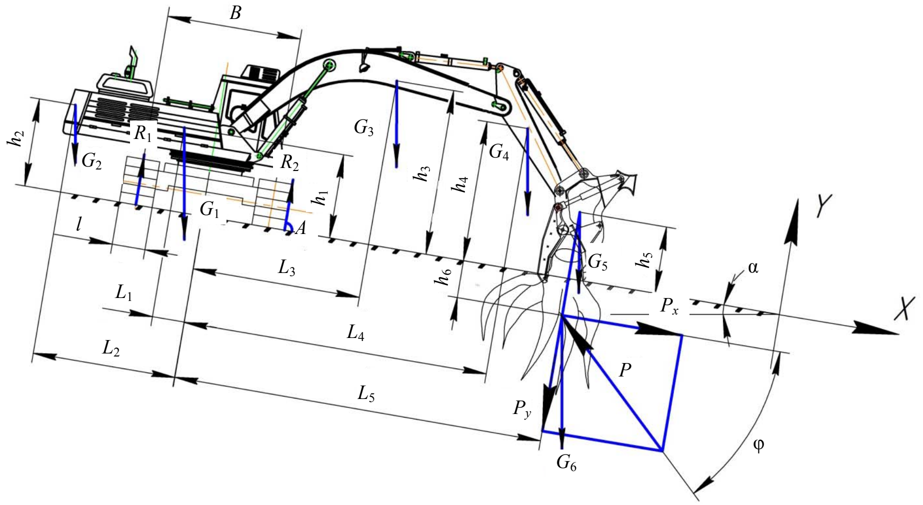

Рис. 4. Расчетная схема корчевателя:
G_1–G_6 – вес базового шасси, противовеса, стрелы и рукояти гидроманипулятора, технологического оборудования и пня соответственно, Н; L_1–L_5 – расстояния от продольной оси базового шасси до его центра тяжести, центров тяжести противовеса, стрелы и рукояти гидроманипулятора, корчуемого пня, м; h_1–h_5 – высоты расположения центров тяжести шасси, противовеса, стрелы и рукояти гидроманипулятора, технологического оборудования и корчуемого пня, м; h_6 – высоты расположения горизонтальной составляющей над опорной поверхностью, м; B – база, м; l – ширина гусеницы, м; P_x, P_y – касательная и нормальная составляющие сопротивления пня корчеванию, Н; P – усилие, необходимое для корчевки, Н; α – уклон местности, град; φ – угол между направлением корчевки и опорной поверхностью, град; A – точка опрокидывания; R_1, R_2 – реакции под гусеницами, Н

Установлено, что увеличение вылета гидроманипулятора (рис. 5) приводит к существенному снижению эксплуатационных свойств.

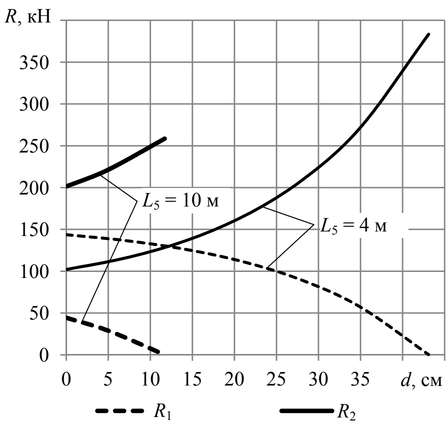

Рис. 5. Влияние диаметра пня (d) и вылета гидроманипулятора (L_5) на распределение опорных реакций корчевателя

Так при корчевке пней на минимальном вылете гидроманипулятора (L_{min} = 4 м) вертикальным усилием без потери устойчивости корчевателя обеспечивается обработка пней максимальным диаметром до 43 см. При увеличении вылета гидроманипулятора в 2,5 раза максимальный диаметр корчуемого пня снижается до 11,7 см.

При работе на уклоне предпочтительным является осуществление корчевки пня, расположенного со стороны возвышенности. Установлено, что при работе на максимальном вылете манипулятора под уклон в 30º корчеватель может осуществлять корчевку пней диаметром до 20 см (рис. 6), а в случае работы с уклона в 10º данная машина не сможет корчевать пни диаметром более 6 см ввиду потери устойчивости, заключающейся в отрыве гусеницы от опорной поверхности.

Кроме рассмотренных выше факторов существенное влияние оказывает способ корчевки, который может осуществляться вертикальным движением технологического оборудования (φ = 90º), горизонтальным к (φ = 0º) или от (φ = 180º) машины и комбинированным к (0º < φ < 90º) или от

(90º < φ < 180º) машины. В результате теоретических исследований установлено, что при осуществлении корчевки пня вертикальным движением технологического оборудования требуемое усилие является наименьшим (рис. 3), однако данный способ не является наиболее эффективным с точки зрения обеспечения высоких эксплуатационных свойств. Так в случае корчевки пня на горизонтальной поверхности движением технологического оборудования к машине под углом 30º к опорной поверхности обеспечивается увеличение опорной реакции R_1 под разгружаемой гусеницей в 2,16–6,25 раза (рис. 7) при изменении диаметра корчуемого пня от 5 см до 10 см, при этом обеспечивается возможность обработки древостоя диаметром до 25 см. Наибольшая устойчивость корчевателя обеспечивается при горизонтальной корчевке пня. При этом обеспечивается корчевка пней диаметром свыше 50 см, а максимальный диаметр ограничивается сцепными свойствами машины.

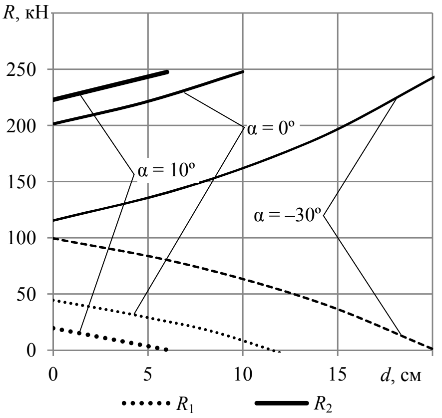

Рис. 6. Влияние диаметра пня (*d*) и уклона местности (α) на распределение опорных реакций корчевателя

Изменение реакций под гусеницами корчевателя при горизонтальном способе извлечения пня зависит от направления усилия корчевки и расположения пня по отношению к горизонту (рис. 8).

Исходя из полученных зависимостей видно, что при расположении усилия корчевки ниже опорной поверхности обеспечивается повышение устойчивости машины. Так при расположении пня над опорной поверхностью происходит уменьшение опорной реакции под разгружаемой гусеницей от 0,53 кН (d = 5 см) до 8,2 кН (d = 50 см) на каждые 10 см подъема, а в случае расположения пня ниже опорной поверхности происходит увеличение опорной реакции под разгружаемой гусеницей от 0,53 кН (d = 5 см) до 8,2 кН (d = 50 см) на каждые 10 см опускания.

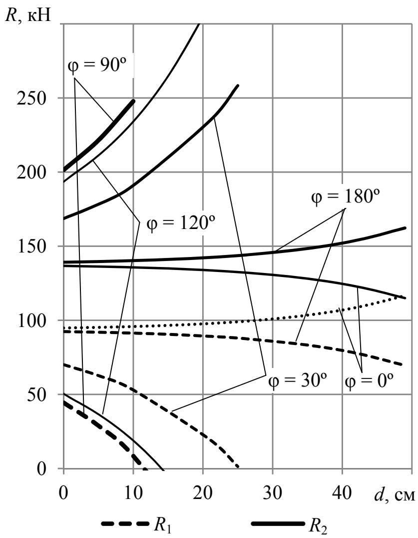

Рис. 7. Влияние диаметра пня (*d*) и угла (α) между направлением корчевки и опорной поверхностью на распределение опорных реакций корчевателя

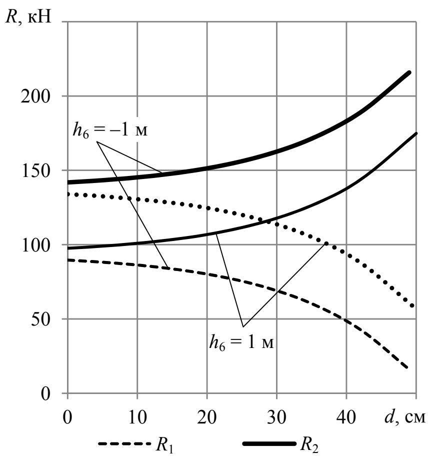

Рис. 8. Влияние диаметра пня (*d*) и высоты (h_6) расположения горизонтальной составляющей усилия корчевки над опорной поверхностью на распределение опорных реакций корчевателя

Следует отметить, что на экскаваторе Newholland E215B могут устанавливаться гусеницы шириной 600, 750 и 900 мм. При этом их габаритные и массовые параметры не оказывают существенного влияния на поперечную устойчивость. Установка гусениц шириной 900 мм вместо 600 мм при работе на максимальном вылете позволит обеспечить возможность обработки пней диаметром до 16 см вместо 12 см. Их применение также дает возможность повысить проходимость корчевателя.

Заключение. В процессе исследований было установлено, что в настоящее время для извлечения пней применяется достаточно разнообразное технологическое оборудование, имеющее различные габаритно-массовые и технические характеристики, а также отличающееся конструктивным исполнением. При этом на процесс корчевания существенное влияние оказывают не только параметры базового шасси и корчуемого пня, но и приемы работы. В последние годы в качестве базового шасси все большее распространение находят гусеничные машины, оснащенные гидроманипулятором и рабочим органом для корчевания. Для оценки функциональных свойств данных машин разработана расчетная схема и проведены теоретические исследования влияния различных факторов на поперечную устойчивость. К основным признакам потери устойчивости относятся: отрыв от плоскости склона одной из гусениц; необратимая потеря устойчивости всей машины и ее опрокидывание. В качестве критического признака потери устойчивости следует рассматривать случай отрыва одной из гусениц, так как при эксплуатации корчевателя в данном случае не обеспечивается безопасность работы [12]. Для проведения теоретических исследований в качестве базового шасси был выбран экскаватор Newholland E215B с технологическим оборудованием производства SIA «ORVI» (Республика Латвия).

В результате исследований было установлено, что при осуществлении корчевки вертикальным усилием потеря устойчивости базового шасси наступает при меньших параметрах пня. В случае корчевки пней движением к себе под углом 60º к вертикальной оси устойчивость против опрокидывания увеличивается в 2,16–6,25 раза в зависимости от диаметра обрабатываемого пня. При этом в случае корчевки пня движением близким к горизонтальному продольная устойчивость шасси обеспечивает возможность корчевки пней диаметром до 50 см на максимальном вылете. Однако при работе на грунтах с низкой несущей способностью существует вероятность бокового сползания.

Учитывая вышесказанное, можно сделать вывод, что для обеспечения эффективности эксплуатации корчевателя извлечение пней на максимальном вылете рекомендуется выполнять под уклон движением технологического оборудования, которое направлено параллельно опорной поверхности. При этом в случае расположения пня выше опорной поверхности большая поперечная устойчивость обеспечивается при движении технологического оборудования от машины, а в случае расположения пня ниже опорной поверхности корчевку следует осуществлять движением к базовой машине. Разработанная расчетная модель позволяет производить оценку эксплуатационных свойств машин манипуляторного типа, осуществляющих корчевку пней вертикальным, горизонтальным или комбинированным движением, сравнивать корчеватели, создаваемые на базе гусеничных манипуляторных машин различных производителей, давать рекомендации по повышению эффективности работы данной техники в различных природно-производственных условиях эксплуатации.

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Productivity of stump extraction with MCR500 bucket in Latvia

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***Abstract*-** **The scope of the is to estimate productivity of stump extraction using experimental excavator bucket MCR500, which can pull and split stumps and prepare mounds for the forest regeneration. Productivity of extraction of the stumps representing different diameter groups, species, as well root rot damages was evaluated using time study method. The study is implemented in 5 stands with total area of 8.2 ha. The results of the study demonstrates that extraction of a stump of healthy tree takes in average 11 % less work time than extraction of rotten stump, mostly because heavily rotten stumps can't be extracted in one piece. Extraction of the coniferous tree stumps is more efficient in compare to the deciduous trees; duration of all work elements is smaller during the pulling and splitting of the coniferous tree stumps. The proposed technology allows to reduce the time spent for a single stump extraction.**

Keywords – productivity, stump extraction, MCR500

I. Introduction

Scientific studies about stump use for biofuel and impact of stump extraction on forest regeneration in Latvia dated back in late 19th century [1]. After Latvia gained sovereignty in the 20th century, the issue about energy independence was outstanding; thus, forest owners returned to stump extraction and solution of the forest regeneration problems. Like nowadays, opposite opinions were declared at that time, for example, Ceichner[2] believed that stump harvesting is facilitating leaching of nutrients and erosion of soil. He did not recommend performing stump extraction in state forests.

Forest bioenergy is becoming increasingly important for the forest owners and forest industry in Latvia. Logging residues from clear-felling for biofuel production has already become widely accepted technology in state and private forests in Latvia. The use of these resources is growing together with an increase in the number of individual boiler houses, which are significant consumers of energy. If you see the GDP, contribution to total forest sector it shall be drawn up around 6%. The number of employees in this sector represents 5% of the workers. The demand for forest fuel is expected to grow due to increase of consumption in district heating sector and forest industries, like pellet production [3]. Besides extraction of harvesting residues form clear-felling, a variety of other forest residues can be utilized for biofuel production. Extraction of stumps started in Finland and to some extent – in Sweden [4]. If cost efficiency is used to evaluate potential of potential resources, stumps are located in the next position after harvesting residues from clear-cuts, both, in terms of available resources and harvesting costs [5].

Stumps consist of wood and bark of a tree below the stump cross-section. Recovery is performed with heavy machines after harvesting and removal of roundwood. Excavators equipped with a special stump extraction buckets that can pull and split stumps into smaller pieces are usually used for production. The harvestable dry mass of a stump-root system is 23...25% of the stem wood biomass, for both spruce and pine [6; 4]. However, elsewhere in the literature of the stump and the root volume, 18-25% for pine, 25-30% for spruce and 20-24% for deciduous trees are pointed [7].

As a comparison, the crown mass and stem ratio is typically 40...60% for spruce and 20...30% for pine in Finnish and Swedish studies [6]. Information about extractable biomass of stumps of deciduous trees is limited [5].

Stump wood resource extraction economic benefits is largely dependent on the technology used and productivity. Stump harvesting productivity increase possibilities, with the associated time consumption for stump removal operations chain and the evaluation of results obtained has been the aim of many researchers [8; 9; 10;1112;13;14]. Technological factors affected stump harvesting operations productivity has been also objectives of this study. These objectives have been chosen to focus on the stump extraction elements duration and how they differ depending on the technology used.

II. Materials and Methods

The trials were established in three forest stands managed by Ltd. "Rīgas meži" nearby Ogre city and two forest stands were established in the JSC company 'Latvijas Valsts Meži' (Table 1). Pine dominant stand (176-18) was on naturally wet mineral soil. It was used generally to adapt to the working method. Four spruce dominant stands were located on naturally dry mineral soil (98-4., 410-58-34., 501-360-9) and drained mineral soil (104-9). Other tree species represented in the experimental stands were silver birch, common aspen and black alder. All stumps of black alder and other rare deciduous species were left in the stands.

All stumps were measured (species, height, diameter and visually identifiable rotting signs) and marked before extraction. The harvesting, forwarding and soil scarification trials were implemented from September to November 2011 at „Rīgas meži", and in the JSC Company 'Latvijas Valsts Meži' it was from November to December 2012. The time studies were implemented according to work elements are listed in Table 2. Field computer with SDI software was used to record work elements. Time consumption is expressed in centiminutes (cmin.), which is 1/100 part of a minute.

TABLE I. CHARACTERISTICS OF EXPERIMENTAL STANDS

Code	Area, ha	Dominant tree specie	Stand type	Stand composition
176-18	1.1	Pine (Pinus sylvestris L.)	Myrtillosospha gnosa	7P3S
98-4	1.7	Spruce (Picea abies (L.) H. Karst.)	Hylocomiosa	6S2P2B + A, Ga
104-9	0.7	Spruce (Picea abies (L.) H. Karst.)	Myrtillosa mel.	7S2P1B + A, Ga
410-58-34	1.7	Spruce (Picea abies (L.) H. Karst.)	Hylocomiosa	8S103 1B83 1P83
501-360-9	3.0	Spruce (Picea abies (L.) H. Karst.)	Hylocomiosa	6S3P1B 98

TABLE II. WORK ELEMENTS

No	Stump extraction
1.	Tower turns
2.	Driving in stand
3.	Reaching
4.	Catching
5.	Pulling
6.	Splitting
7.	Shaking
8.	Dropping
9.	Scarifying
10.	Other operation

Mass of excavator is about 23 metric tons, engine output - 110 kW, boom length without excessive load is 8 m, width of drive chains 60 cm, hydraulic motor produces pressure of at least 37 MPa at high flow hydraulic lines, maximum hydraulic oil feed is at least 200 L min^{-1}. The excavator can reach 6 km h^{-1} speed, while its actual speed outside felling area is 2.3 km h^{-1}. Width of excavators with standard drive chains is 2.6 m. As for New Holland excavator, only one hydraulic line provided maximum pressure; therefore, the stump-splitting knife could be used only on partial capacity (at 20 MPa pressure). Due to this limitation, the excavator could not split larger stumps.

According to the working method, a stump extractor had to lift all stumps with a diameter of more than 10 cm and less than 50 cm. If a diameter of stump was larger than 50 cm, the operator had to decide whether it is more preferable to lift it or leave it.

Data were processed using Microsoft Excel software – Data Analysis, Descriptive Statistics.

III. RESULTS AND DISCUSSION

Average share of extracted stump in „Rīgas meži" is 62% of total extractable biomass of the measured stumps, and in 'Latvijas Valsts Meži' is 85%. Time consumption for rotten stump extraction in all cases is longer of 11% (Table 3) than an undamaged stump extraction. This is due to the strength factors that are lower for rotten wood. Therefore, under the tensile force of such a process, the stump chosen for extraction is broken into several parts, and the operator should to extract every part of that stump separately, which requires extra time. It is useful to have an additional soil preparation [15].

It is acquired during the analysis, when all process had been broken down into work elements (Figure 1) (scarifying was only on three object it is not included in the calculation), that it is breakdown of productive time, most of the time is occupied by stump extraction (30%), followed by stump harvester driving through the felling area (20%), and stump splitting into several parts (12% of the time).Depending on the available crusher, wood stump shredding time can vary significantly.

TABLE III. HARVESTING PRODUCTIVITY OF SOUND STUMPS AND ROTTEN STUMPS

Object	Time consumption per extraction a stump, cmin		Productive time, cmin
	sound stumps	*rotten stumps*	
176-18	134	148	188
98-4	157	182	171
104-9	144	167	181
410-58-34	123	131	129
501-360-9	124	132	127

It is also influenced by the mineralogical particles admixture, which is to be limited to 5% in Latvia. The size of this indicator is connected also with boiler house type.

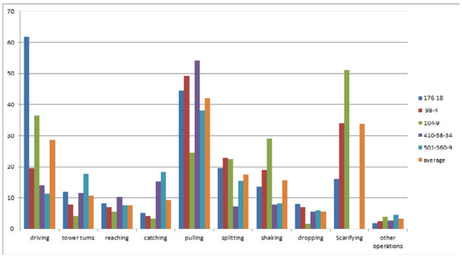

Figure 1. Share of work elements in the breakdown by objects.

The analysis of work elements duration when broken down them by stump size groups, there is a tendency that with increasing stump size averages, rapidly increasing the time spent for pulling it out of ground (Figure 2) has been observed. Consequently, the adopted average stump size range, which is worth for harvesting, has a direct correlation between time spent and the attainable biomass [15]. Leaving at the felling site stumps with diameters up to 10 cm and above 50 cm is a good measure for the promotion of biodiversity. Comparison of productivity of extraction of the stumps of different tree species and dimensions shows that the MCR 500 (Figure 3) can easily extract spruce stumps of any size and productivity constantly increases with the size of stumps [15].

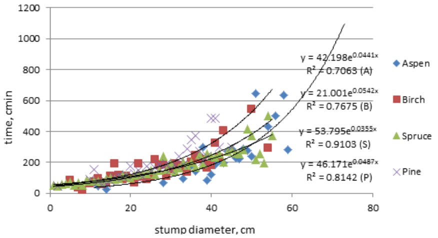

Figure 2. Productivity of stump extraction depending on dimensions of stumps.

Figure 3. Stump extraction MCR 500.

When the correct stump extraction technology is used, it is possible to achieve a greater benefit, that is to say, simultaneously to pull out more as only one stump, if they are situated very close to each other. Distribution of stumps number within a working strip does not change significantly. On average, it is one piece, because at final felling sites a tree is usually not close to each other.

During this project the efforts to develop technological tools for more efficient pulling stump out of the ground were applied. Various techniques are applied, depending on the stumps number at one spot. The first technology: extraction of one single stump (Figure 4). In order to minimize the power and energy used for stump pulling, at the beginning the thickest lateral roots should be cut off (first 3). Only after that, the pulling stump out of ground has been started (4).The second technology–several stump simultaneous extraction (Figure 5). Initially the thickest root (1) is to be cut off, then the roots, which are located between the nearest stump and main stump (2) are cut off. After that, the greater part of main stump is pulled out (3), and then it is finished by the nearest stump extracting (4). Using these technologies, mostly the smaller stump already is be indirectly taken out along with the greatest stump.

Figure 4. Large stamp splitting technology 1.

Figure 5. Large stamp splitting technology 2.

IV. CONCLUSIONS

1. A stump extraction is about 11 % faster than rotten stump extraction. It is more appropriate to combine the work with soil preparation in addition.
2. Conifer stump extraction is more efficient, because duration of work time elements is less than it is in the harvesting hardwood stumps.
3. Using the proposed technology it is possible to reduce the time spent on a single stump extracting process.

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Celmu biokurināmā resursu un to pieejamības apskats egļu audzēs valsts mežos

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Lazdiņš, A., Lazdāns, V., Kalēja, S., Zimelis, A., Prindulis, U., Kļaviņa, D., Rozītis, G. (2014). Celmu biokurināmā resursu un to pieejamības apskats egļu audzēs valsts mežos. Mežzinātne 28(61): 166–179.

Kopsavilkums. Pētījumā, izmantojot Meža statistiskās inventarizācijas (MSI) datus, izvērtēta par 20 cm resnāku celmu sausas koksnes biomasa (turpmāk tekstā – biomasa) egļu audzēs. Celmu pazemes daļu, lielo sakņu (caurmērs lielāks par 5 cm) un sīksakņu biomasa noteikta, pielietojot Zviedrijā izstrādātus biomasas vienādojumus. Virszemes celmu daļas biomasa noteikta, pieņemot, ka celmu vidējais augstums ir 30 cm, bet nosacītais egles koksnes blīvums – 400 kg m^{-3}. Izstrādei pieejamās biomasas aprēķinā pieņemts, ka iegūta celmu un lielo sakņu biomasa. Tehnoloģiskie zudumi – celmi uz kokmateriālu pievešanas ceļiem un lapkoku celmi – pieņemti kā 38 % no izstrādei pieejamās celmu biomasas. Koku caurmēra dalījuma modelēšanai izmantots beta sadalījums. Celmu izstrādes iespējas aprēķinātas teritorijām, kas sasniegušas galvenās cirtes vecumu (81 gadu) vai arī gadījumā, ja valdaudzes koku caurmērs atbilst nosacījumiem par minimālo koku caurmēru kailcirtes veikšanai. Aprēķinos pieņemts, ka celmu ieguvei pieejami visi meža tipi, izņemot grīni, purvāju, viršu āreni un viršu kūdreni. No resursu aprēķina izslēgtas tās teritorijas, kurās noteikts kailcirtes aizliegums. Izmaksu aprēķini veikti atbilstoši LVMI Silava pētījumu rezultātiem par celmu izstrādes darba ražīgumu un izmaksām, strādājot ar MCR-500 celmu rāvēju, aprēķinā iekļaujot arī augsnes sagatavošanai patērējamo laiku.

Par 20 cm resnāku celmu un sakņu tehnoloģiski pieejamā biomasa, pēc kailcirtes un meža tipa kritērija pieejamajās egļu audzēs, ir 48 tonnas ha^{-1}. Lielāka tehnoloģiski pieejamā celmu biomasa ir par 100 gadiem vecākās egļu audzēs.

Tehnoloģiski iegūstamā par 20 cm resnāku celmu un sakņu biomasa izstrādei piemērotās platībās ir 3213 tūkst. tonnas. Tehnoloģiski pieejamā biomasa pārsvarā koncentrēta 61–80 gadus vecās egļu audzēs.

Nozīmīgākie vārdi: celmi, biokurināmais, resursi.

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Abstract. The first scientific studies on stump extraction and forest regeneration after stump harvesting in Latvia are dated with the first half of 19th century (Bode, 1840). When Latvia became independent in the beginning of 20th century the issues related energy self-sufficiency came to the research agenda and scientists turned to stumps as an alternative source of biomass. Just like nowadays, two opposite opinions on stump extraction are proposed nearly 100 years ago; for instance, O. Ceichners in 1929 argued that stump extraction using explosives provoke erosion and leaching of nutrients from soil. He recommended to forbid stump extraction in Latvia (Ceichners, 1929). At the same time this researcher and some of his colleges approved that stump extraction promotes natural regeneration of pine stands and has no negative impact on next generation of trees (Vasiļevskis, 2007). K. Lange was one of the most active advocates of stump harvesting. He argued that leaving of stumps for decay in felling sites in less forested areas in is wrong management approach and recommended to use stumps for biofuel production (Lange, 1925). Latvia produced annually 7–30 thousands of m3 of firewood from stumps before the World War II. It was recommended by the State forest service in 1939 to use for stump extraction all clear-felling sites. At that time stumps were extracted using explosives or special heavers. The productivity norm for stump extraction was 2–2.5 stacks or 1.6–2 m^3 per day (Vasiļevskis, 2007).

When Latvia became independent again 24 years ago, stumps did not appeared in projections of heat and power producers for a longer time because other, considerably cheaper sources of biomass (firewood, harvesting and wood processing residues) were available, but increase of demand and price of biofuel changed the situation and production of biofuel from stumps started again (Lazdiņš, 2006). The studies on stump extraction in clear-felling sites were implemented in 2006 in cooperation with the Forest Research Institute of Sweden Skogforsk. Productivity of stump extraction in these studies was 10.4 m^3 per hour, respectively, about 40 times higher than 60 years ago (Lazdiņš & Thor, 2009).

According to earlier studies on application of the sustainability criteria proposed in the Renewable energy resource directive to solid biomass, the annual stump extraction potential in Latvia is 1.6 million tonnes annually, including 1.0 million tonnes of technologically accessible biomass, if the felling stock remains in a level of 2008. The total area accessible annually for stump extraction is 35.8 thousands ha (Adamovičs *et al.*, 2009).

The scope of the study is to evaluate biomass (dry mass) of stumps with diameter above 20 cm in spruce stands in Latvian state forests on the base of the National forest inventory (NFI) data. Biomass of below-ground part of stumps, coarse roots (diameter above 5 cm)

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and fine roots is determined using allometric biomass equations elaborated in Sweden. Above-ground biomass of stumps is estimated considering that trees are cut down at 30 cm height above ground level and density of wood is 400 kg m^{-3}. The proportion of the biomass available for extraction is determined assuming that only stumps and coarse roots will be extracted. Technological losses – stumps on strip-roads and deciduous tree stumps are assumed to be 38 % from technically available resources. The diameter distribution of trees is modeled using beta distribution function published in Sweden for modeling of diameter distribution in commercial thinning and final felling. Stump extraction is considered in spruce stands that already reached final felling age (81 years) or diameter of the average tree in a stand is above threshold value for final felling in spruce stands. It is assumed in calculation that all forest types are accessible for stump extraction, excluding *Callunoso-sphagnosa, Sphagnosa, Callunosa mel.* and *Callunosa turf. mel.*, where diameter of trees in the final felling age is generally below reasonable threshold for stump extraction (20 cm). It is also considered that stump extraction will not be implemented in areas, where clear-felling is forbidden. Cost calculation of stump extraction is done according to earlier study in LSFRI Silava on productivity of stump extraction with MCR-500 bucket, including time consumption for additional soil scarification (mounding). The methodology for calculation of stump biomass was elaborated within the scope of the "BalBiC – The Development of the Bioenergy and Industrial Charcoal (Biocoal) Production" project.

According to the study results average technologically available biomass of stumps with diameter above 20 cm in the forest stands accessible for final felling according to age or diameter criteria is 48 tonnes ha^{-1}. The highest yields can be obtained in stands older than 100 years. Total technologically accessible biomass of stumps with diameter above 20 cm in spruce stands in Latvian state forests is 3.2 million tonnes. The technologically accessible biomass is mostly concentrated in 61–80 years old spruce stands. According to current status of the spruce stands in the NFI stump extraction is possible right now in 26 % of all spruce stands on naturally dry and drained forest stand types in state forests of Latvian. Forwarding distance is not limiting factor for extraction of stump biomass – 90 % of all technologically accessible resources are located in 400 m distance from the nearest road.

Average cost of stump extraction, processing and delivery is 2630 EUR ha^{-1} (9.1 EUR LV m^{-3}); respectively, stump extraction might be feasible, if the price of biofuel is above 9.1 EUR ha^{-1}. Additional non-accounted benefit of stump extraction is reduction of cost of soil preparation before forest regeneration (about 120 EUR ha^{-1}); however, these expenses are relatively small in comparison to the whole stump extraction and biofuel production cost.

The study is implemented within the scope of the National forest competence centre research program project No. L-KC-11-0004.

Key words: stumps, biofuel, resources.

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Лаздыньш, А. [5]*, Лазданс, В. [5], Калея, С. [6], Зимелис, А. [5], Приндулис, У. [5], Клявиня, Д. [6], Розитис, Г. [5] **Обзор биотопливных ресурсов пней и их доступности в еловых насаждениях государственных лесов.**

Резюме. В данном исследовании, используя данные национального лесного мониторинга (MSI), оценена биомасса пней с диаметром более 20 см в ельниках, созревших для главной рубки. Биомасса пней, крупных (диаметром более 5 см) и мелких корней определён с применением уравнений, разработанных в Швеции. Биомасса наземной части пней определена допуская, что средняя высота пня составляет 30 см, а условная плотность древесины ели – 400 кг $м^{-3}$. Расчёт доступной для выработки древесной биомассы предполагает, что технологически получена древесина пней и крупных корней. Принято, что технологические потери - пни на транспортных дорогах и пни лиственных пород – в общем объёме составляет 38 % от общей досягаемой биомассы. Для моделирования распределения деревьев по диаметру применено уравнение бета-деления. Возможности выработки пней вычислены, имея ввиду леса достигшие возраст главной рубки (81 год) или в тех случаях, когда диаметр деревьев достиг минимальную величину для проведения сплошной рубки. В расчётах предположено, что подходящими для выработки пней являются все типы леса, кроме тех, которые произрастают на самых бедных почвах. Из расчётов исключены территории, где сплошные рубки запрещены. Расчёты расходов были проведены в соответствии с результатами исследований (ЛГИЛ SILAVA) о производительности и стоимости работ, связанных с корчеванием пней (используя MCR-500), в том числе и с затратами на заготовку почвы для последующего восстановления леса.

Технически доступная биомасса пней, с диаметром более 20 см доступных для выработки в еловых лесах после сплошных рубок в среднем составляет 48 т $га^{-1}$. Более значительные ресурсы биомассы в основном сосредоточены в лесах, которые превысили 100-летний возраст.

Технологически доступная биомасса пней с диаметром более 20 см в еловых лесах, подходящих для проведения сплошных рубок, в среднем составляет 3213 тонн. Большинство технологически доступной биомассы сосредоточена преимущественно в ельниках, достигших 61–80-летнего возраста.

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Ключевые слова: пни, биотопливо, ресурсы.

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Ievads

Pirmie zinātniskie pētījumi par celmu izmantošanu biokurināmā sagatavošanai un par celmu izstrādes ietekmi uz meža atjaunošanos Latvijā veikti 19. gadsimta pirmajā pusē (Bode, 1840). Pēc neatkarības atgūšanas 20. gadsimta sākumā aktualizējās energoresursu pieejamības jautājumi, un mežsaimnieki atgriezās pie celmu izstrādes problēmām. Tāpat kā tagad, arī agrāk pastāvēja pretēji viedokļi; piemēram, O. Ceichners uzskatīja, ka celmu spridzināšana sekmē barības vielu izskalošanos un augsnes eroziju, tāpēc ieteica celmu izstrādi neveikt (Ceichners, 1929). Tajā pat laikā viņš un citi pētnieki atzina, ka celmu izstrāde sekmē dabisko atjaunošanos priežu mežos un nerada negatīvu ietekmi uz nākamās aprites kokiem (Vasiļevskis, 2007). K. Lange bija viens no aktīvākajiem celmu izmantošanas aizstāvjiem un uzskatīja celmu atstāšanu cirsmās satrūdēšanai mazmežainos rajonos par nepareizu (Lange, 1925). Pirms 2. pasaules kara, neatkarīgajā Latvijā, gada laikā sagatavoja 7–30 tūkst. m^3 celmu malkas gadā. Celmu malkas sagatavošanai 1939. gadā ieteica izmantot visas kailcirtes. Tajā laikā celmus apstrādāja ar spridzināšanas metodi vai, izmantojot šim nolūkam konstruētas sviras. Vidējā celmu izstrādes norma bija 2–2,5 steri vai 1,6–2 m^3 dienā (Vasiļevskis, 2007).

Pēc neatkarības atgūšanas celmu koksne ilgstoši nenonāca siltuma un elektroenerģijas ražotāju interešu lokā, jo bija pieejami lētāki koksnes resursi (malka, kokapstrādes un mežizstrādes atliekas), taču, pieaugot pieprasījumam un palielinoties kurināmā cenai, celmu koksnes ieguve atsākās (Lazdiņš, 2006). Pētījumi par celmu izstrādes iespējām kailcirtēs veikti 2006. gadā sadarbībā ar Zviedrijas mežzinātnes institūtu *Skogforsk*. Pētījumā konstatētais celmu izstrādes darba ražīgums bija 10,4 m^3 stundā – attiecīgi 40 reizes lielāks nekā pirms 60 gadiem (Lazdiņš, Thor, 2009).

Saskaņā ar iepriekš veikto pētījumu rezultātiem teorētiskais ikgadējais celmu kurināmā potenciāls Latvijā ir 1 606,6 tūkst. tonnu tajā skaitā 958,3 tūkst. tonnas pieejamas tehnoloģiski. Izpētes projektā, kurā novērtēti atjaunojamo energoresursu direktīvā definētajiem ilgtspējības kritērijiem atbilstošie meža biokurināmā resursi, konstatēts, ka, mežizstrādes apjomam saglabājoties 2008. gada līmenī, katru gadu celmu ieguvi var veikt līdz 35,8 tūkst. ha lielā platībā (Adamovičs *et al.*, 2009).

Materiāls un metodes

Aprēķinu metodika balstīta uz pētījumu projekta "*BalBiC – The Development of the Bioenergy and Industrial Charcoal (Biocoal) Production*" ietvaros izstrādātajiem vienādojumiem (Lazdiņš *et al.*, 2012a). Aprēķinos izmantoti MSI kopsavilkuma atsevišķu parauglaukumu vai to sektoru dati. Metodika attiecas uz koku ciršanu meža zemēs, kas atbilst MSI mežaudzes klasifikatoram (10. kods).

Veicot resursu aprēķinus, vispirms mežaudzes atlasītas pēc aizsardzības pazīmēm – parauglaukumiem, kas atrodas teritorijās, kur aizliegta galvenā un kopšanas cirte, atzīmējot, ka šie resursi tehnoloģiski nav pieejami; attiecīgi celmu biokurināmā resursi izskaitļoti tikai tām audzēm, kurās atļauta kailcirte.

Kailcirtes veikšanai piemēroto mežaudžu identificēšanai sākotnēji veikta atlase pēc vecuma – atlasīti parauglaukumi, kur valdošās sugas vecums ir lielāks vai vienāds par galvenās cirtes vecumu attiecīgajai sugai, atzīmējot, ka tajos atļauta izstrāde kailcirtē. Papildu atlase veikta pēc caurmēra – parauglaukumos, kuros valdošās sugas caurmērs ir vienāds vai lielāks par galvenās cirtes caurmēru (Ministru Kabinets, 2012), atzīmējot, ka tajos atļauta izstrāde kailcirtē. Pēc tam papildu atlase veikta arī sanitārajai cirtei piemērotās audzēs – atlasot parauglaukumus, kuru valdaudzes šķērslaukums ir mazāks par kritisko (Ministru Kabinets, 2012).

Pēc tam veikts darba apstākļu novērtējums, atlasot parauglaukumus, kur izstrāde iespējama tikai ziemā (slapjaiņi un kūdreņi, 1. tab.).

Pēc izstrādei piemēroto audžu atlases aprēķināts caurmēra sadalījums (dažāda caurmēra koku skaitam), izmantojot beta sadalījuma vienādojumu (1. formula).

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

Minimālais caurmērs ir $a = 0{,}4 \cdot d$, bet maksimālais – $b = 1{,}7 \cdot d$, kur d ir audzes vidējā koka caurmērs 1,3 m augstumā. Minimālajam (a) un maksimālajam (b) caurmēram jābūt 6–60 cm (Arlinger, 1997). Ņemot vērā, ka praksē tas ne vienmēr iespējams, ierobežojums ignorēts, bet caurmēra pakāpes aprēķinātas no 8 līdz 64 cm ar soli 2 cm, attiecīgi, ja šajā diapazonā iekļaujas tikai daļa audzes koku, pārējiem vidējais caurmērs un pārējie dendrometriskie rādītāji iegūti pēc

1. tabula, *Table 1*

Darba apstākļu novērtējums*
*Evaluation of work conditions**

Edafiskā rinda *Growth conditions*	Meža tips *Forest stand type*	Celmu raušana pēc kailcirtes *Stump extraction after clearfelling*
Sausieņi *Dry mineral soils*	Mētrājs (*Vacciniosa*)	visu gadu (*all seasons*)
	Lāns (*Myrtillosa*)	visu gadu (*all seasons*)
	Damaksnis (*Hylocomiosa*)	visu gadu (*all seasons*)
	Vēris (*Oxalidosa*)	visu gadu (*all seasons*)
	Gārša (*Aegipodiosa*)	visu gadu (*all seasons*)
Slapjaiņi *Wet mineral soils*	Slapjais damaksnis (*Myrtilloso-sphagnosa*)	ziemā (*winter*)
	Slapjais vēris (*Myrtillosoi-polytrichosa*)	ziemā (*winter*)
	Slapjā gārša (*Drypteriosa*)	ziemā (*winter*)
Āreņi *Drained mineral soils*	Niedrājs (*Caricoso-phragmitosa*)	visu gadu (*all seasons*)
	Dumbrājs (*Dryopterioso-caricosa*)	visu gadu (*all seasons*)
	Liekņa (*Filipendulosa*)	visu gadu (*all seasons*)
Purvaiņi *Wet organic soils*	Mētru ārenis (*Vacciniosa mel.*)	ziemā (*winter*)
	Šaurlapju ārenis (*Myrtillosa mel.*)	ziemā (*winter*)
	Platlapju ārenis (*Mercurialosa mel.*)	ziemā (*winter*)
Kūdreņi *Drained organic soils*	Mētru kūdrenis (*Vacciniosa turf. mel.*)	ziemā (*winter*)
	Šaurlapju kūdrenis (*Myrtillosa turf. mel.*)	ziemā (*winter*)
	Platlapju kūdrenis (*Oxalidosa turf. mel.*)	ziemā (*winter*)

* "visu gadu" – celmu izstrāde iespējama visu gadu; "ziemā" – celmu izstrāde veicama pēc augsnes sasalšanas / *"all seasons" – stump extraction possible all over the years, "winter" – stump extraction possible on frozen soil.*

caurmēra sadalījuma aprēķināšanas tiem kokiem, kas iekļaujas sadalījumā. Koeficients m izskaitļots ar 2. vienādojumu. Koeficients n visām sugām aprēķināts ar 3. vienādojumu:

$$m = 0{,}3 + 0{,}08 \cdot (d - 6) \quad (2)$$

$$n = m \cdot \left(\frac{b-a}{d-a} - 1\right) \quad (3)$$

Koku skaits katrā caurmēra pakāpē ir proporcionāls vērtībai 4. vienādojumā:

$$n = (x - a)^{m-1} \cdot (b - x)^{n-1}\text{, kur} \quad (4)$$

x –audzes vidējā koka caurmērs, cm.

Saskaņā ar Somijā un Latvijā veikto pētījumu rezultātiem, nav lietderīga par 20 cm tievāku celmu izstrāde (Kärhä, 2012; Lazdiņš *et al.*, 2012b; Lazdiņš & Zimelis, 2012a), tāpēc no caurmēra sadalījuma atlasīti koki, kas 1,3 m augstumā ir vismaz 16 cm resni, nosakot to skaitu un vidējā koka caurmēru. Caurmēra atlases kritērijs izraudzīts atbilstoši nepublicētiem Meža nozares kompetences centra pētījumu datiem par sakarību starp caurmēru 1,3 m augstumā un pie zemes virsmas (1 % no koka augstuma), ko raksturo lineārās regresijas vienādojums (5. formula):

$$D_0 = 1{,}17 \cdot D_{1,3} + 1{,}67\text{, kur} \quad (5)$$

D_0 –koka caurmērs pie zemes virsmas (1 % no koka augstuma), cm;

$D_{1,3}$ –koka caurmērs 1,3 m augstumā, cm.

Celmu un pazemes biomasa aprēķināta 4 frakcijām – celma pazemes daļai (6. vienādojums), rupjajām saknēm (7. vienādojums), smalkajām saknēm (8. vienādojums) un celma virszemes daļai (9. vienādojums). Celma caurmēra aprēķiniem izmantots 10. vienādojums: vidējā celma augstums pieņemts par 30 cm, atbilstoši agrāk veikto pētījumu datiem (Zimelis *et al.*, 2013). Vienādojumi celma pazemes daļas un sakņu biomasas aprēķiniem aizgūti no Zviedrijā veiktajiem pētījumiem (Marklund, 1988), savukārt celma caurmēra un virszemes daļas biomasa aprēķināta atbilstoši Latvijā aprobētai metodikai (Lazdiņš & Von Hofsten, 2009; Lazdiņš & Zimelis, 2012b).

$$B_{celmi} = \exp\left[-3{,}36+10{,}67 \cdot \frac{D_{1,3}}{D_{1,3}+17}\right] \cdot n\text{, kur} \quad (6)$$

B_{celmi} – celmu pazemes daļas biomasa, kg ha^{-1};

$D_{1,3}$ – vismaz 20 cm resnu koku vidējais caurmērs, cm;

n – vismaz 20 cm resnu koku skaits gab. ha^{-1}.

$$B_{balstsaknes} = \exp\left[-6{,}39+13{,}37 \cdot \frac{D_{1,3}}{D_{1,3}+8}\right] \cdot n\text{, kur} \quad (7)$$

$B_{balstsaknes}$ – balstsakņu biomasa, kg ha^{-1}.

$$B_{saknes} = \exp\left[-2{,}5706+7{,}63 \cdot \frac{D_{1,3}}{D_{1,3}+8}\right] \cdot n\text{, kur} \quad (8)$$

B_{saknes} – par 5 cm tievāko sakņu biomasa, kg ha^{-1}.

$$B_{celma\ augšdaļa} = \frac{\frac{D_0^2}{100}}{4} \cdot \pi \cdot 0{,}3 \cdot n \cdot 394\text{, kur} \quad (9)$$

$B_{celma\ augšdaļa}$ – celma virszemes daļas biomasa, kg ha^{-1};

D_0 – celma caurmērs, cm;

394 –nosacītais koksnes blīvums, kg m^{-3}.

$$D_0 = 1{,}35135 \cdot D_{1,3} - 0{,}9459 \quad (10)$$

Resursu pieejamības novērtēšanai nošķirti potenciālie, tehniski un tehnoloģiski pieejamie resursi:

- potenciālie resursi – visi celmi un saknes, kas iegūstamas atcelmošanai piemērotās platībās,
- tehniski pieejamie resursi – celmu virszemes un pazemes daļas, kā arī lielo sakņu biomasa,
- tehnoloģiski pieejamie resursi – celmi un lielās saknes, atskaitot ražošanas zudumus

(38 % celmu un lielo sakņu biomasas).

Mežos, kas aug slapjās un susinātās augsnēs, tehnoloģiski pieejamos resursus paredzēts iegūt tikai ziemas apstākļos, attiecīgi celmu biokurināmais dalāms 2 grupās – resursi, kas pieejami tikai ziemā un neatkarīgi no sezonas. Celmu biokurināmā enerģētiskā vērtība pieņemta 5,3 MWh t^{-1} (Phyllis2, 2008).

Pievešanas attāluma modelēšanai ar programmu QGIS aprēķināts attālums no katra MSI parauglaukuma centra līdz tuvākajam celmu izvešanai piemērotajam ceļam.

Celmu šķeldu cena, aprēķinot ieņēmumus, pieņemta 10 EUR ber. m^{-3}, pārrēķinu koeficients no sausnas tonnām (biomasas) uz berkubikmetriem – 6, t.i. 1 tonna = 6 ber. m^3 (Lazdiņš *et al.*, 2012b; Lazdiņš & Zimelis, 2012a). Celmu biokurināmā pašizmaksa aprēķināta ar pakāpes vienādojumu (11. formula), kas izstrādāts Latvijā veiktajos pētījumos (Lazdiņš, 2012).

Biokurināmā pašizmaksa,

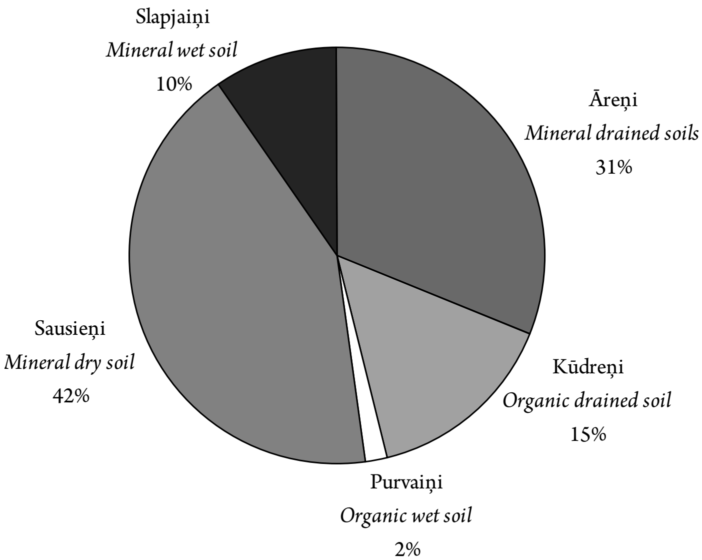
$$EUR\ ber.\ m^{-3} = 14{,}882 \cdot B_c^{-0{,}1281},\ \text{kur} \qquad (11)$$

B_c – tehnoloģiski pieejamā celma un sakņu biomasa, kg.

Rezultāts un diskusija

Saskaņā ar aprēķinu rezultātiem, celmu izstrādi valsts mežos var veikt 26 % egļu audžu (75 tūkst. ha). Tehnoloģiski pieejamā biomasa atbilst 16807 GWh primārās enerģijas. Tehnoloģiski pieejamā biomasa ir 50 % no kopējās celmu biomasas izstrādei piemērotajās egļu audzēs.

Lielākā daļa tehnoloģiski pieejamās celmu biomasas koncentrēta sausieņos, āreņos un kūdreņos (1. att.), kur darba apstākļi celmu izstrādei ir optimāli, t.i. tehnikas pārvietošanās nav apgrūtināta un saknes sausā laikā viegli atdalāmas no augsnes.



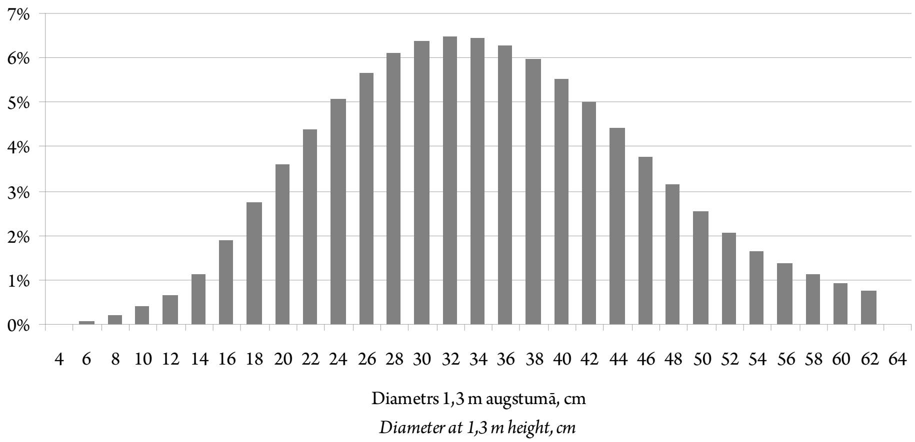
1. attēls. Tehnoloģiski pieejamās celmu biomasas sadalījums pēc meža tipu edafiskajām rindām.
Figure 1. Distribution of accessible stump biomass by growth conditions.

Biokurināmā sagatavošanai ieteikts izmantot vismaz 20 cm resnus celmus (Kärhä, 2012; Lazdiņš, 2012), jo, raujot mazākus celmus, būtiski palielinās sagatavotā biokurināmā pašizmaksa. Vidējais koku skaita sadalījums caurmēra pakāpēs ($D_{1,3}$) celmu izstrādei piemērotajās egļu audzēs valsts mežos parādīts 2. attēlā. Salīdzinoši visvairāk ir 30–36 cm resnu koku celmu; valsts mežos egļu audzēs ir arī daudz par 50 cm resnāku egļu celmu, kuru izstrāde ir ekonomiski izdevīgāka, taču tad nepieciešama arī smagāka un jaudīgāka tehnika.

Vidējā celma un sakņu biomasa, saskaņā ar aprēķinu rezultātiem, ir 224 kg, vidējā celmu un pazemes biomasa – 95 t ha^{-1} (2. tab.). Vidējais attālums no atcelmošanai piemērotajām platībām līdz tuvākajam ceļam ir 303 m, būtiski lielāks tas ir kūdreņos un slapjaiņos, vismazākais – āreņos (3. tab.).

Vidējā, par 20 cm resnāku celmu un sakņu biomasa egļu audzēs valsts mežos ir 95 t ha^{-1}; tehniski pieejamā biomasa – 78 t ha^{-1}, bet tehnoloģiski pieejamā biomasa – 48 t ha^{-1}. Lielāka tehnoloģiski pieejamā celmu krāja ir par 100 gadiem vecākās egļu audzēs (4. tab.). Liela celmu krāja 41–60 gadus vecās audzēs uzskatāma par nejaušu, jo šajā vecuma desmitgadē celmu izstrādei piemēroto platību atlases kritērijiem atbilst tikai 15 MSI parauglaukumi.

Kopējā, par 20 cm resnāku celmu biomasa izstrādei piemērotās platībās ir 6,3 milj. t, izstrādei pieejamā biomasa – 5,2 milj. t, tehnoloģiski iegūstamā biomasa 3,2 milj. t (5. tab.). Tehnoloģiski pieejamā biomasa pārsvarā koncentrēta 61–80 gadu vecās egļu audzēs. Lielais biomasas uzkrā-



2. attēls. Koku skaita sadalījums caurmēra pakāpēs kailcirtei piemērotajās mežaudzēs.
Figure 2. Distribution of trees by diameter in spruce stands suitable for stump extraction.

2. tabula, *Table 2*

Celmu biomasa atcelmošanai piemērotajās egļu audzēs

Biomass of stumps in spruce stands suitable for stump extraction

Edafiskā rinda *Growth conditions*	Potenciālie resursi *Potential resources*						
	celms, t ha^{-1} *stump, t ha^{-1}*	rupjās saknes, t ha^{-1} *coarse roots, t ha^{-1}*	smalkās saknes, t ha^{-1} *fine roots, t ha^{-1}*	celma virszemes daļa, t ha^{-1} *above-ground part of stump, t ha^{-1}*	vidējā celma biomasa, kg *average stump biomass, kg*	kopā, t ha^{-1} *total, t ha^{-1}*	kopā, tūkst. t *total, thsd. t*
Āreņi *Drained mineral soils*	28	51	20	12	111	216	1975
Kūdreņi *Drained organic soils*	25	47	19	11	102	207	952
Purvaiņi *Wet organic soils*	16	32	14	7	69	184	118
Sausieņi *Dry mineral soils*	23	41	16	10	89	247	2701
Slapjaiņi *Wet mineral soils*	19	35	15	8	77	198	617
Visi meža tipi *All conditions*	24	44	17	10	95	224	6363

3. tabula, *Table 3*

Celmu izstrādei piemēroto audžu platība un attālums no izvešanai piemērota ceļa sadalījumā pa meža augšanas apstākļiem

Distribution of spruce stands suitable for extraction of stumps and roots by growth conditions and average forwarding distances

Edafiskā rinda *Growth conditions*	Platība, tūkst. ha *Area, thsd. ha*	Attālums līdz ceļam, m *Distance to road, m*
Āreņi *Drained mineral soils*	19,44	274
Kūdreņi *Drained organic soils*	10,88	362
Purvaiņi *Wet organic soils*	2,20	254
Sausieņi *Dry mineral soils*	33,81	295
Slapjaiņi *Wet mineral soils*	8,64	355
Visi meža tipi *All conditions*	74,97	303

jums par 151 gadu vecākās egļu audzēs (5. tab.) skaidrojams ar to, ka šajā kategorijā iekļautas visas par 151 gadu vecākas audzes, tādēļ iegūtais rezultāts neraksturo attiecīgā vecuma desmitgadi. Pētījumā noskaidrots, ka liels biomasas potenciāls ir pāraugušās egļu audzēs, un, plānojot izstrādes tehnikas iegādi, jārēķinās, ka daudzās cirsmās būs izstrādājami par 50 cm resnāki celmi, kas prasīs īpaši izturīgu un jaudīgu tehniku. Vairāk nekā 50 % no tehnoloģiski pieejamajiem celmu resursiem izvietoti līdz 300 m attālumā no izvešanai piemērotiem ceļiem, vēl 40 % izvietoti līdz 400 m attālumā no ceļiem.

Vidējā celmu šķeldu pašizmaksa, tajā skaitā pievešanai, smalcināšanai un piegādei patērētās izmaksas, saskaņā ar aprēķinu rezultātiem, ir 9,1 EUR ber. m^{-3}; izmaksas mazākas ir vecākās audzēs, kur izstrādājamo celmu dimensijas ir lielākas. Vidējās celmu izstrādes un biokurināmā sagatavošanas izmaksas ir 2630 EUR ha^{-1}, tajā skaitā arī augsnes sagatavošanai meža atjaunošanas veikšanai. Kopējās izmaksas visu tehnoloģiski pieejamo celmu izstrādei ir 160 milj. EUR, prognozējamie ieņēmumi – 174 milj. EUR.

4. tabula, *Table 4*

Vidējā – par 20 cm resnāku celmu – biomasa egļu audzēs dažādās vecuma desmitgadēs
Average biomass of stumps with diameter of more than 20 cm in spruce stands representing different age classes

Rādītājs *Characteristic*	4	5	6	7	8	9	10	11	12	13	14	15+
Kopējā biomasa, t ha^{-1} *Total biomass, t ha^{-1}*	70	134	82	73	110	85	87	89	99	117	107	110
Pieejamā biomasa, t ha^{-1} *Available biomass, t ha^{-1}*	57	109	66	60	88	69	71	74	82	99	91	93
Tehnoloģiski iegūstamā biomasa, t ha^{-1} *Accessible biomass, t ha^{-1}*	36	67	41	37	55	43	44	46	51	61	57	58

5. tabula, *Table 5*

Kopējā – par 20 cm resnāku celmu – biomasa egļu audzēs dažādās vecuma desmitgadēs
Total biomass of stumps with diameter of more than 20 cm in spruce stands representing different age classes

Rādītājs *Characteristic*	4	5	6	7	8	9	10	11	12	13	14	15+
Kopējā biomasa, tūkst. t *Total biomass, thsd. t*	63	437	713	797	1278	687	661	339	347	248	131	662
Pieejamā biomasa, tūkst. t *Available biomass, thsd. t*	52	353	574	648	1019	556	536	280	288	209	110	558
Tehnoloģiski iegūstamā biomasa, tūkst. t *Accessible biomass, thsd. t*	32	219	356	402	632	345	333	173	179	129	68	346

Prognozējamie ieņēmumi visās vecuma desmitgadēs pārsniedz izmaksas, ja tirgus cena šķeldai ir 10 EUR ber. m^{-3}. Ietaupījumi uz augsnes sagatavošanas rēķina, veicot celmu izstrādi visās tam piemērotajās egļu audzēs, ir aptuveni 10 milj. EUR, ja augsnes sagatavošana ar disku arklu izmaksā 115 EUR ha^{-1}.

Saskaņā ar Valsts meža dienesta datiem, pēdējos 5 gados valsts mežos vidēji izstrādāti 2,66 tūkst. ha egļu audžu. Pieņemot, ka valsts mežu kailcirtēs izstrādā galvenokārt 8., 9. un 10. vecuma desmitgades egļu audzes, vidēji no 1 ha iegūstamas 44 t celmu. Attiecīgi, no visām kailcirtē izstrādātajām egļu audzēm vidēji gadā iegūstamas 117 tūkst. t (700 tūkst. ber. m^3) celmu biokurināmā. Papildus ieņēmumi no celmu šķeldu realizācijas, atbilstoši pētījumā izmantotajiem pieņēmumiem par šķeldu cenu, ir aptuveni 7 milj. EUR gadā.

6. tabula, *Table 6*

Celmu izstrādes izmaksu un ieņēmumu izvērtējums
Evaluation of cost and income of stump extraction

Vecuma desmitgade *Age decade*	Ražošanas izmaksas, EUR ber. m^{-3} *Production cost per loose volume m^3, EUR*	Ražošanas izmaksas, EUR ha^{-1} *Production cost, EUR ha^{-1}*	Ražošanas izmaksas, tūkst. EUR *Production cost, thsd. EUR*	Prognozējamie ieņēmumi, tūkst. EUR *Income forescast, thsd. EUR*
4	9,3	2 453	1 419	1 566
5	9,4	3 973	12 906	13 887
6	9,3	2 431	19 587	21 013
7	9,1	2 156	22 703	24 667
8	9,6	2 446	27 051	28 723
9	9,3	2 271	15 646	16 761
10	9,1	2 693	15 623	16 940
11	9,0	2 670	8 886	9 919
12	9,0	2 819	9 961	11 160
13	8,9	3 406	6 663	7 583
14	8,7	2 961	3 396	3 873
15	8,9	3 049	15 980	18 220
Visās vecuma desmitgadēs *All age decades*	9,1	2 630	159 819	174 311

Secinājumi

1. Egļu audžu kailcirtēs valsts mežos tehnoloģiski pieejamā par 20 cm resnāku celmu un sakņu koksnes biomasa vidēji ir 48 t ha^{-1}, bet kopējā tehnoloģiski iegūstamā celmu un sakņu biomasa izstrādei piemērotajās platībās ir 3213 tūkst. t.
2. Celmu izstrādei valsts mežos tehnoloģiski pieejami 26 % no visām egļu audzēm sausieņu, āreņu un kūdreņu meža tipos.
3. Pievešanas attālums nav celmu izstrādi limitējošs faktors – 90 % no tehnoloģiski pieejamajiem celmu resursiem izvietoti līdz 400 m attālumā no celmu izvešanai piemērotiem ceļiem.
4. Celmu biokurināmā sagatavošanas un piegādes vidējās izmaksas ir 2630 EUR ha^{-1} (9,1 EUR ber. m^{-3}).

Pateicība: pētījums veikts Meža nozares kompetences centra ERAF projekta "Metodes un tehnoloģijas meža kapiltālvērtības palielināšanai" (līgums Nr. L-KC-11-0004) ietvaros.

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COMPARISON OF PRODUCTIVITY OF CBI AND MCR-500 STUMP LIFTING BUCKETS IN LATVIA

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Abstract
The stump lifting trials were implemented in 5 forest compartments of the JSC 'Latvia state forest' Vidusdaugava, Rietumvidzeme, Zemgale and Ziemeļkurzeme forestries in autumn, 2012. Total extracted area was 3.5 ha, excluding constrol. Two stump extraction buckets were compared in these trials – CBI (made in Canada) and MCR-500 (made in Latvia). The scope of the study was to estimate if the prototype of the MCR-500 can compete with stump lifting buckets having positive feedback from industry. Considering that the CBI head cannot prepare soil, this operation was not done by the MCR-500 either. In total 1796 stumps were marked and their main parameters were taken in all trial areas. Extracted biomass was estimated theoretically using biomass expansion factors elaborated in Nordic countries. Allegro CX field computers with SDI software were used in time studies to obtain information about productivity and distribution of productive time in a work cycle. The study demonstrated that productivity of stump extraction with both stump lifting buckets did not differ significantly in 6 cases out of total 10 comparisons.
Key words: stump extraction, time study, biomass dry matter, productivity.

Introduction

First scientific studies about stump use for biofuel and impact of stump extraction on forest regeneration in Latvia dated back in late 19th century (Bode, 1840). After Latvia gained sovereignty in the 20th century, the issue about energy independence was outstanding; thus, forest owners returned to stump extraction and solution of the forest regeneration problems. Like nowadays, opposite opinions were declared at that time, for example, O. Ceichner believed that stump harvesting is facilitating leaching of nutrients and erosion of soil. He did not recommend to perform stump extraction in state forests (Ceichners, 1929). At the same time, he and other researchers agreed that stump extraction is facilitating natural regeneration of pine stands and does not affect trees of the next generation (Vasiļevskis, 2007) in any harmful way. K. Lange was one of the most active advocates of stump extraction. He believed that leaving of stumps in clear-felling areas for decaying is wrong (Lange, 1925). Before the World War Two, a production of firewood from stumps reached 730 thousand m^3 annually. In 1939, the Forest Administration recommended to utilize all clear-felling areas for stump extraction. At that time the most conventional method for stump extraction was blasting or mechanical extraction using special devices. Average productivity of stump extraction was 2...2.5 stacked m^3 or 1.6...2 m^3 per day (Vasiļevskis, 2007).

After retrieval of independence stump biomass for long a time was out of the field of interests of forest practitioners, because cheaper resources of woody biomass (firewood, residues from sawmills and harvesting) were available; however, with an increase in demand and rise of firewood cost, extraction of stumps were resumed (Lazdiņš, 2006). In cooperation with the Forest Research Institute of Sweden Skogforsk studies of productivity of mechanized stump extraction in clear-felling areas were implemented in 2006. A caterpillar excavator with a specialized stump lifting bucket was used in these studies. Average productivity of stump extraction was 10.4 m^3 per hour; respectively, it was 40 times higher than 60 years ago (Lazdiņš and Thor, 2009); however, these studies did not solve issues related to the forest regeneration. According to research data, stump extraction improves soil structure, lowers density and improves aeration of soil, thus creating favourable conditions for development of new trees. Removal of rotten coniferous stumps from clear-felling areas decreases the risk of getting infected with root rot for trees of the next generation (Vasaitis et al., 2008).

According to theoretical studies, the annual potential of stump biomass in Latvia is 1607 thousand tons, including 985 thousand tons that are available by applying currently used technologies. With the amount of harvesting remaining on average 10 million m^3 per year the same as current clear-felling proportion, stump extraction each year can be performed in 35.8 ha area. The average stump wood resources are 26.7 dry tons ha^{-1} (Adamovičs et al., 2009).

During analysis of the stump biofuel production technology, it was found out that the most effective solution to decrease costs is soil preparation during stump extraction and implementation of two-stage stump crushing – first into large pieces (diameter approx. 20 cm) at a log yard, at the same time shaking off most of excessive soil, and then into ordinary chips at a customer side. For the second stage crushers with electric engines are more preferable (Zimelis et al., 2012).

Research goal: to compare the productivity of a stump lifting bucket MCR-500 and CBI produced bucket.

The main tasks:

1. Measure stumps and estimate stump biomass stock in the experimental areas.
2. Perform time studies of stump extraction processes.
3. Compare productivity of both stump lifting devices.

Materials and Methods

Five experimental plots (Table 1) were established in the JSC company 'Latvijas Valsts Meži' Rietumvidzeme, Ziemeļkurzeme, Zemgale and Vidusdaugava Forestry in clear-felling areas (former spruce dominant forest stands of the same age and density) considerably affected by root rot. Sample plots were established in areas, where root rot was found in at least 50% of stumps. The idea behind establishment of the trials in diseased spruce stands was to have sample plots, where distribution of root rot after stump extraction can be compared with traditional forest regeneration. About half of all stands were left for traditional forest regeneration practices. Area of each extracted sample plot was at least 0.5 ha, excluding 10 m wide buffer zone.

The CBI bucket was mounted on a caterpillar excavator Komatsu PC210LC and the MCR-500 – on New Holland E215B excavator.

Mass of both excavators is about 23 tons, engine output - 110 kW, boom length without excessive load is 8 m, width of drive chains 60 cm, hydraulic motor produces pressure of at least 37 MPa at high flow hydraulic lines, maximum hydraulic oil feed is at least 200 L min^{-1}. The excavators can reach 6 km h^{-1} speed, while its actual speed outside felling area is 2.3 km h^{-1}. Width of excavators with standard drive chains is 2.6 m. As for New Holland excavator, only one hydraulic line provided maximum pressure;therefore, the stump splitting knife could be used only on partial capacity (at 20 MPa pressure). Due to this limitation, the excavator could not split larger stumps.

According to the working method, a stump extractor had to lift all stumps with a diameter of more than 10 cm and less than 50 cm. If a diameter of stump was larger than 50 cm, the operator had to decide whether it is more preferable to lift it or leave it. Taking into account previous experience with spruce stump extraction, the operator was advised to lift all spruce stumps (apart from too large in diameter) and leave only larger pine stumps. This restriction does not apply to places with high groundwater level, where pines usually have a shallow root system. There was no previous experience with extraction of birch and aspen, so the working method was perfected over time; thus, larger birch stumps were left, but all aspen stumps were extracted disregarding their diameter. The operator was advised to leave all black alder, linden and other stumps of broad-leaved tree species. Also, stumps within 4 m distance from ecological trees were not extracted. The operator was directed to extract stumps from all strip-roads, considering that forwarding of stumps biomass will be done in winter time.

All stumps with a diameter above 10 cm were marked at the felling-area before extraction. Soil preparation was not performed at extracted areas with a stump lifting device. This was planned for the spring time using a forest trencher.

Measurements were made from the topsoil till the top of the stump surface in 2 repetitions. Bottom of the stump is thought to be the horizontal soil layer, which is a hard cover and cannot be deformed easily. If there are mosses, lichens, snow or branches on the topsoil, those are to be removed until the top of the soil is visible and touchable.

Allegro CX field computers with SDI software were used in time studies.

For calculating stump biomass, breast height diameter ($D_{1,3}$) is used; therefore, stump measurement data at first are recalculated to breast height diameter. For spruce, which is the dominant tree species in all trial objects, 1st equation is used, for pine – 2nd equation, for birch – 3rd equation. For other species equations of spruce are used. Prior to this study, these equations were used in the JSC 'Latvia state forest' study on solid biofuel production from stumps at final felling (Thor et al., 2008).

Table 1

Identified research objects

Object ID	Area, ha	Sampling plot marking	Stump lifting head	Stand type
65-03-07-410-58-34	1.7	Nītaure	MRC-500	Dm (*Hylocomiosa*)
82-04-07-714-188-9	2	Stende	CBI	Vr (*Oxalidosa*)
82-05-07-712-437-8	3.4	Dursupe	CBI	Dm (*Hylocomiosa*)
83-05-07-603-326-7	1.4	Jaunpils	CBI	Vr (*Oxalidosa*)
80-29-07-501-360-9	3	Ogre	MRC-500	Dm (*Hylocomiosa*)

$$D_{1.3} = 0.7 + 0.74 \times D_0 \text{ ; where} \tag{1}$$

$D_{1.3}$ – diameter at 1.3 meter height, cm;
D_0 – average stump diameter, cm.

$$D_{1.3} = -1.89 + 0.87 \times D_0 \text{ ; where} \tag{2}$$

$D_{1.3}$ – diameter at 1.3 meter height, cm;
D_0 – average stump diameter, cm.

$$D_{1.3} = -6.7 + 0.916 \times D_0 + \frac{50.5}{D_0} \text{ ; where} \tag{3}$$

$D_{1.3}$ – diameter at 1.3 meter height, cm;
D_0 – average stump diameter, cm.

Stump biomass is calculated using 4th equation for spruce, 5th – for pine (Marklund, 1988) and 6th – for birch (Repola et al., 2007). The equation for birch biomass includes also coarse roots. Spruce biomass equation is used to determine stump and root biomass for other tree species.

$$M_S = \exp\left(-3.36 + 10.67 \times \frac{D_{1.3}}{D_{1.3}+17}\right)\text{; where} \tag{4}$$

M_S - biomass dry matter, kg.

$$M_S = \exp\left(-3.97 + 11.05 \times \frac{D_{1.3}}{D_{1.3}+15}\right)\text{; where} \tag{5}$$

M_S - biomass dry matter, kg.

$$M_S = \exp\left(-3.68 + 11.54 \times \left(\frac{2+1.25 \times D_{1.3}}{2+1.25 \times D_{1.3}+26} + 0.02 + 0.05\right)\right)\text{; where} \tag{6}$$

M_S - biomass dry matter, kg.

Biomass of coarse spruce and pine roots (diameter above 5 cm) is calculated using other equations: for spruce – 7th equation but for pine – 8th equation (Marklund, 1988).

$$M_S = \exp\left(-6.39 + 13.37 \times \frac{D_{1.3}}{D_{1.3}+8}\right)\text{; where} \tag{7}$$

M_S - biomass dry matter, kg.

$$M_S = \exp\left(-6.34 + 13.29 \times \frac{D_{1.3}}{D_{1.3}+9}\right)\text{; where} \tag{8}$$

M_S - biomass dry matter, kg.

Biomass of fine roots (diameter below 5 cm) is calculated separately, using 9th equation for spruce and 10th – for pine (Marklund, 1988).

$$M_S = \exp\left(-2.57 + 7.63 \times \frac{D_{1.3}}{D_{1.3}+12}\right)\text{; where} \tag{9}$$

M_S - biomass dry matter, kg.

$$M_S = \exp\left(-3.84 + 8.88 \times \frac{D_{1.3}}{D_{1.3}+10}\right)\text{; where} \tag{10}$$

M_S - biomass dry matter, kg.

Additional stump biomass above root collar is calculated by determination of volume as of cylinder volume (equation No. 11), and then dry substance biomass using equation No. 12 (Hakkila, 1975) is calculated.

$$V_C = \frac{\left(\frac{D_0}{100}\right)^2}{4} \times \pi \times H \text{ ; where} \tag{11}$$

V_C – stump volume, m^3;
D_0 – stump diameter, cm;
H – stump height, m.

$$M_S = V_C \times B_K \text{ ;where} \tag{12}$$

M_S – stump biomass dry matter, kg;
V_C – stump volume, m^3;
B_K – wood relative density, kg m^{-3}.
(spruce – 394 kg m^{-3}, pine – 476 kg m^{-3}, birch – 510 kg m^{-3}).

Extracted biomass constitutes of above- and below-ground parts of stump as well as coarse roots. It has to be taken into account, that such calculations of biomass can be inaccurate, as they are based on unverified equations. In addition, the diameter of stump is measured at cross-cut point that usually is above a root collar; hence, it is possible that there is a systematic error underestimating stump biomass in all calculations. However, these uncertainties have systematic characteristics and will not affect comparison of 2 stump lifting devices as far as the trial sites are similar and the same approach is used in measurements and calculations in all sites.

Data were processed using Microsoft Excel software - Data Analysis, Descriptive Statistics, F-test Two-Sample for Variances.

Results and Discussion

Stumps were measured in the autumn 2012 about 2 weeks before extraction. In total 1796 stumps were marked in all sites. Table 2 shows the summary of results of stump measurement.

Table 2

Stump measurement results

Object	Indicator	Hardwoods	Spruce	Pine
65-03-07-410-58-34	Number, pcs.	7	207	1
	Diameter (D), cm	45.7 ± 9.5	37.4 ± 0.9	24.0 ± 0.1
	Height (H), cm	32.0 ± 4.8	32.6 ± 0.8	23.0 ± 0.1
82-04-07-714-188-9	Number, pcs.	30	215	20
	Diameter (D), cm	29.7 ± 1.7	25.8 ± 0.7	29.0 ± 1.6
	Height (H), cm	31.6 ± 1.5	31.3 ± 0.6	29.1 ± 1.8
82-05-07-712-437-8	Number, pcs.	5	125	30
	Diameter (D), cm	35.8 ± 1.0	35.3 ± 1.6	40.4 ± 1.3
	Height (H), cm	35.2 ± 4.3	29.8 ± 1.0	27.5 ± 1.2
83-05-07-603-326-7	Number, pcs.	69	279	9
	Diameter (D), cm	38.6 ± 1.2	38.2 ± 0.7	40.8 ± 3.4
	Height (H), cm	24.7 ± 1.4	28.7 ± 0.7	20.0 ± 2.3
80-29-07-501-360-9	Number, pcs.	122	639	38
	Diameter (D), cm	35.9 ± 0.9	32.4 ± 0.5	37.3 ± 1.8
	Height (H), cm	27.8 ± 1.0	27.7 ± 0.5	20.0 ± 1.5
Number, pcs.		233	1465	98
Diameter (D), cm		37	34	34
Height (H), cm		30	30	24

Stumps, which were not extracted, were estimated according to the time study data by identification of those stump IDs, which did not appear in the study results. Stumps, which appeared during time studies (usually on strip-roads), were treated as average stumps in the stand. According to the time studies, 1568 stumps were extracted, including 82% of marked stumps that could be noticed and 5% extracted without markings (labels were lost).

Spruce stump diameter differences were analyzed by ANOVA single factor method. It was indicated that the differences in general were considered to be statistically significant (F = 26.20 > = 2.38 Fcrit). Comparing the experimental site in pairs by LSD

Table 3

Extracted stump total and available biomass with both technical devices

Bucket	Sample plot	Indicator	Species					All species
			other	aspen	birch	spruce	pine	
CBI	Dursupe	total biomass, kg	2149	-	284	14290	3905	20628
		accessible biomass, kg	1862	-	284	12411	3329	17887
	Jaunpils	total biomass, kg	3567	-	4376	29053	651	37648
		accessible biomass, kg	3136	-	4376	25089	556	33156
	Stende	total biomass, kg	494	-	1152	10818	1130	13594
		accessible biomass, kg	418	-	1152	9005	939	11514
	All	total biomass, kg	**6210**	**-**	**5813**	**54161**	**5686**	**71870**
		accessible biomass, kg	**5415**	**-**	**5813**	**46505**	**4823**	**62557**
MCR-500	Nītaure	total biomass, kg	858	7	753	23013	34	24665
		accessible biomass, kg	746	7	753	19874	27	21407
	Ogre	total biomass, kg	3183	3608	3612	46856	3163	60421
		accessible biomass, kg	2765	3608	3612	39971	2687	52643
	All	total biomass, kg	**4041**	**3614**	**4365**	**69869**	**3197**	**85086**
		accessible biomass, kg	**3510**	**3614**	**4365**	**59845**	**2714**	**74049**
Both devices		total biomass, kg	**10251**	**3614**	**10178**	**124030**	**8882**	**156956**
		accessible biomass, kg	**8926**	**3614**	**10178**	**106351**	**7537**	**136606**

(Least significant difference) test, the following results were obtained:

- Nītaure – Ogre: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 3.27$);
- Nītaure − Dursupe: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 1.26$);
- Nītaure − Jaunpils: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 1.62$);
- Nītaure − Stende: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 7.87$);
- Ogre − Dursupe: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 1.37$);
- Ogre − Jaunpils: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 5.43$);
- Ogre − Stende: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 6.13$);
- Jaunpils − Dursupe: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 9.65$);
- Jaunpils − Stende: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 2.74$);
- Stende − Dursupe: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 5.96$).

According to the time study results and theoretical estimation of stump biomass, actual extracted stump biomass is 92% out of extractable biomass of marked stump. Together in all objects 137 tons of extractable stump biomass were produced, including 63 tons with the CBI bucket and 74 tons – with the MCR-500 bucket (Table 3). The most of the actually extracted biomass (78%) was spruce stumps.

Average time consumption for stump extraction converted into engine hours, excluding longer delays, is 0.42 hour ton^{-1}, but expressed as productive working time – 0.37 hour ton^{-1}. The smallest productivity has been identified in areas with high groundwater level (Ogre, Dursupe, Stende, Table 4).

Spruce stump extracting productive time differences were analyzed by ANOVA single factor method. It was indicated that the differences in general were considered to be statistically significant ($F = 17.28 > = 2.38$ Fcrit). Comparing the experimental site in pairs by LSD (Least significant difference) test, the following results were obtained:

- Nītaure – Ogre: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 1.16$);
- Nītaure − Dursupe: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 0.09$);
- Nītaure − Jaunpils: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 1.61$);
- Nītaure − Stende: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 7.30$);
- Ogre − Dursupe: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 0.89$);
- Ogre − Jaunpils: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 0.71$);
- Ogre − Stende: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 7.07$);
- Jaunpils − Dursupe: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 6.39$);
- Jaunpils − Stende: diameter difference is not statistically significant ($t = 2.24 > t_{n;\,a} = 1.33$);
- Stende − Dursupe: diameter difference is statistically significant ($t = 2.24 < t_{n;\,a} = 6.54$).

It means that productivity of both stump lifting heads does not differ significantly in 6 cases out of total 10 comparisons.

Stump lifting buckets MCR-500 and CBI are different; during the trials MCR-500 did not use a splitting knife, so the extraction quality was worse; therefore the working method was adapted, like the use of shaking instead of dropping of stumps to get rid of soil particles. Figure 1 shows, that MCR-500 spent more time on lifting and splitting stumps (mainly because opening and closing of splitting knife took more time than for CBI); however, additional working time expenditure was retrieved by more efficient

Table 4

Summary of results of time studies

Stump lifting head	Sampling plot	Total biomass, kg	Working hours, h ton^{-1}	Productive time, h ton^{-1}	Productive time share
CBI	Dursupe	17887	0.58	0.43	94.40%
	Jaunpils	33156	0.29	0.27	96.90%
	Stende	11514	0.5	0.44	98.10%
	All plots	62557	0.43	0.37	96.70%
MCR-500	Nītaure	21407	0.37	0.34	98.20%
	Ogre	52643	0.42	0.4	95.20%
	All plots	74049	0.41	0.38	95.90%
Both devices	**All plots**	**136606**	**0.42**	**0.37**	**96.20%**

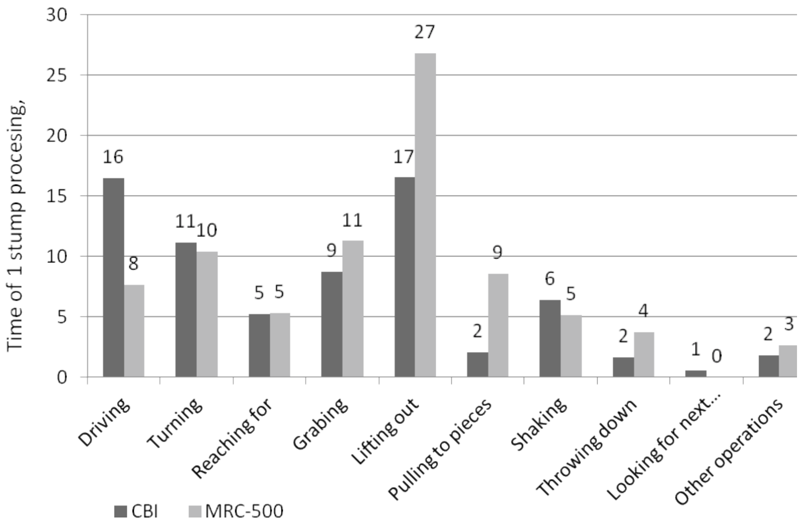

Figure 1. Comparison of structure of productive time consumption.

manoeuvring and spending less time for passages. It means that normally (ensuring necessary pressure in both hydraulic lines) MCR-500 would work faster than CBI lifting head. Probably there would be changes in productivity if other operator would be chosen. It is characteristic for harvester operators (a case of MCR-500) to use a crane more intensively to reach a tree before felling, whereas excavator operators usually operate in different manner when they drive or manoeuvre the excavator to select better position before stump extraction. In this case a more intensive use of crane was more beneficial approach according to the study results.

It has to be taken into account that allometric equations, developed in Sweden, have not been tested in Latvia, and can overestimate or underestimate amount of extracted biomass. It means that actual productivity can be different; therefore, the results can be used only to compare two stump lifting heads. Actual amount of extracted stumps could be determined after crushing of stumps, where it is possible to weigh chip trucks.

Conclusions

During stump extraction, operators noticed 87% of all stumps; as a result, the sample plot area is well extracted, and obtained data allows us to analyse productivity of both devices objectively.

1. Production time consumption analysis shows the difference between time spent on stump extraction and splitting by both head units compared in trials.
2. Performing statistical processing of productivity data of both stump lifting heads show the usefulness of further research on the use of the MCR-500.

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SYSTEM ANALYSIS OF PRODUCTIVITY AND COST OF STUMP EXTRACTION FOR BIOFUEL USING MCR 500 EXCAVATOR HEAD

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Abstract
In the 30ies of the 20th century stump extraction was identified as one of the most prospective technologies of forest sector to secure deliveries of solid biofuel. Now we are returning to the same challenges having the same targets – to secure energy independence and competitiveness of forest sector. MCR 500 is the prototype of combined stump extraction and mounding bucket for caterpillar excavator produced in Latvia by the LSFRI Silava and engineering company Orvi SIA. The device is made for extraction of stumps with diameter up to 50 cm. Additional benefit of the device is its ability to prepare soil for the forest regeneration by making mounds. The article summarizes results of productivity trials of stump extraction using the MCR 500 head and following forwarding of the material. Data from earlier studies are used to characterize comminution and road transport of stumps and chips. In total 3.5 ha were extracted during the studies. A harvested amount of stumps was estimated using biomass equations. It will be updated in further comminution studies. Average stock of extractable biomass (stumps and coarse roots) on the experimental sites was 28 tons ha^{-1}. Productivity of stump extraction was 2.4...3.4 tons per efficient hour. Consumption of efficient time for scarification of soil was 3.4...4.3 hours per ha. Forwarding took 30 min per load (2.6 tons per efficient working hour). Prime cost of chips according to biomass equations is 9.78 Ls LV m^{-3}, according to expert judgement based harvested stock is 6.38 Ls LV m^{-3}.
Key words: stump harvesting, forwarding, prime cost.

Introduction

Forest bioenergy is becoming increasingly important for the forest owners and forest industry in Latvia. Logging residues from clear-felling for biofuel production has already become widely accepted technology in state and private forests in Latvia. The demand for forest fuel is expected to grow due to increase of consumption in district heating sector and forest industries, like pellet production (Kons, 2011). Besides extraction of harvesting residues form clear-felling, a variety of other forest residues can be utilized for biofuel production. Extraction of stumps started in Finland and to some extent – in Sweden (Eriksson and Gustavsson, 2008). If cost efficiency is used to evaluate potential of potential resources, stumps are located in the next position after harvesting residues from clear-cuts, both, in terms of available resources and harvesting costs (Lazdiņš and Thor, 2009). However, stump biofuel has specific quality characteristics, making use of stumps complicated in conventional biomass boilers (Walmsley and Godbold, 2009).

Stumps consist of wood and bark of a tree below the stump cross-section. Recovery is performed with heavy machines after harvesting and removal of roundwood. Excavators equipped with a special stump extraction buckets that can pull and split stumps into smaller pieces are usually used for production. The harvestable dry mass of a stump-root system is 23...25% of the stem wood biomass, for both spruce and pine (Hakkila, 2004; Eriksson and Gustavsson, 2008). As a comparison, the crown mass and stem ratio is typically 40...60% for spruce and 20...30% for pine in Finnish and Swedish studies (Hakkila, 2004). Information about extractable biomass of stumps of deciduous trees is limited (Lazdiņš and Thor, 2009). The energy content of stumps varies in different references. About 140to160 MWh ha^{-1} can be harvested according to studies in Finland (Hakkila, 2004); in other publications 170 MWh ha^{-1} are mentioned (Nylinder, 1979); Tekes reported 200 MWh ha^{-1} (TEKES, 2004). Stump recovery can also reduce the cost of site preparation for replanting (Eriksson and Gustavsson, 2008).

Information about possibilities to merge extraction of stumps and scarification of soil is limited; however, there is scientific evidenceof improved natural regeneration, less insect damages and reduction of root rot distribution in the next generation stand (Saarinen, 2006). Therefore, the aim of the study is to evaluate productivity and prime cost of simultaneous stump extraction and soil preparation with the experimental stump extraction head MCR-500, forwarding and conventional soil preparation with a disc trencher as a control. The experiment will be continued with forest regeneration studies, which will provide information about the impact of stump extraction on the whole forest regeneration cycle.

Materials and Methods

The trials were established in 3 forest stands managed by Ltd. "Rīgas meži" nearby Ogre city (Table 1). Pine (P) dominant stand (176-18) was on naturally wet mineral soil. It was used generally to adapt to the working method. Two spruce (S) dominant stands were located on naturally dry mineral soil

Table 1

Characteristics of experimental stands

Code	Area, ha	Dominant tree specie	Stand type	Age decade	Stand composition	Harvested volume, m^3
176-18	2.7	Pine (*Pinus sylvestris* L.)	*Myrtilloso-sphagnosa*	11	7P3S	949
98-4	3.8	Spruce (*Picea abies* (L.) H. Karst.)	*Hylocomiosa*	9	6S2P2B + A, Ga	1542
104-9	1.5	Spruce (*Picea abies* (L.) H. Karst.)	*Myrtillosa mel.*	9	7S2P1B + A, Ga	293

Table 2

Work elements

No	Stump extraction	Disc trenching	Forwarding
1.	Tower turns	Preparations in the field	Driving in stand
2.	Driving in stand	Scarification	Manipulations with crane
3.	Reaching	Manoeuvring	Catching
4.	Catching	Other operations	Loading
5.	Pulling	Non-work operations	Unloading
6.	Splitting	Repairs	Sorting
7.	Shaking	-	Other operations
8.	Dropping	-	Non-work operations
9.	Scarifying	-	Weighing
10.	Other operation	-	Empty driving
11.	Non-work operations	-	Loaded driving

(98-4) and drained mineral soil (104-9). Other tree species represented in the experimental stands were silver birch (S), common aspen (A) and black alder (Ga). All stumps of Ga and other rare deciduous species were left in the stands.

All stumps were measured (species, height, diameter and visually identifiable rotting signs) and marked before extraction. The harvesting, forwarding and soil scarification trials were implemented from September to November, 2011. The time studies were implemented according to work elements are listed in Table 2. Forwarder loads was weighed using CAS scales RW-15P. Field computer with SDI software was used to record work elements. Time consumption is expressed in centiminutes (cmin.), which is 1/100 part of a minute.

Quality of soil scarification was estimated after stump forwarding using transect method – a set of 25 m^2 large sample plots located after each 25 m on the longest diagonal of the sample plot. Area and distance between mineralized spots were measured; minimal distance between suitable planting spots is at least 1.5 m.

The prime cost of production of stump chips was calculated using adapted version of the Flis cost calculation model (Thor et al., 2008). Productivity figures for stump extraction and forwarding were taken from the productivity studies. Maintenance costs and investments were considered as for new machines. Productivity figures and maintenance cost of stump truck, crusher, loader and chip truck were borrowed from earlier studies (Thor et al., 2008) using updated values for fuel cost and salaries.

Biomass was calculated using by recalculation of stump level diameter to diameter at breast height ($D_{1.3}$) and application of biomass expansion equations to estimate above- and below ground fractions of stumps (1st for spruce and pine and 2nd – for birch). For other species equation of dominant tree specie was applied. The same equations were used in previous studies (Thor et al., 2008).

$$D_{1.3} = a + b * D_0; \text{where}$$
$$D_{1.3} - \text{diameter at breast height, cm;}$$
$$D_0 - \text{diameter of stump, cm;}$$
$$a - \text{coefficient, 0.7 for spruce and -1.89 for pine;}$$
$$b - \text{coefficient, 0.74 for spruce and 0.87 for pine.} \quad (1)$$

$$D_{1.3} = -6.7 + 0.916 * D_0 + \frac{50.5}{D_0} \quad (2)$$

$$M_s = exp\left(-3.36 + 10.67 * \frac{D_{1.3}}{D_{1.3}+17}\right); where \quad (3)$$

M_s – dry biomass, kg.

$$M_s = \exp\left(-3.97 + 11.05 * \frac{D_{1.3}}{D_{1.3}+15}\right) \quad (4)$$

$$M_s = exp\left(-3.68 + 11.54 * \left(\frac{2+1.25*D_{1.3}}{2+1.25*D_{1.3}+26} + 0.02 + 0.05\right)\right) \quad (5)$$

$$M_s = \exp\left(-6.39 + 13.37 * \frac{D_{1.3}}{D_{1.3}+8}\right) \quad (6)$$

$$M_s = \exp\left(-6.34 + 13.29 * \frac{D_{1.3}}{D_{1.3}+9}\right) \quad (7)$$

Table 3

Characterization of extracted stumps according to biomass equations

Object	Number of extracted stumps per ha^{-1}	Extractable biomass of harvested stumps, kg ha^{-1}	Share of extracted stumps, %		Prepared mounds per ha^{-1}
			from number of stumps	from extractable biomass of stumps	
176-18	377	22907	90	72	315
98-4	324	27752	71	62	355
104-9	384	24970	63	53	1496

Stump biomass was calculated using exponential regression equations: spruce – 3rd equation, pine – 4th equation (Marklund, 1988), birch – the 5th equation (Repola et al., 2007). Equation for birch includes also large roots; for spruce and pine biomass of extractable roots was calculated separately usingthe 6th and 7th equation (Marklund, 1988), respectively. Above-ground part of stump is calculated separately using volume formula of cylinder and wood density factors from the guidelines for the greenhouse gas inventories (Penman, 2003). In this article.total biomass of stump and large roots (D > 5 cm) is called extractable biomass.

Results and Discussion

Average extracted biomass of stumps and roots according to the biomass calculations is 25.7 tons ha^{-1}. Average share of extracted stump biomass is 62% of total extractable biomass of the measured stumps. Average extractable biomass of stump is 73 kg (Table 3). If compared to harvested roundwood stock, share of extracted stump biomass is 7%. According to other study in Latvia, it is 12% (Thor et al., 2008). The same study also noted incongruity between the Swedish biomass equations and actually extracted biomass.

Average productivity of stump extraction is 2.7 tons per productive hour, but if soil scarification is not accounted – 3.4 tons per productive hour. Average time consumption for soil scarification is 3.4 hours ha^{-1}, when sufficient number of planting spots are prepared – 4.3 hours ha^{-1}. The most efficient stump extraction was in object No 104-9 (Table 4). In optimal working conditions an excavator can prepare 346 mounds per productive hour (10 sec per mound), if time consumption for stump extraction relevant work elements is not accounted (Table 5). According to the study results, it is possible to scarify 0.29 ha per productive hour. Notably that in the last stand (104-9) the productivity of soil scarification was 3 times

Table 4

Productivity of stump extraction

Object	Productivity of stump extraction, tons per hour		Productivity of mounding, mounds per hour	Productivity of soil preparation, ha per hour	
	total productive time	productive time for stump extraction		modelled scarification time[1]	to prepare 2000 mounds ha^{-1}
176-18	2.4	2.7	106	0.34	0.05
98-4	3.0	3.7	106	0.30	0.05
104-9	2.5	3.8	346	0.23	0.17

1 Excluding time consumption for stump extraction and treatment.

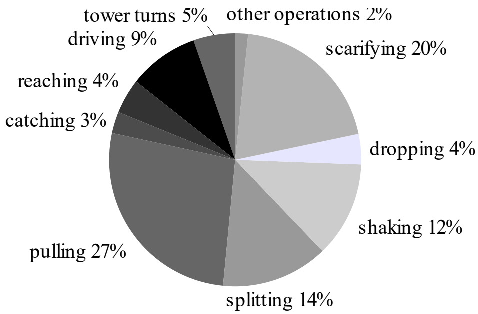

Figure 1. Share of work elements in productive time consumption.

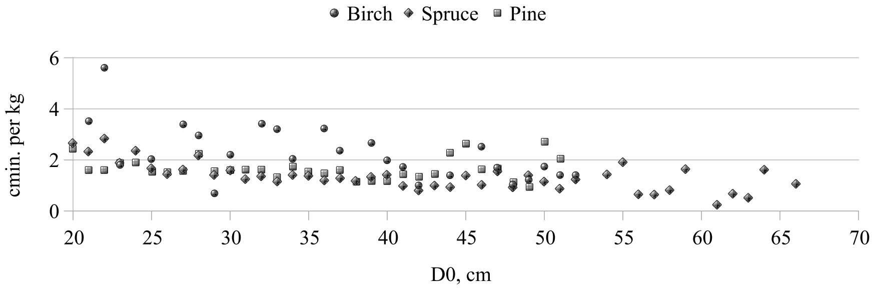

Figure 2. Productivity of stump extraction depending on dimensions of stumps.

higher than in the beginning. It is very probable that in real conditions the productivity will be similar to results obtained in the 104-9 or will be even better, if the pressure in the main cylinder of cutting knife is increased.

The most time consuming work elements are pulling, splitting and scarifying (61% of the total productive time, Figure 1). Technical improvements (increase of pressure in cylinder of the cutting knife) could increase productivity of pulling, splitting and shaking (cleaning of stumps). Productivity of scarifying can be increased by reduction of mounds per ha; however, much more studies are necessary to identify optimal number of the dedicated planting spots in different growing conditions.

Comparison of productivity of extraction of the stumps of different tree species and dimensions showsthat the MCR 500 can easily extract spruce stumps of any size and productivity constantly increases with the size of stumps (Figure 2). Productivity of extraction of birch stumps increases until D_0 reaches about 45 cm, then it becomes constant or decreases; however, productivity of large birch stumps is higher than of small stumps. Different results are obtained with pine stumps – there is no significant difference between productivity of smaller or larger stumps, but significant drop in productivity was observed, if D_0 of stumps is more than 45 cm. Productivity of the largest pine stumps is smaller than productivity of extraction of smaller pine stumps.

Comparison of work cycles, when 1 or several stumps are extracted approves hypothesis that simultaneous extraction is beneficial (Table 5), which means that in practice an operator should start pulling with the biggest stump, which will take also smaller surrounding stumps in a group of stumps, and not with smaller ones, which will be pulled out one by one.

Productivity of extraction of rotten stumps was significantly higher than average productivity figures. Time savings per stump, except time for soil scarification, was 17% on average. Most of reductions of the time consumption was in pulling and splitting operations (Figure 3). The damages by root rot may significantly reduce biomass of stumps, which is complicated to estimate using biomass equations; therefore, increase in productivity in practice might be lost in reduction of extracted biomass.

Average forwarder load was 7651 ± 272 kg. Average consumption of productive time in forwarding when calculated according to biomass equations was 22.8 ± 6.6 min ton^{-1} or 2.6 ± 0.8 tons per productive hour (Table 6). If time per load (20.3 min for loading and 10.1 min for unloading) is recalculated, results of the study are comparable with earlier stump

Table 5

Productivity of extraction of multiple stumps

Number of stumps per cycle	Share of total number of stumps	Share of total extractable biomass	Average extractable biomass of stump, kg	Average time consumption, seconds per stump
1 stump	85.9%	84.6%	69	62
2 stumps	12.4%	13.3%	76	60
3 stumps	0.9%	0.8%	62	58
≥ 4 stumps	0.8%	1.3%	41	27
More than 1	14.1%	15.4%	78	60

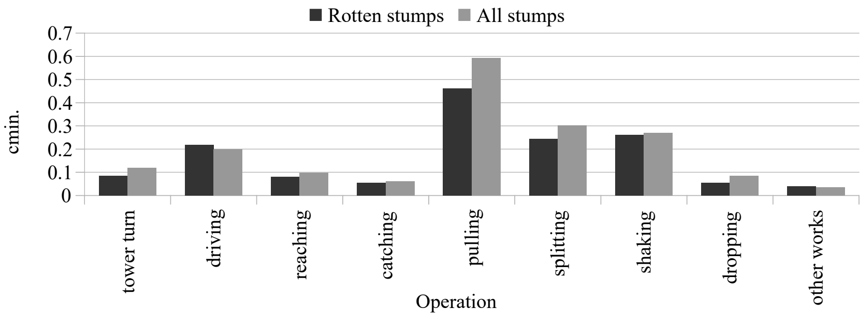

Figure 3. Productivity of extraction of rotten stumps – comparison of work elements.

forwarding studies (Thor et al., 2008); however, average load calculated by the biomass equations is 2 to 3 times smaller than in the same studies calculated according to weighed biomass. Average load according to biomass equations is 1.3 ± 0.4 tons, according to weighing data – 3.8 tons of dry mass.

The significant correlation was found between the load size and efficient time for loading ($R^2 = 0.78$). It can be expressed as a power regression (8th equation, Figure 4). It is also noticeable in Figure 5 that average load size depends on work conditions – it was considerably bigger in the object 98-4, where stock per ha was also greater than in other stands due to a larger dimensions of stumps.

$$E_0 = 1950.15 * M_s^{-1}; \text{ where}$$
$$E_0 - \text{productive time of loading, cmin.,}$$
$$M_s - \text{biomass per load, kg} \quad (8)$$

Average productive time for scarifying of soil is 89 ± 18 min ha^{-1}. The soil preparation was more time consuming in *Myrtillosa mel.* stand type (106 min ha^{-1}).

Table 6

Productivity of forwarding

Value	Measurement unit	Numeric value
Average speed		
driving empty	km per hour	2.5 ± 0.2
driving loaded	km per hour	2.8 ± 0.2
Average load according to the biomass equations	tons	1.3 ± 0.4
Average unloading time	min load^{-1}	10.1 ± 0.6
Average loading time	min load^{-1}	20.3 ± 1.3
Average time per load, excluding driving	min load^{-1}	30.2 ± 1.3
Productivity		
total excluding driving	tons per hour	2.6 ± 0.8
total excluding driving and unloading	tons per hour	3.9 ± 2.3
unloading	tons per hour	7.9 ± 0.5

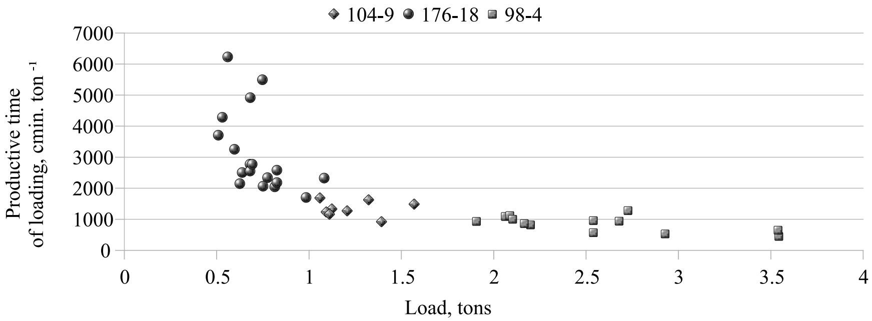

Figure 4. Productivity of loading depending on load size.

Table 7

Summary of prime cost calculation according to biomass equation figures

Position	Excavator	Forwarder	Stump truck	Crusher	Loader	Chip truck	Totals
Costs, thousands Ls year							
Investment	20.7	18.7	20.2	68.7	5.9	20.2	154.4
Staff	45.0	36.0	36.0	29.3	29.3	36.0	211.6
Operating	52.6	44.3	47.7	173.4	35.6	47.7	401.3
Total	118.4	99.0	103.9	271.4	70.7	103.9	767.3
Productivity (conversion factor ton to LV m^3 = 6), LV – loose volume							
LV m^3 per hour	12.50	7.54	18.84	60.00	250.00	25.93	-
LV m^3 yearly	217425	139640	64552	196632	768900	88875	-
Prime cost							
Ls LV m^3	2.35	3.07	1.65	1.42	0.10	1.20	9.78
Total cost, Ls ha^{-1}							1509
Proposed income, Ls ha^{-1} (price of chips assumed 7 Ls LV m^{-3})							1079
Compensation for soil scarification, Ls ha^{-1}							110
Net balance, Ls ha^{-1}							-319

Average productivity of disc trencher in the trials was 89 min ha^{-1}; cost of soil preparation with disc trencher 110 Ls ha^{-1}. Average number of planting spots in area prepared by the trencher was 1352 ± 50 per ha^{-1}, in area prepared by excavator – 1250 ± 72 per ha^{-1}.

According to the study results, prime cost of wood chips from stumps including stump extraction, forwarding, communition and road transport using the biomass equations derived values of harvested stock is 9.78 Ls LV m^3. Net balance according to average market price of wood chips is still negative (Table 7). If biomass is recalculated from forwarder loads obtained in other studies (Lazdinš et al., 2009), prime cost of chips would decrease to 6.38 Ls LV m^{-3}, if soil scarification is not included, thus, making stump extraction feasible.

Conclusions

1. The biomass equations used for calculations might underestimate biomass of stumps; therefore, the productivity figures and costs should be recalculated after comminution of stumps.
2. The experimental trials approved that simultaneous extraction of several stumps increases productivity. Extraction of rotten stumps also took less time – by 17% in comparison to average time consumption. However, it should be considered that biomass of rotten stumps might be smaller.
3. Average consumption of productive time for soil preparation, excluding loading and unloading of the device is 2.8 times less than during preparation of soil with excavator during stump extraction. This means that stump extraction, if directly compared to disc trenching is not feasible, but it might provide better growth conditions for seedlings, which can compensate additional cost.
4. Statistically significant difference between number of planting spots in extracted and control sites was found only in compartment No 176, where operator learned working method; therefore, the

result approves that stump extraction secures at least the same quality of soil preparation as disc trencher meeting national regulations on forest regeneration.
5. Productivity of forwarding per ton is twice less than estimated in other studies showing similar productivity results per load, which again points to necessity to use comminution derived data on produced biomass.
6. Prime cost of stump biofuel production, if biomass equations derived figures of productivity are used, is 9.78 Ls LV m^3; 55% of the cost relies to extraction and forwarding. Hourly cost of forwarder is significantly higher than service cost paid in trials, because old forwarder was used for the experiments and investment cost was not taken into account. The prime cost might significantly reduce after updating of the biomass figures; if expert judgement based values are used, production of chips would cost 6.38 Ls LV m^{-3}

Acknowledgements

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EVALUATION OF FOREST REGENARATION RESULTS AFTER STUMP EXTRACTION IN JOINT STOCK COMPANY 'LATVIAN STATE FORESTS'

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Abstract
With the increase in demand for renewable energy resources, new studies are carried out about under - utilized resources, namely, stumps. To begin to use stumps in industrial application, it is necessary to find out stump extraction influence on the environment, biodiversity, forest regeneration and other important factors. In Zemgale forestry, Misas and Klīves forest districts managed by Joint stock company "Latvian State Forests" (LSF) study on stump extraction in woodlands where clear-cuttings done in 2006 was carried out in the block No. 177, compartments No. 1 and 5, as well as the block No. 176, compartments No. 3 and 9. In these territories two research objects were made where in November-December 2007 stump extraction as well as soil preparation were performed. Main tasks of the project were to evaluate the results of forest natural seeding and coppice ingrowths in natural regeneration areas and evaluate the use of different methods for artificial reforestation with spruce and pine containerized seedlings. It was observed that more seedlings were cut off in the areas where soil scarification with stump extractor was performed if compared to areas prepared with a disc trencher.
Key words: forest regeneration, soil preparation, stump extraction.

Introduction

In Latvia, the use of tree biomass in energy production has two main advantages – resources are renewable and available locally. Forest area in Latvia counts for 3497.08 thousand hectares (+/- 23.53 thousand hectares or 0.67%) and covers 54.14% of Latvia's territory (Jansons, 2009). During the last ten years annual cutting volume of timber resources has been 10 to 12 million m^3 (State Forest Service, 2011). Unused annual potential of stump biomass in Latvia is around 1.3 million tons$_{dry\ mass}$ (Adamovičs et al., 2009).

Extraction of stumps improves soil structure by reducing its density and improving aeration processes, thus making favourable conditions for development of new stands. Removal of rotten spruce stumps from felling area reduces risk of new stand trees infection with root rot (Vasaitis et al., 2008).

In 2007, Joint stock company "Latvia State Forests" (LSF) in clear-cuttings of Zemgale forestry, Misas and Klīves forest districts performed stump extraction and soil preparation for afforestation with a specialized stump extractor bucket. Number of planting spots in extracted area and mineralised lines in control area were made in amount that corresponds to a necessary number of spruce or pine seedlings (Stādīšanas, sēšanas un …, 2011).

All forest stands in these sample plots were clear-cut with a harvester in the autumn 2006. Tree branches in all sample plots were compacted into strip roads, except in the block No. 177, parcel No. 5, where branches were left scattered in the felling area.

The extraction of stumps was done in November – December, 2007, a year after felling. Stump extraction in felled areas must be performed alongside with soil preparation for regeneration of areas where stumps have been removed by natural or artificial reforestation.

Aim: Verify whether it is possible to combine the stump extraction with soil preparation in Latvia weather conditions to prepare necessary number of planting spots to regenerate forest area with the spruce or pine containerized seedlings

Tasks:
1. Divide in rows and mark areas for the research;
2. Perform forest regeneration with the spruce of pine containerized seedlings;
3. Establish and monitor sample plots.

Materials and Methods

The total area of the study plots is 7 ha from which 5.7 ha were regenerated with spruce containerized seedlings and 1.3 ha with pine containerized seedlings.

There are *Hylocomiosa and Myrtillosa* forest growth types in the research areas located in the block No. 177, parcels No. 1 and No. 5; therefore, the parcel No. 1 was afforested with spruce containerized seedlings, but the parcel No. 5 with pine containerized seedlings.

After stump extraction, splitting and putting in piles along strip roads (stump piling along skid trail), with extraction-splitting device, it is possible to make soil scarification in mineralized ridges or small mounds. Stump extraction-splitting device in open position is pressed into soil and then by pulling upper tongue of device mineralized ridge in length of 1 to 2 meters or small mound by overturning turf is made. Stump extracting excavator while standing in one place can reach area from 24 to 28 m^2 (extraction-splitting device maximal reach range is 7 meters). Thus, it can prepare 6 to 8 mineralized ridges or small mounds. It ensures necessary number of beds for planting spruce, pine or any other deciduous tree seedlings in felling area with removed stumps.

Research objects of the project - clear-cuttings with extracted stumps were placed in LSF Zemgale forestry, Misa forest district block No. 177, parcels No. 1 and 5, and for comparison clear-cuttings in Klīve forest district block No.176, parcels No. 3 and 9 were chosen.

In the block No. 177, parcel No. 1 four rows were established: the first row for 'natural regeneration', second row 'planting in rows', third row 'irregular planting' and fourth row 'ridges prepared with scarifier'. In the first row 'natural regeneration' stump extraction alongside soil preparation was done; the row was established at the side of the felling area provided for natural regeneration that borders with full-grown forest with superior stand of spruce ensuring afforestation of this area with natural seeding. In the second row 'planting in rows' stump extraction together with soil preparation was done; along the longest side of the felling area a line was stretched for an employee who will perform regeneration of the row to move along the line and plant spruce containerized seedlings. In the third row 'irregular planting' stump extraction as well as soil preparation was performed; in the row an employee would freely choose places where to plant spruce containerized seedlings. In the fourth row 'ridges prepared with scarifier' stump extraction simultaneously with soil preparation was performed where after that the soil was prepared with a scarifier 'Bracke T21.1'; employee would plant the spruce containerized seedlings in ridges prepared with a scarifier at the bottom of the ridge or on the top, depending on the conditions of the area. In the block No. 177, parcel No. 5 identical rows are established according to aforementioned method, where pine containerized seedlings are used in order to perform row afforestation.

In the block No. 176, parcel No. 9 soil was prepared with a scarifier prior to stump extraction. Reforestation was completed with spruce containerized seedlings planted in ridges prepared with a scarifier.

In the block No. 176, parcel No. 3 soil for afforestation was prepared with a scarifier in the spring 2007 and afforested with spruce containerized samplings planted in ridges prepared with a scarifier.

In all sample plots planting of spruce and pine containerized seedlings was done with a tree planting tool.

Planting material was delivered from the LSF nursery garden.

For further monitoring of seedling development, sample plots were established in spruce and pine afforested areas. In each plot on the longest diagonal four round shaped sample plots were established with the radius of 2.82 meters (25 m^2) (Noteikumi par koku ..., 2009). The number of trees was estimated with a similar method described in Cabinet Regulation No. 892 'Regulation on Tree Felling in Forest Lands'.

Data was processed using Microsoft Excel program Data Analysis, Descriptive Statistics.

Results and Discussion

Results of young forest stand preservation in sample plots (SP) are given in Table 1. Stand inventory results show that total loss of seedlings during the first vegetation period was not significant, especially taking into account a dry summer period from May to August in 2007 (Laika apstākļi gada …, 2007). However, during a young stand weeding process in irregularly planted areas around 600-700 seedlings per hectare was cut down. Here the large number of cut seedlings is related to dense vegetation and irregular planting method which requires additional concentration during weeding operation in order to find every seedling.

When making weeding in the areas where soil preparation was done with a disc trencher and a straight line planting of spruce containerized seedlings was done in ridges prepared with a disc trencher, the number of cut seedlings was 200 per hectare whereas in the areas where soil scarification was performed with a stump extraction-splitting device, the number of cut seedlings was 400 per hectare which could be explained with the fact that during the planting process it was not always possible to find prepared planting place for seedlings right next to the straight line. Therefore, planting here was done more in irregular manner. One can conclude that in irregularly regenerated forest areas where spruce containerized seedlings have not been planted in straight lines, the number of cut seedlings is two times larger and the weeding operation here should be done more carefully. Caution in weeding operation results in decrease of productivity and increase of costs.

After weeding in areas where soil preparation was done with a disc trencher and a straight line planting of pine containerized seedlings was done in the ridges, the number of cut down seedlings was 700 per hectare, but in the areas where soil scarification was performed with a stump extraction-splitting device and pine seedling planted irregularly, the number of cut down seedlings was 700 per hectare. In areas where the soil scarification was performed with a stump extraction-splitting device and the aim was to perform regular planting of pine containerized seedlings, it was not always possible to find a prepared planting place for seedlings right next to the straight line and planting there was done irregularly resulting in 400 cut

Table 1

Survival of seedlings in sample plots

Block and parcel No.	Code of enumerated sample plots	Number of seedlings in 25 m^2 sample plots						
		After planting		Dried and decayed seedlings		Cut down seedlings		Remaining number of seedlings, units per ha
		Number of seedlings, units per ha	Number of seedlings per SP	Number of seedlings, units per ha	Number of seedlings per SP	Number of seedlings, units per ha	Number of seedlings per SP	
Block No. 177, Parcel No. 1	St - E	2600	6.5 ±0.3	200	0.5 ±0.5	400	1 ±0.4	2000
	N - E	1800	4.5 ±0.5	200	0.5 ±0.5	500	1.3 ±0.5	1100
	F – E	2100	5.3 ±0.5	100	0.3 ±0.3	200	0.5 ±0.5	1800
Block No. 177, Parcel No. 5	St – P	3600	9 ±0.6	400	1 ±0.6	900	2.3 ±0.5	2300
	N – P	2600	6.5 ±0.3	-	-	700	1.8 ±1.0	1900
	F – P	3600	9 ±0.6	-	-	700	1.8 ±0.6	2900
Block No. 176, Parcel No. 9	A - F	2500	6.3 ±0.3	100	0.3 ±0.3	500	1.3 ±0.5	1900
Block No. 176, Parcel No. 3	N - F	2700	6.8 ±0.6	400	1 ±0.4	500	1.3 ±0.5	1800

Abbreviations:
St-E – Planting in rows;
N-E – Irregular planting;
F-E – Ridges prepared with a scarifier;
A-F - Ridges prepared with a scarifier, after that stump extraction was done;
N-F - Ridges prepared with a scarifier.

seedlings per hectare during the weeding operation. One can conclude that in irregularly regenerated forest areas where pine containerized seedlings have not been planted in straight lines, the number of cut down seedlings is 29% larger than in regularly planted areas.

It is possible to ensure favourable soil preparation for natural regeneration in sufficient quality as well as prepare necessary number of planting spots for planting forest when the stump extraction is done alongside soil preparation for the forest regeneration (Lazdiņš, 2011). In both areas - testing, and control, pioneer tree species like aspen and birch were more active in natural regeneration, but naturally regenerated pine and spruce seedlings were observed in very small quantities. Faster natural regeneration with aspen and birch matches with forest natural stabilization process, when after felling or destruction of a forest site, pioneer tree species are first to take over the area, forming unstable secondary forest sites (Bisenieks and Gavrilovs, 2006).

Conclusions

1. In Latvia, with the use of stump extraction-splitting device, it is possible to prepare necessary number of planting spots to regenerate forest area with the spruce or pine containerized seedlings.
2. The number of cut down seedlings was by 29% larger in areas where regeneration with a pine containerized seedlings done in straight lines than in areas where it done irregularly.
3. To reduce cut down seedlings during young stand weeding, it is necessary to work out teaching aids for the young stand weeding operation in areas where the soil preparation has been done with a stump extraction-splitting device.

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PRODUCTIVITY OF STUMP LIFTING HEAD MCR-500

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The first studies on stump extraction for bioenergy in Latvia are dated with second half of 19th century. During independence (20ths and 30ths of 20th) century stump extraction was identified as one of the most prospective and challenging tasks of forest sector to secure sustainable deliveries of solid biofuel for households and industry. In that time stump extraction using explosives was considered to be a conventional forestry technology. Now we are facing the same challenges and tasks, the only real difference is more advanced and powerful technologies.

MCR-500 is the first prototype of combined stump extraction and mounding head for caterpillar excavator produced in Latvia by the LSFRI Silava and engineering company Orvi SIA. The device is supposed to be used for extraction of stumps with diameter up to 50 cm in coniferous and deciduous tree stands (Figure 1). The main benefit of the device is ability to prepare soil by making mounds for the following forest regeneration.

Figure 1. Stump lifting head MCR-500.

The MCR-500 head was tested in autumn (2011) in clear-felling sites on fertile mineral soils nearby Riga city. It was mounted on New Holland 215B excavator and operated by professional instructor of forest machines with limited experience on excavators. All extracted sites were regenerated with Norway spruce during next spring. The reference method of soil scarification was disc-trenching completed few weeks after stump extraction. In total 3.5 ha were extracted during the studies. Harvested amount of stumps was estimated using biomass equations; therefore, might be corrected after estimation of the actual biomass weight during comminution studies. Preliminary data from forwarding studies confirms concerns proposed

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in earlier trials, that biomass equations borrowed from Nordic countries considerably underestimates below-ground biomass of stumps.

The figures of productivity were recorded using Allegro field computer with SDI program. Time consumption was accounted separately for a single stump. The height, diameter and specie of all stumps with diameter above 20 cm was determined before the time studies. The working time was split into: (1) turning of tower; (2) driving in stand; (3) reaching a stump; (4) catching; (5) lifting; (6) splitting; (7) shaking and (8) dropping to get rid of soil; (9) scarification – site preparation; (10) other unexpected operations and (11) non-working time elements.

Average calculated stock of extractable biomass (stumps and coarse roots) in the experimental sites was 28 tons ha^{-1} (7.6 % of extracted roundwood expressed in m^3); average extractable biomass of stumps was 73 kg, average diameter – 32 cm. Share of extractable biomass of harvested stumps was 62 % of the biomass of all stumps with diameter above 20 cm.

Productivity of stump extraction was 2.4...3.4 tons per efficient hour (2.5 tons in case of good quality of soil preparation). Productivity of soil scarification was 3.4...4.3 hours per ha. The figures of time consumption for stump extraction per area unit are comparable with others obtained in Latvia; however, calculated output of biomass is considerably smaller. Scarification of soil with stump lifting head consumes twice more time than conventional trenching; however on wet soils productivity figures come closer making excavator competitive.

Average number of prepared mounds was 571 per ha^{-1} (315...1496), total efficient time – 9.5 hours ha^{-1} including 7.6 hours for stump extraction and 1.9 hours for mounding. Productivity was considerably affected by lack of experience of the operator – in the last stand (104-9) scarification took by 73 % more time than at the beginning, but number of produced mounds increased by 162 %. Similarly, productivity of stump extraction in the last stand increased by 20 % in compare to the first stand (Table 1). The quality of scarification increase as well with every stand. If not accounting operations relevant to stump extraction, average time for soil scarification would be 3.4 hours ha^{-1}.

Table 1. Productivity figures recalculated to area units

Object code	Number of extracted stumps, per ha	Extractable biomass, kg ha^{-1}		Number of prepared mounds per ha	Efficient time, hours per ha			
		extracted stumps	all stumps		total	for stump processing	for mounding	for soil prepa-ration
176-18	377	22907	31774	315	9.4	8.3	1.0	3.0
98-4	324	31828	48511	355	10.4	8.5	1.9	3.4
104-9	384	24970	47242	1496	9.8	6.6	3.3	4.3

According to the study time consumption for stump extraction depends from species and diameter of the stump (Figure 2). For birch productivity continuously to grow until stumps reach diameter of approximately 45 cm; then productivity remains relatively constant. For pine the productivity slightly increases until stumps reach approximately 40 cm in diameter. For spruce slight increase in productivity continues even if stumps are more than 60 cm in diameter.

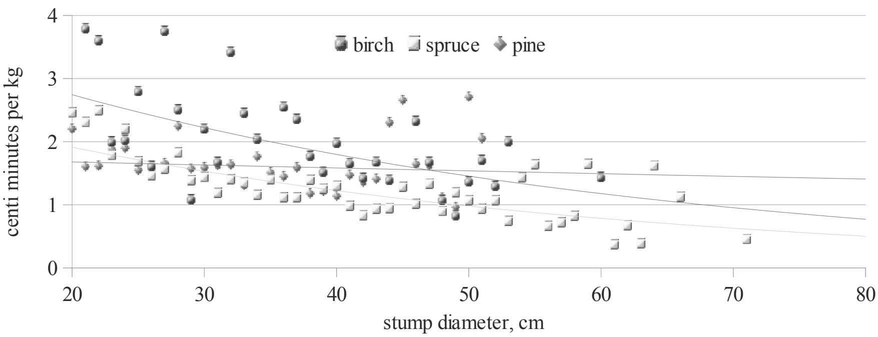

Figure 2. Productivity depending from diameter and species of trees.

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