Vertical force requirement for stump lifting

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ABSTRACT: In harvest areas the soil preparation is occasionally necessary before reforestation including the removal, collection and transportation of stumps from the soil. Issues related to climate change and the shortage of fossil energy sources call for an increased rate of renewable energy sources. Using the stumps removed from the soil as fuel is a significant resource for biomass. For lifting a stump together with its roots a grab mounted on a shovel is generally used. To rationalise this operation, analyses of stump lifting time have been carried out. We tested a machine mounting one grab for stump lifting on three tree types (Scots pine, robinia and poplar) and found functions correlating stump extraction force and stump diameter, which can be used in order to choose the right machine and determine the cost of the operation.

Keywords: bio-energy; stump diameter; stump extraction force; stump extraction machines; stump lifting

As a long-term objective, the European Union aims at 20% of renewable energy sources within the total energy consumption in each member state. The renewable energy utilisation plan of Hungary sets the effective use of potential biomass as an important target. According to certain calculations the total potential biomass production of Hungary is around 350–360 mill. t, the majority of which is based on wood. The utilisation of forestry by-products for energy purposes determines an additional income and, therefore, improves profitability. This action serves also regional political goals, offering development possibilities for underdeveloped regions. The technical and technological development of wood based biomass production may significantly increase the above total potential biomass production. A detailed analysis of the effects of the utilisation of forestry by-products and mechanisation development are important research fields. In the course of reforestation with complete soil preparation, stumps remaining in the soil have to be removed. This is necessary if the forest stands are not renewed in a natural way (e.g. on sandy soil). In Hungary, over the extensive continuous areas of the Broad Hungarian Plain, soil preparation, including stump extraction, is carried out before reforestation. Kiskunság Forestry and Timber Industrial Inc. carries out stump extraction over naturally non-renewable woodlands, on an average area of 700—800 ha per year. For stump extraction machines able to grab and lift the stumps themselves are currently used. This research explores the theoretical background of stump lifting.

MATERIAL AND METHODS

Lifting the stumps left in the soil is one of the most energy demanding forest operations (Laitika et al. 2008; Kärhä, Mutikainen 2009). Szepesi (1966) estimated the force required for stump extraction, based on the weight below the cutting plane, the branching roots and the texture of various soils, as several hundred thousand Newton. Pirkhoffer (1974) carried out measurements in order to determine the stump extraction force, by using machines with a mounted lifting fork, in widespread use at that time. He set up a hydraulic force meter, placed in the winch rope that moves at an angle of 30° to the horizontal plane. His results showed that

Fig. 1. Stump lifting by means of an extraction machine mounting one grab

the extracting force exponentially increased with the increasing stump diameter. This was a consequence of the significant horizontal force component that occurred when the stump was lifted.

However, stump lifting technology applied nowadays significantly differs from the above-mentioned one (Horváth 2003). The force required by the current method has not been investigated yet. No data were found in the literature, concerning the magnitude of the vertical stump extraction force. Measurements were carried out by means of a hydraulic stump grabbing machine for various tree types (Fig. 1). Pressure values for stump lifting were measured and recorded by using a pressure measurement device connected to the hydraulic system of the stump extraction machine. Then, the stump extraction force along a vertical direction was determined based on the geometry and mechanical characteristics of the machine. According to the tests performed a stump extraction machine mounting one grab is able to lift stumps up to 40 cm at the cutting plane. When the stump diameter is larger than 40 cm, several grabs are required for lifting, unless the side roots are cut. During the tests the tree types occurring in the Broad Hungarian Plain (i.e. Scots pine or *Pinus sylvestris*, robinia or *Robinia* spp. and poplar or *Populus* spp.) were surveyed, as the removal of their stumps is very often required. The tests were carried out in sandy soils having 20% averaged field capacity. Soil compaction and moisture content were determined using a 3T System measurement device.

RESULTS AND DISCUSSION

The time elapsed between the lifting of the stumps and the cutting of the trees was approximately constant for all samples (five months), so that this parameter was not indicated as a variable during the tests. The stump diameter at the cutting plane was measured to the nearest 1 cm, while the stump extraction force was determined to the nearest 100 N (Fig. 2).

The stump extraction force was compared with the results obtained by Pirkhoffer (1974), using a machine mounting a lifting fork on Austrian oak, robinia and hornbeam (Fig. 3). Based on Fig. 3 it can be stated that the force required to extract stumps having a diameter larger than 25 cm is significantly lower when the stump extraction is performed by using a grabbing machine instead of a lifting fork. This can be explained by the absence of the so called bowl effect in the soil when the stump is lifted vertically and no horizontal forces occur (Sitkei 2001).

Based on the collected data and measurement results, correlations between stump extraction force

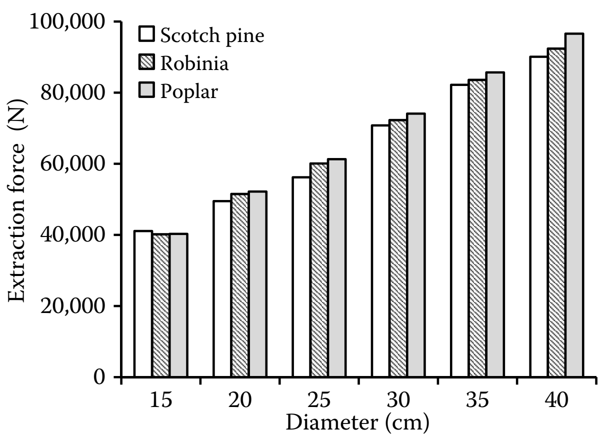

Fig. 2. Stump extraction force as a function of the stump diameter at the cutting plane

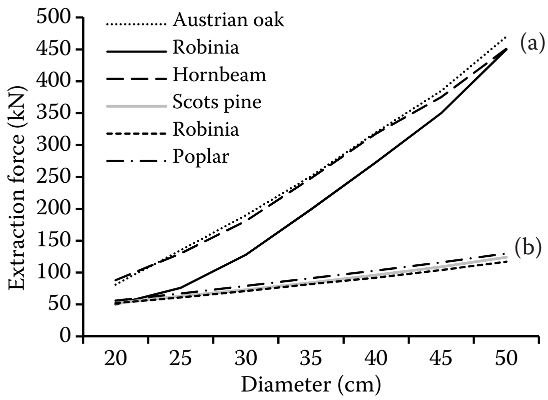

Fig. 3. Comparison of stump extraction force using different machines: (a) mounting a lifting fork, on Austrian oak, robinia and hornbeam and (b) grab-equipped, on Scots pine, robinia and poplar

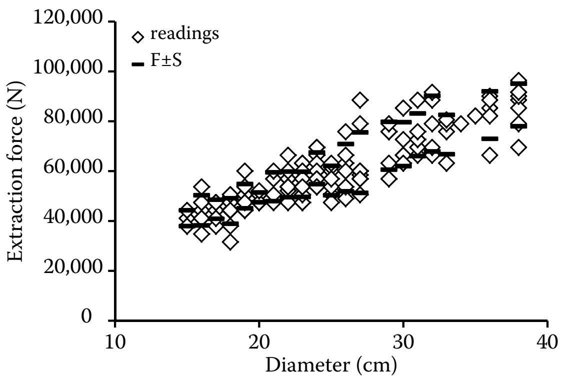

Fig. 4. Measurement results of stump extraction force as a function of the stump diameter

F – measured value; S – standard deviation

and stump diameter were studied. More than 150 data were available for each tree type. However, standard deviation of these data was occasionally high (Fig. 4). For an easier statistical analysis the moving average of 3-3 neighbouring data was calculated. The force necessary to vertically lift tree stumps was determined in three different ways: by calculation; by regression estimate; by averaging the measurement results.

After determining several possible equations, the regression function describing the correlation between the stump extraction force and the stump diameter, based on logical factors [e.g. fulfilment of the clauses that f(0) = 0 and $\lim_{x\to+\infty} f(x) = +\infty$] and statistic ones (unfitting analysis, e.g. *F*-test, reliability analysis), was assumed to be as follows:

$$f(x) = a \times (x^b + e^{cx} - 1) \qquad (1)$$

where:
$f(x)$ – stump extraction force (N),
x – stump diameter (cm),
a, b, c – unknown parameters, to be determined.

Eq. (1) best fits the measurement data if the difference between the squared extraction forces measured and those calculated from the regression function is the smallest (smallest squares principle). Eq. (1) is non-linearisable with two unknown parameters. The equation system composed of normal equations cannot be solved in an exact way, so that the method of continual approaches has to be applied (Czupy, Horváth-Szováti 2005). For example, the method of continual approaches is the iteration procedure performed by the Taylor series expansion. In its course, Eq. (1) is linearly approximated by the Taylor series expansion [the function can be written by a linear approach only if the residue ε in the Taylor series keeps to zero; this is true if the secondary mixed partial derivatives are equal; Eq. (1) fulfils this clause].

First step of iteration: the value of the unknown parameters is estimated: a_0, b_0 and c_0. Then, the $f(x_i,a,b,c)$ function with three variables is solved by the Taylor series expansion around the (x_i, a_0, b_0, c_0) place until the linear members:

$$f(x_i,a,b,c) = f(x_i,a_0,b_0,c_0) + f'_a(x_i,a_0,b_0,c_0) \times (a - a_0) + f'_b(x_i,a_0,b_0,c_0) \times (b - b_0) + f'_c(x_i,a_0,b_0,c_0) \times (c - c_0) + \varepsilon \qquad (2)$$

where:
$x_1, x_2, \dots x_n$ – measured diameters for each tree type,
$i = 1, 2, \dots n$ – stumps for each tree type,
a, b, c – unknown parameters,
a_0, b_0, c_0 – estimated initial values of the unknown parameters,
ε – the residual.

The values of a_0, b_0 and c_0 unknown parameters in the first step are estimated on the basis of measurement data (preliminary estimate).

Restructuring:

$$\hat{y}_{i_0} = f(x_i,a,b,c) - f(x_i,a_0,b_0,c_0) = f'_a(x_i,a_0,b_0,c_0) \times (a - a_0) + f'_b(x_i,a_0,b_0,c_0) \times (b - b_0) + f'_c(x_i,a_0,b_0,c_0) \times (c - c_0) + \varepsilon \qquad (3)$$

where:
$\hat{y}_{i_0}$ – difference vector,
x_i – measured stump diameters for each tree type,
a, b, c – unknown parameters,
a_0, b_0, c_0 – estimated initial values of the unknown parameters,
ε – the residual.

The first term is the y values of the measurement results (therefore force values), the second term is into iteration steps with a_0, b_0 and c_0 parameters calculated function values.

The above formula is placed for the sum of squares applied within the smallest squares principle, and the minimum of the function with three variables obtained in this way is searched. Primary partial derivatives according to *a*, *b* and *c* of the sum of squares to be minimised are made equal to zero (normal equations). The (4)–(6) matrix algebra indications, where index 0 marks the vectors or matrixes related to the starting values of the estimated parameters, are introduced:

$$\bar{y}_i = \begin{bmatrix} \hat{y}_{1_0} \\ \hat{y}_{2_0} \\ \vdots \\ \hat{y}_{n_0} \end{bmatrix}, \quad Z_0 = \begin{bmatrix} f'_a(x_1,a_0,b_0,c_0) & f'_b(x_2,a_0,b_0,c_0) & f'_c(x_3,a_0,b_0,c_0) \\ f'_a(x_2,a_0,b_0,c_0) & f'_b(x_2,a_0,b_0,c_0) & f'_c(x_2,a_0,b_{0,}c_0) \\ \vdots & \vdots & \vdots \\ f'_a(x_n,a_0,b_0,c_0) & f'_b(x_n,a_0,b_0,c_0) & f'_c(x_n,a_0,b_0,c_0) \end{bmatrix}$$

$$\bar{x}_0 = \begin{bmatrix} a - a_0 \\ b - b_0 \\ c - c_0 \end{bmatrix} \qquad (4)\text{–}(6)$$

where: the explanation of symbols see the text above, and at Eqs (2) and (3).

With these the normal equations can be written by matrix Eq. (6) in which Z^T is the transpose of matrix Z.

$$Z_0^T \times \bar{y}_0 = Z_0^T \times Z_0 \times \bar{x}_0 \quad (7)$$

where:
T – the transpose of the matrix,
the other symbols are explained in the text above, and at Eqs (2) and (3).

From this, by multiplying from left by the inverse of the $Z_0^T \times Z_0$ matrix, the difference between the real parameters and the starting values ($\bar{x}_0$) can be estimated as follows:

$$\bar{x}_0 = (Z_0^T \times Z_0)^{-1} \times Z_0^T \times \bar{y}_0 \quad (8)$$

where:
T – the transpose of the matrix,
$^{-1}$ – the exponent indicates the inverse of the matrix,
the other symbols are explained in the text above, and at Eqs (2) and (3).

The inverse matrix can be obtained as described above (see terms of applicability of the linear regression) (Mundruczó 1981). Using the appropriate coordinates of the obtained $\bar{x}_0$ vector, the starting values of the parameters are modified, so that the new refined values of the parameters a_1, b_1 and c_1 are obtained. Second step of iteration: the procedure is repeated using the new starting values (all vectors and matrixes have index 1):

$$\bar{x}_1 = (Z_1^T \times Z_1)^{-1} \times Z_1^T \times \bar{y}_1 \quad (9)$$

where: explanation of symbols see the text above, and at Eqs (7) and (8).

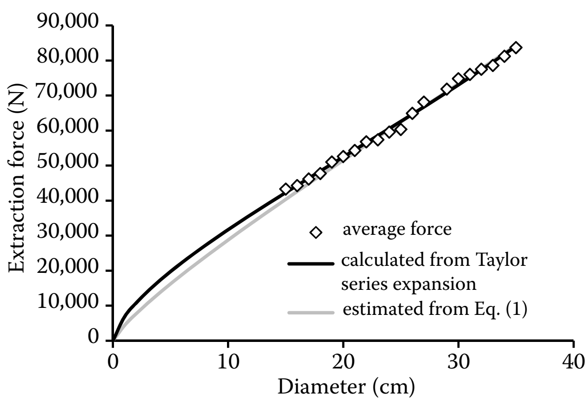

Fig. 5. The estimated and calculated regression curves describing stump extraction force as a function of the stump diameter (calculated, regression estimate and averaged)

Table 1. The initial iteration values used for analysing the parameter values measured for Scots pine

Step	*a*	*b*	*c*
0.	4200.0000	0.8079	0.035000
1.	5964.4973	0.6433	0.050449
2.	6601.4450	0.6293	0.042248
3.	6543.7354	0.6368	0.041236
4.	6541.5993	0.6369	0.041189
5.	6541.6217	0.6369	0.041189
6.	6541.6226	0.6369	0.041189
7.	6541.6226	0.6369	0.041189

step – number of iteration steps; *a*, *b*, *c* – value of the unknown parameters in the current iteration steps

Using the appropriate coordinates of vector $\bar{x}_1$, the starting values of the parameters are modified again. The iteration is continued until the parameters show striking convergence. These results are shown in Fig. 5. The convergence of the method was proved by Hartley (1961).

The MAPLE computer algebra system was applied for analysing 150 data measured for each tree type, due to the complexity of the calculation. The parameter values calculated by iteration are documented in Table 1.

For the three tree types the following functions of stump extraction force – stump diameter were obtained:

Scots pine:

$f(x) = 6541.6226 \times (x^{0.6369} + e^{0.041189x} - 1)$,
$r^2 = 0.9987$; mean standard deviation: 6.317 N.

Robinia:

$f(x) = 62881.8911 \times (x^{0.6526} + e^{0.038167x} - 1)$,
$r^2 = 0.9985$; mean standard deviation: 6.041 N.

Poplar:

$f(x) = 5432.1293 \times (x^{0.7199} + e^{0.038392x} - 1)$,
$r^2 = 0.9978$; mean standard deviation 5.879 N.

where:
$f(x)$ – stump extraction force (N),
x – stump diameter at the cutting plane (cm),
r^2 – correlation coefficient.

Based on the above equations, the vertical force required for extracting the stumps of the surveyed tree types can be determined for diameters from 15 to 40 cm. Based on the method presented in this paper, the correlations between the stump extraction force and the stump diameter can be easily determined for different soil textures or tree types.

CONCLUSION

In the nearest future energy utilisation of stumps extracted in harvest areas is expected to increase in Hungary. According to the test results the force necessary for removing the stumps left in the soil depends on the following factors:

- method of stump extraction,
- tree type (roots),
- stump diameter,
- time elapsed between the lifting of the stump and the cutting of the tree,
- soil texture,
- soil moisture content.

It can be stated that, among various stump extraction methods, the force necessary for the vertical stump lifting is the smallest one. The functions of stump extraction force and stump diameter determined for the surveyed tree types can be applied also elsewhere, in order to choose the appropriate machine and determine the cost of the operation.

References

Czupy I., Horváth-Szováti E. (2005): Experimental definition of the primary force of stump. Hungarian Agricultural Engineering, ***18***: 64–66.

Hartley H.O. (1961): The modified Gauss-Newton method for fitting of non-linear regression functions. Technometrics, ***2***: 269–280.

Horváth B. (ed.) (2003) Erdészeti gépek. [Forestry Machinery.] Budapest, Szaktudás Kiadó Ház Rt.: 417. (in Hungarian)

Kärhä K., Mutikainen A. (2009): Testing two novel stump lifting heads in a final felling norway spruce stand. In: Savolainen M. (ed.): Proceedings of the 4th International Bioenergy Conference and Exhibition. Bioenergy 2009. Jyväskylä, 31. August–4. September 2009. Jyväskylä, The Bioenergy Association of Finland: 441–449.

Laitika J., Ranta T., Asikainen A. (2008): Productivity of stump harvesting for fuel. International Journal of Forest Engineering, ***19***: 37–47.

Mundruczó G. (1981): Alkalmazott regressziószámítás. [Applied Regression Analysis.] Budapest, Akadémiai Kiadó: 258. (in Hungarian)

Pirkhoffer J. (1974): Magyarországon használt tuskókiemelő gépek maximális emelőképessége meghatározásának vizsgálati módszerei. [Examination of the Stump Lifting Machines in Hungary.] [PhD. Thesis.] Sopron, University of West Hungary: 132. (in Hungarian)

Sitkei G .(2001): Mechanika a mezőgazdasági tudományokban. [Mechanics of agricultural sciences.] In: Glatz F. (ed.) Közgyűlési előadások I. [General Assembly lectures I.] Budapest, Hungarian Academy of Science: 501–518. (in Hungarian)

Szepesi L. (1966): Erdőgazdasági gépek jellemzői és használata. [Characteristics of Forest Machinery.] Budapest, Mezőgazdasági Kiadó: 406. (in Hungarian)

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