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SUSTAINABLE SUPPLY OF ENERGY FROM BIOMASS

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The study concerns sustainable supply of primary energy from biomass and considers the interrelation between the amount of energy captured in biomass by photosynthesis and the total land area under perennial species grown for the purpose. The authors analyse available experimental data statistically relevant to natural growths comprising a large number of individual trees of grey alder (*Alnus incana*), a well-known fast-growing species broadly spread in Latvia and for centuries being used as firewood. By graphical approximation of the growth-rate data available for growths up to 50 years of age the optimum age for harvesting dependent on the age at which the maximum growth-rate of biomass is reached is shown to be 18 years confirming traditional popular knowledge. With account for long-term sustainable supply of energy under condition of 18-year rotation, the average yield of energy from highest quality sites of the total land area permanently occupied by alder is calculated to be ca. 85 GJ/ha and the required land equivalent – slightly less than 12 ha per TJ of primary energy from photosynthesis.

1. INTRODUCTION

Awareness of approaching the limits of world reserves of non-renewable fossil resources has triggered discussions of going back to renewable resources to subsist on [1–3] and preparing the transfer of economic activities to limited flows of renewable sources of biomass [4].

Biodiversity, soil, and other assets provided by the biosphere today are supported by photosynthesis transforming and accumulating the energy flow the planet receives from the Sun. The energy abundantly accumulated in fossil fuels and lavishly used by humans has been the price paid for the industrial revolution and economic prosperity reached by industrialised countries. After the energy fossilised during earlier history of the planet is used up, the current insolation transformed into wind, hydropower, and products of photosynthesis will again become the sole resource of energy to support civilization and drive the economy as it used to be during the whole human history until a couple of centuries ago.

Energy from biomass is closely linked to another vital and limited asset – the land. Utilisation of the products of photosynthesis of any kind ultimately is the problem of land-use. Producing bio-fuels from food crops (corn, soy beans, etc.) has already brought up the dilemma of energy competing with food for the yield of cultivated crops and land. Today we speak of second- and third-generation bio-fuels as a more acceptable solution of satisfying the need for energy [2]. Lignocellulosic biomass from forest industries and agricultural residues or by-products is regarded as the most acceptable source for bio-fuels. However, the question of whether the present level of energy consumption from fossil fuels comprising about 10% [5, 6] of the net product of photosynthesis can be satisfied at the expense of burning biomass still requires some attention, especially with regard to land use.

The present study is an attempt to estimate from available experimental data the density of primary energy per unit area accumulated by photosynthesis in biomass. The necessary catchment area per energy unit may serve as a measure of the ecological footprint of using biomass as a source of energy.

2. THE METHOD

The energy content of wood biomass E_b is proportional to stock S of the growth which is a function of time (age) t:

$$E_b = const\ S(t). \tag{1}$$

Usually, the stock is expressed in terms of biomass volume per unit area, in which case the constant can be presented as the product of heat content of biomass E_c expressed as the energy per unit mass and the density of biomass ρ:

$$E_b = E_c \cdot \rho \cdot S(t) \tag{2}$$

and is given as the energy per unit area. The stock expressed through growth- rate (annual increment) $y(t)$, also a function of time, is a function of the upper limit of integration – the age of the growth at time t_o:

$$S(t) = \int_0^{t_o} y(t)\, dt = S(t_o) \tag{3}$$

To satisfy the current demand for the annual amount of energy E from biomass, the area under the growth to be cut at age t_o is equal to the ratio of E to the energy of biomass per unit area E_b:

$$A = \frac{E}{E_b} = \frac{E}{const\ S(t_o)} \sim \frac{1}{S(t_o)} \tag{4}$$

being dependent on the age of the growth. For sustainable supply of the required annual amount of energy that area has to be multiplied by the number of years needed to reach the cutting age of the growth equal to t_o. So the total area under growth is a function of time – the age t_o at which the biomass of the growth is harvested:

$$A(t_o) = const \cdot \frac{t_o}{S(t_o)} = const \cdot f(t_o) \tag{5}$$

Behaviour of function $f(t_o)$ can be used to determine the most suitable age for harvesting the biomass corresponding to the minimum of $A(t_o)$.

Function $f(t_o)$ can be approximated from experimental data on growth-rates of stocks. As an example for calculations we shall apply the data [7] available on presumably natural grey alder (*Alnus incana*) growths up to the age of 50 years. The fast-growing perennial species of grey alder since long has been used for firewood in Latvia.

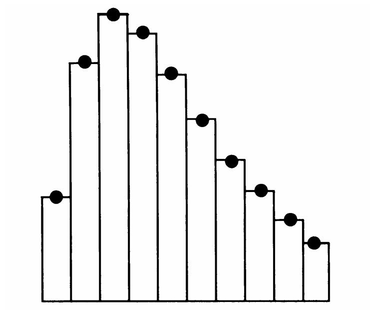

Fig. 1. Dynamics of the 5-year mean growth-rate of alder stock [7] represented in a graph of arbitrary scale. The 5-year mean in further calculations is used as the actual growth-rate at the mid-time of the relevant 5-year period.

The 5-year mean increase in the stock of a first-quality site of grey alder growth [7] is illustrated in Fig. 1. Assuming that 5-year mean growth-rate is very close to the actual growth rate at the age corresponding to middle of the relevant 5-year period shown by solid circles in Fig. 1 a growth-rate function $y(x)$ can be generated. The result of interpolations and approximations is presented in Fig. 2.

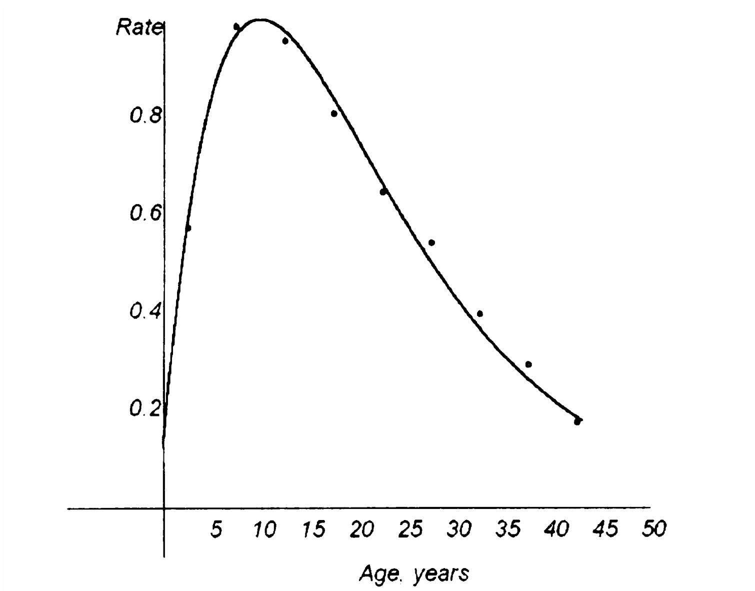

Fig. 2. Graphical representation of the growth rate:
solid line – approximation, circles – experimental data of 5-year mean increase in stock [7] normalised against the growth-rate maximum.

The constructed $y(t)$ curve and the experimental data are normalised against the maximum growth rate. By varying the possible value of the maximum growth rate (not known from the experiment) the correlation between the approximated

$y(t)$ curve and the experimental 5-year mean values was reached to be 0.9965, the age at the growth-rate maximum being taken to be 10 years. The mean difference between the normalised experimental values and approximation $y(t)$ shown in Fig. 3 was found to be close to zero: 0.00039 ± 0.025.

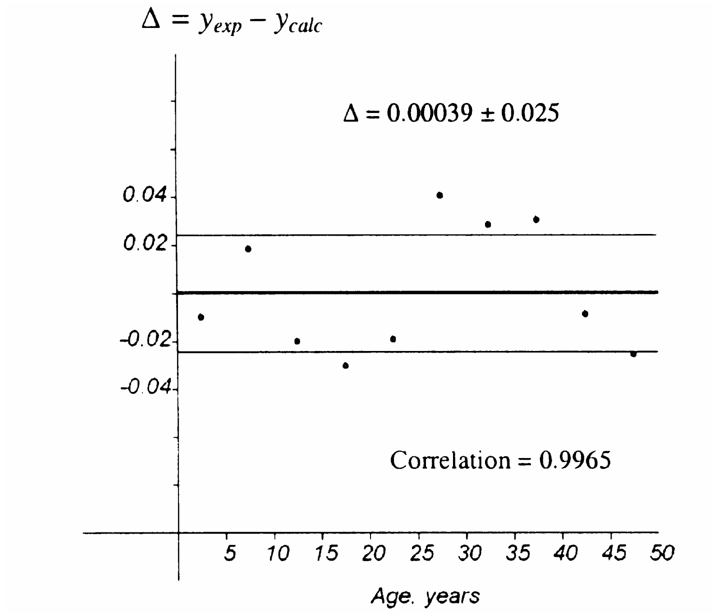

Fig. 3. The mean difference between the experimental 5-year mean growth-rate values and those obtained from the approximated growth-rate curve $y(t)$. The mean difference is ~ 0.04 % ± 2.5 %. The differences are presented by dots, the interval of standard deviation is shown by two horizontal lines (above and below the bold zero line). Correlation between the two sets of values is 99.65 %.

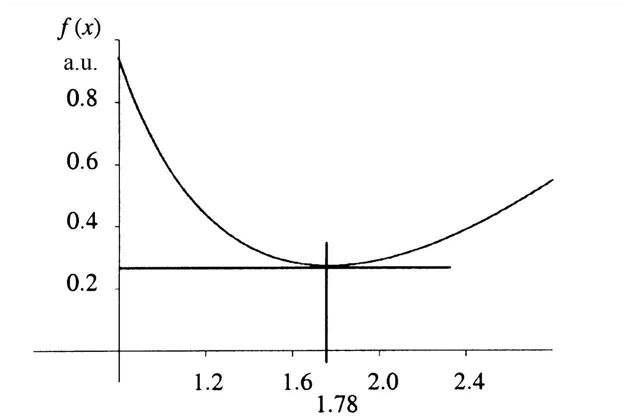

Fig. 4. Behaviour of function $f(x)$ from Eq. (5) around its minimum. Variable x is chosen as the age of the growth normalised against the age at growth-rate maximum (see Fig. 2)

The approximated curve $y(t)$ was further used to construct function $f(x)$ where variable x was chosen as the age of the growth normalised against age t_m – the age of maximum growth rate $y(t_m) = y_{\max}$:

$$x = \frac{t_o}{t_m}\,. \tag{6}$$

Function $f(x)$ shown in Fig. 4 has a shallow minimum around $x = 1.78$ corresponding to the cutting age of 18 years in our case. We have obtained a result consistent with what our grandfathers had learned from their grandfathers that alder must be harvested at the age of 20 years.

3. RESULTS AND DISCUSSION

To calculate the total area of first-quality alder growths necessary for sustainable supply of energy the relevant values of the biomass heat content, density of wood, and stock of an 18-year old grey alder growth should be put in Eq. (2) providing the energy value per unit area of the growth. Taking 15 $MJ\cdot kg^{-1}$ as the mean of the heat content of wood [8] and approximating the density to 500 $kg\cdot m^{-3}$ (which is within the 430–530 $kg\cdot m^{-3}$ limits between absolutely dry and air-dry alder wood [9]) the energy equivalent of the alder stock is 7.5 GJ/m^3.

The average annual increase in stock between the age of 15 and 20 is found from data [7] on 15- and 20-year growths: 226 m^3/ha – 171 m^3/ha = 55 m^3/ha, wherefrom the average growth rate is found to be equal to 11 m^3/ha. Neglecting the slowing of growth rate after it has reached the maximum at the age of 10, the stock of 18-year old growth is calculated to be 204 m^3/ha. Multiplying by the energy equivalent of 7.5 GJ/m^3 we find the energy of an 18-year old grey alder growth at a 1st-quality site being equal to 1530 GJ/ha (or 0.425 GWh/ha).

To provide 2.4 GWh of primary energy − the amount necessary for 1 MW flow during 2400 hours (100 days), the area of alder growth to be cut is found from Eq. (4) as

$$A = \frac{2.4\ \text{GWh}}{0.425\ \text{GWh/ha}} \cong 5.65\ \text{ha}\,. \tag{7}$$

This result can be used further to calculate the cutting area needed to provide 1 GWh (or 1 GJ) of primary energy from wood, i.e. the ecological "footprint" F of using energy from the wood being

$$F = \frac{5.65\ \text{ha}}{2.4\ \text{GWh}} = 2.353\ \text{ha/GWh}\,. \tag{8}$$

The results of further calculations with stocks of 18- and 20-year old growths are presented in Table 1.

As seen from the table, the difference of the energy density and the "footprint" between 18- and 20-year cutting age alder growths does not exceed 1%. It is the area that differs by 11% if rotation period is 20 years instead of 18. The advantage of perennial alder plantations for firewood compared with annually harvested oil crops grown for bio-fuels is obvious – on the average, 1 ha of alder stores 85 GJ of the solar energy accumulated in wood biomass, more than 20 times of the annual oil yield of rapeseed. For that reason, growing hemp and flax is a more rational solution from the point of land use: the same area provides natural fibre and some plant oil for fuel.

Table 1

Densities and footprints of biomass energy from alder and some oil crops

Biomass	Stock	Current supply				Long-term sustainable annual supply			
		density		footprint		density		footprint	
Alder growth at age of	m^3/ha	TJ/ha	GWh/ha	ha/TJ	ha/GWh	GJ/ha	MWh/ha	ha/TJ	ha/GWh
18 years	204	1.530	0.425	0.654	2.35	85.0	23.61	11.76	42.35
20 years	226	1.695	0.471	0.590	2.12	84.75	23.55	11.80	42.46
Energy crops*	l/ha	GJ/ha	kWh/ha	ha/TJ	ha/GWh				
Rapeseed	1190	4.070	1131	246	884	–	–	–	–
Flax	478	1.635	454	612	2203	–	–	–	–
Hemp	363	1.242	345	805	2900	–	–	–	–

* [10]

Sustainable supply of energy from biomass to provide 50 MW at 35% efficiency for a co-firing power plant working 7500 h per year would require growing 46585 ha = 465.85 km^2 of alder.

It should be remembered, however, that quantitative estimates of biomass yields are extremely approximate and good for tentative appraisals of mean values only, since the yield of photosynthesis depends on a variety of factors not taken into account by simple models. For that reason the questions particularly related to the accuracy (either of the data or the method) have not been considered in the present study.

4. CONCLUSIONS

Sustainable annual supply of fuel from biomass requires a definite land area being permanently exploited to grow the species selected for the purpose. The total area to grow perennial species depending on the rotation period is a function of the age at which the maximum rate of growth is reached, for which reason fast-growing species are preferable to minimise the necessary total land area.

Analysis of growth-rate data available for grey alder (*Alnus incana*) growths of 1^{st}-quality sites up to the age of 50 years shows that 18 years is the most appropriate age for harvesting the biomass to be used as the source of energy.

With account for long-term sustainable annual supply of energy the grey alder growths of first-quality sites in Latvia at the cutting age of 18 years might provide primary energy from photosynthesis of the order of 85 GJ/ha averaged over the total area.

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BIOMASA KĀ ILGSPĒJĪGS ATJAUNOJAMĀS ENERĢIJAS NESĒJS

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K o p s a v i l k u m s

Darbā aplūkota ilgstoši nepārtraukta enerģijas apgāde, izmantojot kā primārās enerģijas avotu fotosintēzes produktos (biomasā) uzkrāto starojuma enerģiju un šim nolūkam nepieciešamo platību ar ilggadēju sugu audzēm. Pamatojoties uz LVMI „Silava" publicēto pirmās bonitātes baltalkšņa (*Alnus incana*) audžu krājas pieauguma datu grafiskas aproksimācijas analīzi, autori secina, ka enerģijas iegūšanai audzēto baltalkšņa dabisko audžu optimālais rotācijas periods pie minimālās audzēm nepieciešamās zemes kopplatības ir 18 gadi. Ievērojot primārās enerģijas ilgtermiņa nodrošināšanai nepieciešamo kopplatību pie šāda rotācijas perioda, baltalkšņa pirmās bonitātes audzes vidējais primārās enerģijas blīvums sastāda 85 GJ/ha, bet nepieciešamā kopplatība ir nepilni 12 ha uz TJ. Salīdzinājumā ar rapša eļļas enerģētisko vērtību, baltalksnis ir vairāk kā 20 reizes izdevīgāks, pat neievērojot rapša audzēšanā ieguldāmo enerģiju.

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