FACTORS DETERMINING AND LIMITING SUSTAINABLE MAXIMUM YIELDS OF WOOD BIOMASS.
CASE STUDY OF EVEN-AGE STANDS OF GREY ALDER

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1 Definitions

Sustainability with regard to **cutting** and **burning** forest is considered with concern to **annual yields** of wood biomass and consumption of wood as a **renewable source of energy**.
Sustainable yield is defined as amount of wood biomass from forest *obtainable annually for unlimited span of time*.
Sustainable use of the **energy from forest** implies emissions affecting climate – *neutrality with respect to CO_2* (and other greenhouse gases).
Sustainability of yields is envisaged in a plantation of stands of the same area and sequential age the number of which is equal to cutting age (rotation period).
Results obtained from the employed analytical forest growth model [1] are illustrated by data [2] from field measurements of natural grey alder (*Alnus incana*) stands.

2 The model

Restraints on reasonable harvests of wood imposed by sustainability are considered on the grounds of Richards' equation:

$$S(t) = \left(1 - e^{-bt}\right)^c; \qquad S \text{ – stock, } t \text{ – time, } b \text{ and } c \text{ – constants} \qquad (1)$$

The values of constants b and c are found from rate of growth [1]:

$$\frac{dS}{dt} = \left(1 - e^{-bt}\right) \cdot e^{-bt} \qquad (2)$$

by introducing time x normalised to the time t_m at the maximum of the growth-rate curve:

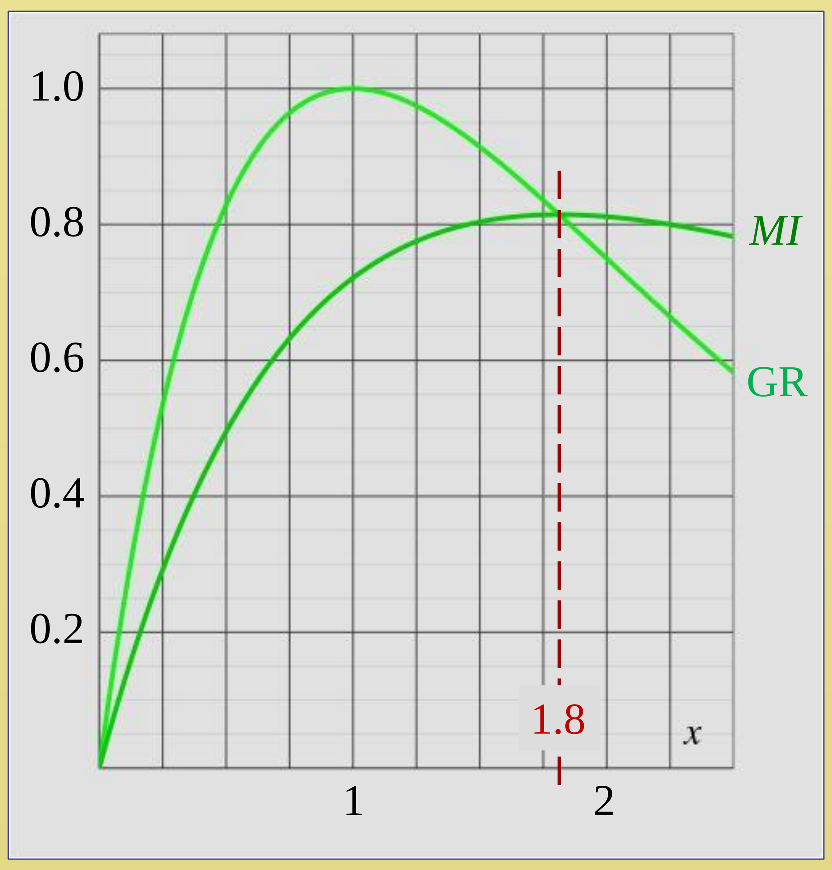
$$x = \frac{t}{t_m}; \qquad x_m = 1 \qquad (3) \qquad\qquad \frac{d^2S}{dt^2}(t_m) = 0 \qquad (4)$$

and rewriting Eq. (1) as integral of Eq (2) in normalised time:

$$S(x) = \left(1 - e^{-bx}\right)^c, \qquad (5)$$

are equal to $b = ln2$, $c = 2$ (Eqs. 2 and 5, Fig. 1).

The mean increment $MI = \frac{S(x_c)}{x_c}$ has maximum at cutting age $x_c \cong 1.8$ providing maximum productivity with respect to time and forest land area cut annually under conditions of sustainable harvesting (Fig. 1).



$$MI = \frac{S(x_c)}{x_c}; \qquad x_c \text{ – cutting age}$$

$$GR = \left(1 - e^{-bx}\right) \cdot e^{-bx}; \quad b = ln2$$

Fig. 1. *Growth rate (**GR**) and mean (annual) increment (**MI**) in normalised coordinates.*

3 Results

3.1 Carbon uptake and CO_2 neutrality
The normalised time interval Δx corresponding to a year of real time is equal to :

$$\Delta x = \frac{1.8x}{t_c}; \qquad t_c \text{ – cutting age (years).} \qquad (6)$$

The increment of stock over the interval Δx_i is found from the rate of growth as

$$\Delta S_i = \frac{dS}{dx}\left(x_i - \frac{\Delta x}{2}\right) \cdot \Delta x, \qquad i = 1, 2, \dots, t_c; \qquad (7)$$

$$\text{Obviously,} \qquad \sum_{i=1}^{i=t_c} = S(t_c); \qquad \sum_{i=1}^{i=t_c} \frac{\Delta S_i}{S(t_c)} = 1 \qquad (8)$$

The addends in the last sum present annual increments as proportions (per cent) of the stock accumulated by cutting age. Proportion of the annual uptake of carbon is the same as proportion of stock. Proportions of biomass and carbon annually accumulated at 18- and 20-year rotations are shown in Fig. 2. As visualised in Fig. 2 and easily grasped from Eq (7), the annual uptake of carbon by a plantation is equal to the amount of carbon accumulated in the harvested biomass and subsequently released at burning. Burning wood sustainably harvested from a plantation is CO_2-neutral.

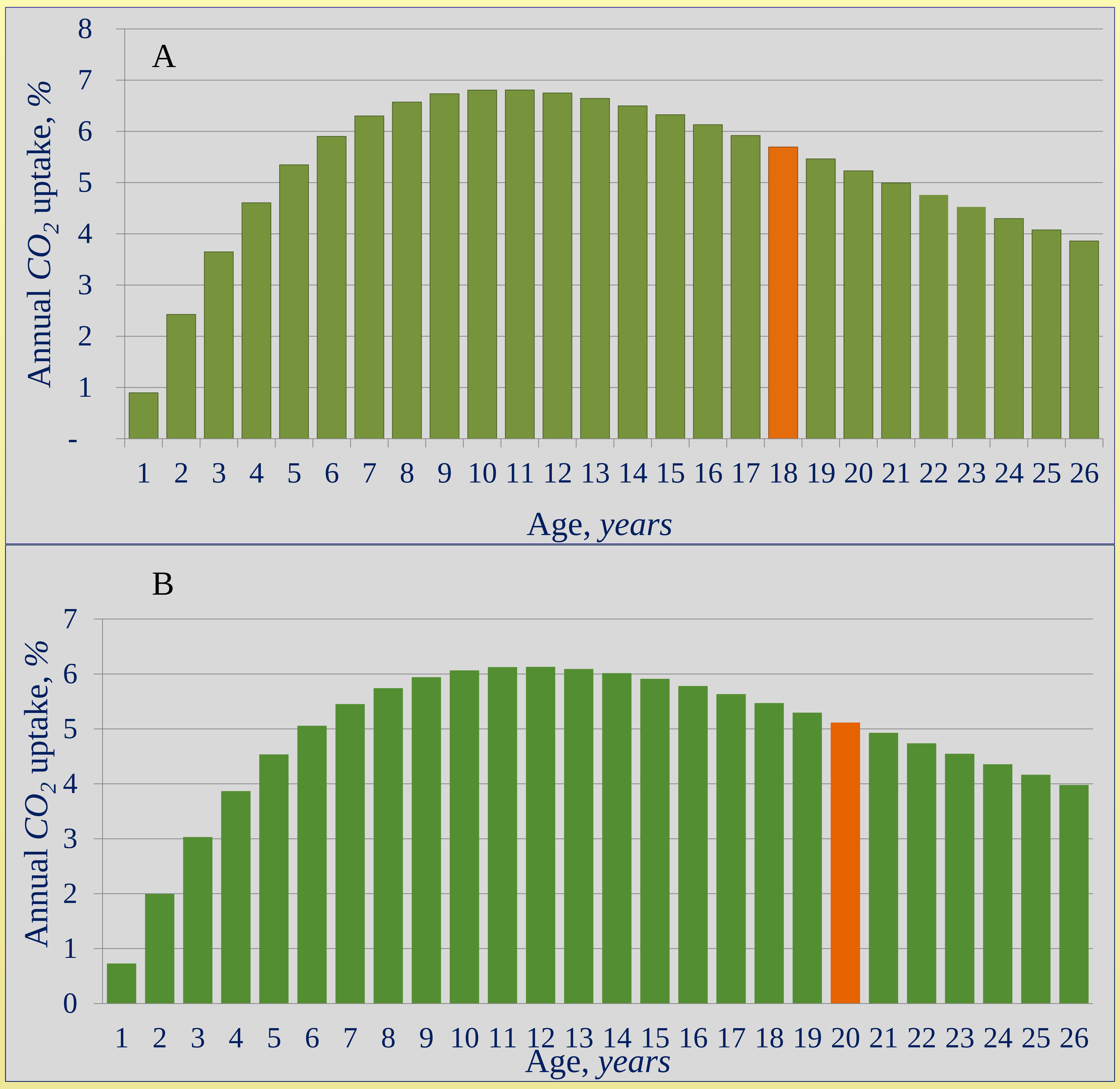


Fig. 2. *Annual CO_2 uptake as function of age, % of the amount of CO_2 stored by unit area stand at optimum rotation of 18 years (**A**) and 20 years (**B**).*

3.2 The Carbon "footprint"
The area of living forest necessary to accumulate released CO_2 can be considered as the "footprint" of burning wood. As follows from Fig. 2, 15 *ha* of growing stands at ages between 9 and 13 years, or 22 ha at the age of 5 years, or an 18-*ha* plantation of 1 to 18 years old stands is required to absorb carbon released at burning the harvest from 1 *ha* of stand at optimum age of 18 years.

3.3 The case of grey alder
Optimum rotation for grey alder is 18 years on high-fertility sites and 20 years on average-fertility sites. Productivity of biomass, energy per unit of annually harvested land area and per unit area of plantation, the area to be cut per *GWh* of primary energy, and the annual carbon uptake by grey alder plantations are summarised in Table 1.

Table 1. Biomass and energy yield from natural grey alder stands, land area per GWh of primary energy, and annual uptake of carbon providing CO_2-neutrality

Optimum rotation	biomass yield		primary energy yield		land-use per *GWh*		annual carbon uptake by plantation, *t*	
	actual	per plantation	actual	per plantation	annual cut	plantation		
years	***m³ ha⁻¹***		***MWh ha⁻¹***		***ha***	***ha***	***total***	***avr. / ha***
18	**200**	**11.1**	**488**	**27.1**	**2.05**	**36.9**	**43.0**	**2.4**
20	**150**	**7.5**	**366**	**18.3**	**2.73**	**54.6**	**32.5**	**1.6**

4 Conclusions

CO_2-neutrality of wood fuel is ensured by sustainably harvested plantations comprising forest stands of sequential ages up to cutting age.

Sustainable yields of wood limited by land area available for growing forest plantations are not compatible with unrestricted consumption of energy from forest.

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