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ORIGINAL PAPER

The influence of forest biomass growth on evaporation intensity and possible regional climate changes

Platon Tretyak✉, Yurij Chernevyy

Precarpathian Professional College of Forestry and Tourism, Zamkova st., 14, Bolekhiv, Ivano-Frankivsk region, Ukraine

ABSTRACT

We investigated the material and energy impacts of forest vegetation on local climate formation in the atmospheric boundary layer. Photosynthesis productivity directly and proportionally determines carbon dioxide absorption from the atmosphere and phytomass increase, including carbon deposition. At the same time, oxygen and transpiration water vapour are emitted directly and proportionally into the ambient air. Phytomass photosynthesis and accompanying transpiration consume a significant amount of energy, leading to cooling of the lower air layer. Quantitatively, these effects are confirmed by the appropriate proportions and calculations of matter and energy transfer between forest vegetation and the lower air layer (0-30 m agl). Calculations show that the forest vegetation of Europe, with annual wood increments 2-7 $m^3 \cdot ha^{-1}$, annually transpires 1.5-8.6 $kt \cdot ha^{-1}$ of water vapour. This process requires annual energy consumption of 1.0-5.9 $GWh \cdot ha^{-1}$ from the environment. As a result, the 30-meter agl air layer can cool by 1-6.3°C. Therefore, deforestation is a significant cause of aridification and warming of the surface air layer. The maximum effect will occur in the case mixed stands with a range of ages, including, among other trees, about 100 elite old-aged trees per ha, for example, *Abies alba* or *Fagus sylvatica* trees 100 years old, as well as *Quercus robur* exceeding 200 years. The annual increment of such stands reaches 6-16 $m^3 \cdot ha^{-1}$. Potentially, they can cool the 30-meter surface air layer by 5-14°C. By increasing the area of forests and their productivity, we can prevent unwanted changes in the regional climate.

KEY WORDS

air cooling, energy consumption, forest climate, change, photosynthesis, phytomass increment, transpiration

Introduction

Hypothetically, modern climate change in the biosphere is generally associated with the greenhouse effect in the atmosphere. It is traditionally explained that the greenhouse effect in the atmosphere occurs due to the reflected radiation absorbed and reflected by water vapour, carbon dioxide, methane, and ozone (Pachauri *et al.*, 2014; Khan, 2017). For 30 years, the world's leading environmental and political paradigm for the cause of climate change has been the Carbon Theory. It asserts that the main cause of global warming and climate change is the increase of anthropogenic carbon dioxide in the atmosphere (Solomon, 2007; Stocker *et al.*, 2013). However, other

✉Tel. +38 067 6626841, e-mail: platon.tretyak@gmail.com

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researchers do not agree that atmospheric CO_2 is a weather or climate driver or that CO_2 atmospheric emission from human activities control them change (Segalstad, 1998; Hertzberg and Schreuder, 2016; IPCC, 2018). At the same time, there is another convincing theory concerning the leading role of water vapour in the air as for greenhouse effect formation (Stephens and Tjemkes, 1993; Maurellis and Tennyson, 2003; Schneider *et al.*, 2010). It is determined, if the water content in the air increases by 10%, it leads to an increase in its temperature by 1.34°C as a result of greenhouse effect. If the water content in the atmosphere decreases by 10%, the air temperature will be reduced by 1.6°C (Rákóczi and Iványi, 1999-2000). Water vapour is the most abundant and powerful greenhouse gas in Earth's atmosphere and is emitted not only as a result of natural processes, but also by human activities. In particular, it is substantiated that in addition to passive evaporation, the intensity of transpiration is especially important for the climate change formation (NACCA, 2011).

Globally, total evaporation accounts for 39% of total precipitation. Approximately 60% of total water evaporation results from transpiration; in tropical forests this share reaches 71% (Schlesinger and Jasechko, 2014), and in humid boreal forests it is 35-47% (Hadiwijaya *et al.*, 2020). Moisture transferred from the forest to the atmosphere forms large clouds that reflect solar energy and cause air cooling (Sanderson *et al.*, 2012). The high cooling capacity of atmospheric moisture and its relationship to forest transpiration are summarized in a review article (Ellison *et al.*, 2017). Therefore, deforestation leads to significant changes in evaporation and in climate water balance on regional and global scales (Gorte and Sheikh, 2010; Lauren, 2017).

The transpiration function of vegetation should be considered as a powerful air conditioner. Transpiration not only enriches the boundary layer of the atmosphere with moisture, but also absorbs a lot of energy for evaporation, which cools the air. Accordingly, the air temperature decrease causes relative humidity to increase (Antoine equation). Unfortunately, this scientific question about the effect of transpiration on air cooling has been little studied and is almost never found in the scientific literature, as evidenced by a literature review (Gupta *et al.*, 2018). This article draws attention to the importance of the statement that the air temperature around trees is changed by transpiration cooling due to the consumption of latent heat of vaporization. Chen *et al.* (2019) first published a method for calculating the cooling effect from tree canopy transpiration, which was determined by measuring sap flow in tree trunks of different diameters.

As yet, the global warming potential of water vapour emissions, and their radiative effects are not formally quantified in the literature (Sherwood *et al.*, 2018). Only the protective functions of water vapour in the atmosphere are well studied, in particular with regard to the absorption of reflected radiation (Vaquero-Martínez *et al.*, 2020). Perhaps, that is why modern climate models (Bonan, 2019; Konapala *et al.*, 2020) of terrestrial ecosystems are imperfect, because they do not take into account the energy aspects of evaporation as a factor in atmospheric cooling. Thus, the biophysical effects of ambient air cooling during the plant growth remain unclear. (Wang *et al.*, 2021). Perhaps this is due to the fact that the models used do not account for the energy absorption effect during evapotranspiration, which cools the air.

The magnitude of evapotranspiration, including transpiration, depends on climatic and soil conditions, as well as on the species of plants (Arkley, 1963; Lewak, 2009). These factors are represented by the transpiration ratio, that is, grams of water used for evapotranspiration to form one gram of dry phytomass. For various plants, the transpiration ratio ranges from 200 to >1000. Examples are: millet – 273, wheat – 507, rye – 724, alfalfa – 859, linden – 1038, beech – 1043, and larch – 1165 (Kowalik and Scalenghe, 2009). Unfortunately, these physiological properties of different tree species are not sufficiently studied, and therefore there are no other summary data.

Evapotranspiration in temperate deciduous forests may exceed the annual rainfall. For example, the temperate humid-continental climate of the mixed forests of Central and Eastern Europe is characterized by an average annual rainfall of 500 to 800 mm. The climatic water balance is negative (from –30 to –120 mm per year). That is, total annual evaporation is from 30 to 120 mm higher than total annual precipitation (Ziernicka-Wojtaszek, 2015). Similarly, research in a forested catchment in Wielkopolska Region found a negative water balance; precipitation was 347-535 mm per year, and evaporation from the pine-oak forest was 616-723 mm per year (Liberacki *et al.*, 2008). Thus, annual totals of evaporation in Poland reach at least 550 mm, and in most cases, they are higher than 600 mm. A similar climatic situation is also typical for the forest plain area of Ukraine. In the Carpathians, the average annual rainfall is 800-1600 mm. However, the annual evaporation amount is less than this value, by approximately 1 mm·day^{-1} (Kołodziej, 2008), or 600-1200 mm·year^{-1}.

The proportion of transpiration in total evapotranspiration can vary. For example, it was previously thought that in Central Europe this may be 300-400 mm·year^{-1} for beech forest, and half that amount for spruce forest (Köstner, 2001). That is, transpiration is approximately 25% to 65% of annual totals of precipitation and potential evapotranspiration. Estimating by proportions is a popular method, which, however, gives very variable results. Modern experimental studies have shown that the sap flow speed and volume depends on the tree species, the tree biometric values, in particular DBH, the crown openness, meteorological conditions. For example, trees standing alone had nearly three times the daily sap flux density of closed canopy trees (Harrison *et al.*, 2020; Ponte *et al.*, 2021).

Thus, it is not yet possible to consider separately the impact of stand transpiration on climate change. However, there are particularly good reasons to study the impact of terrestrial evaporation on global climate (Laguë *et al.*, 2021). This article shows that changes in the intensity of evaporation flows from the terrestrial surface are especially important for the greenhouse effect formation and air cooling or heating. Therefore, in our opinion, the vapour transpiration flows from the forest can significantly affect the overall evaporation power. However, the potential evaporation from forest ecosystems and its impact on air cooling still needs to be studied.

The aim of our study, nearly the first, was to study theoretically the problem of estimating the air cooling effect depending on the productivity of forest stands. The problem concerns the material-energy effects of photosynthesis and transpiration processes on cooling of the boundary atmosphere, which is associated with the forest phytomass increment. Our concept was first published in the article 'Matter and energy influence of forest vegetation on the environment' (Tretiak and Chernevyi, 2020). It assumes that, based on the laws of thermodynamics, for a certain amount of released water vapour, it is possible to calculate the amount of energy consumed and, accordingly, the temperature decrease gradient for a certain volume of air. The transpired moisture total mass can be obtained by multiplying the forest dry phytomass increment by the transpiration ratio. The annual increase in dry phytomass of the forest can be calculated on the basis of the annual growth of the stand.

Methods and materials

We calculate the material and energy balance and the evapotranspiration cooling effect conditionally for a 30 m air layer, which corresponds to the stand height of mean productivity at the age of 100 years (I site class). As shown above, the evaporation annual amount (ET) from the forest plain area in Poland and Ukraine is in most cases greater than 600 mm. That is why this value is conventionally taken as the minimum for the example illustrating the basic method of the cooling air effect calculation (Table 1).

The substance and energy transfer proportions of the photosynthesis overall equations are presented in Table 2. Specifically, for each 1 ton of carbon deposition 3.668 tons of carbon dioxide and 1.5 tons of water were consumed, along with an energy input of 11.042 kWh (E_{ph}). This process produces 2.5 tons of hexose ($C_6H_{12}O_6$) and 2.67 tons of oxygen. The photosynthesis consumption and production indicators were calculated based on these proportions (Tables 3, 6).

The initial data, presented in Table 3, for forest productivity (Z_{st}) in regions of Europe, the European Union, Poland, and Ukraine, were obtained from official sources (Forest Europe, 2015; Raport o stanie lasów…, 2018; Publichnyy…, 2020). Prospective productivity of the Ukrainian Carpathian forests is presented in Table 6. These are our own calculations made on the basis of our research on the structure of natural stands and the growth patterns of older trees

Table 1.

An example illustrating the method of basic calculation of material-energy balance and the obtained cooling effect for the 30 m high air layer

ET – annual total evaporation	600 $mm\cdot yr^{-1}$ or 600 $kg\cdot m^{-2}\cdot yr^{-1}$
L – specific heat of water vaporization at 20°C	2,453 $kj\cdot kg^{-1}$ or 0.681 $kWh\cdot kg^{-1}$
E_{yr}=ET×L – evaporation energy consumption during the year	408.9 $kWh\cdot m^{-2}$
E_h=E_{yr}/8766 – evaporation energy consumption during the hour	46.6 $Wh\cdot m^{-2}$
V – air volume	30 m^3
m – mass of air	38.79 kg
c – the specific heat of air at temperature at 20°C	1.006 $kj\cdot kg^{-1}\cdot K^{-1}$ or 0.279 $Wh\cdot kg^{-1}\cdot K^{-1}$
m×c – the thermal energy required to heat the air by 1°C	10.78 Wh
$\Delta T=E_h/(m\times c)$ – air cooling gradient	4.32°C

Table 2.

Substance and energy proportions of the general equation photosynthesis reaction

$6CO_2$	+	$6H_2O$	+	E_{ph}	=	$C_6H_{12}O_6$	in that C_6	+	$6O_2$
264 g	+	108 g	+	0.795 kWh	=	180 g	72 g	+	192 g
1.467 t	+	0.6 t	+	4,417 kWh	=	1 t	0.4 t	+	1.067 t
3.668 t	+	1.5 t	+	11,041 kWh	=	2.5 t	1.0 t	+	2.668 t

Table 3.

Photosynthesis productivity of European countries and regional forest cover

Forest of region, country	Annual increment		Photosynthesis			
			consumption			products
	Z_{st} [$m^3\cdot ha^{-1}$]	Z_c [$t\cdot ha^{-1}$]	CO_2 [$t\cdot ha^{-1}$]	H_20 [$t\cdot ha^{-1}$]	E_{ph} [$MWh\cdot ha^{-1}$]	O_2 [$t\cdot ha^{-1}$]
North Europe	3.5	2.10	7.70	3.15	23.2	5.60
South-East Europe	2.4	1.44	5.28	2.16	15.9	3.84
South-West Europe	2.2	1.32	4.84	1.98	14.6	3.52
Central and Western Europe	7.2	4.32	15.85	6.48	47.7	11.53
Central and Eastern Europe	4.1	2.46	9.02	3.69	27.2	6.56
EU-28	4.5	2.70	9.90	4.05	29.8	7.20
Poland	5.7	3.43	12.58	5.15	37.9	9.15
Ukraine	3.9	2.34	8.58	3.51	25.8	6.24
Ukrainian Carpathians	5.0	3.00	11.00	4.50	33.1	8.00

Z_{st} – standing forest volume increment, Z_c – deposited carbon volume, E_{ph} – photosynthesis energy consumption

Table 4.

Annual volume of transpiration and total energy consumed by forest cover in European regions and countries

Region, Country	Z_{dr} [t·ha^{-1}]	E_{ph} [MWh·ha^{-1}]	m_{tr} [kt·ha^{-1}]		E_{tr} [MWh·ha^{-1}]		E_v [MWh·ha^{-1}]		E_{aa} [MWh·ha^{-1}]		E_g [MWh·ha^{-1}]	
			A	*M*	*A*	*M*	*A*	*M*	*A*	*M*	*A*	*M*
North Europe	4.20	23.2	2.52	4.20	1,716	2,860	0.21	0.34	0.21	0.34	1,740	2,884
South-East Europe	2.88	15.9	1.73	2.88	1,177	1,961	0.14	0.24	0.14	0.24	1,193	1,977
South-West Europe	2.64	14.6	1.58	2.64	1,079	1,798	0.13	0.22	0.13	0.22	1,094	1,813
Central and Western Europe	8.64	47.7	5.18	8.64	3,530	5,884	0.42	0.71	0.42	0.71	3,579	5,933
Central and Eastern Europe	4.92	27.2	2.95	4.92	2,010	3,351	0.24	0.40	0.24	0.40	2,038	3,379
EU-28	5.40	29.8	3.24	5.40	2,206	3,677	0.27	0.44	0.27	0.44	2,236	3,708
Poland	6.85	37.9	4.11	6.85	2,799	4,665	0.34	0.56	0.34	0.56	2,838	4,704
Ukraine	4.68	25.8	2.81	4.68	1,912	3,187	0.23	0.38	0.23	0.38	1,938	3,214
Ukrainian Carpathians	6.00	33.1	3.60	6.00	2,452	4,086	0.29	0.49	0.29	0.49	2,486	4,120

Z_{dr} – dry substance volume, m_{tr} – annual transpired water volume, E_{tr} – transpiration energy consumption, E_v – vascular upward fluid transport energy, E_{aa} – roots active absorption energy, E_g, – consumed energy total amount or forest increment energy support, A – average value, M – maximum value

(Tretiak and Chernevyy, 2012, 2013; Tretyak and Chernevyy, 2018a,b). In particular, the above-mentioned works present the average potential growth rates of tree trunks in mixed stands containing various species and ages, growing in the Carpathian part of the Dniester River basin. They grew in various mountain altitudinal zones in typical conditions of moist medium rich brown soils (Dystric/Eutric Cambisols). Model calculations were carried out for conditional stands containing 100 large old trees. This is a realistic indicator, since the best forest stands

Table 5.

Expected forest increment energy consumed (E_g) and cooling temperature gradient (ΔT) of the boundary 30 m air layer by forest cover in European regions and countries

Region, Country	E_g [MWh·ha^{-1}·yr^{-1}]		E_g [KWh·m^{-2}·h^{-1}]		ΔT [°C]	
	A	M	A	M	A	M
Northern Europe	1,740	2,884	19.85	32.90	–1.84	–2.97
South-Eastern Europe	1,193	1,977	13.62	22.57	–1.26	–2.09
South-Western Europe	1,094	1,813	12.49	20.70	–1.16	–1.92
Central and Western Europe	3,579	5,933	40.85	67.73	–3.79	–6.28
Central and Eastern Europe	2,038	3,379	23.26	38.57	–2.16	–3.58
EU-28	2,236	3,708	25.53	42.33	–2.37	–3.93
Poland	2,838	4,704	32.39	53.70	–3.00	–4.98
Ukraine	1,938	3,214	22.13	36.69	–2.05	–3.40
Ukrainian Carpathians	2,486	4,120	28.38	47.03	–2.63	–4.36

A – average value, M – maximum value

Table 6.

Perspective productivity and photosynthesis intensity of forests in the Ukrainian Carpathians, which in stands 100 older trees per hectare contain. Annual increment data and localization (Tretyak and Chernevyy, 2018)

Tree species, trees age [years]	Annual increment		Photosynthesis consumption			Photosynthesis product
	Z_{st} [m^3·ha^{-1}]	Z_c [t·ha^{-1}]	CO_2 [t·ha^{-1}]	H_2O [t·ha^{-1}]	E_{ph} [MWh·ha^{-1}]	O_2 [t·ha^{-1}]
Carpathian Foothills						
Abies alba, 100	12.0	7.20	26.41	10.80	79.5	19.21
Abies alba, 140	16.5	9.90	36.31	14.85	109.3	26.41
Fagus sylvatica, 75	5.0	3.00	11.00	4.50	33.1	8.00
Fagus sylvatica, 100	9.0	5.40	19.81	8.10	59.6	14.41
Quercus robur, 100	5.0	3.00	11.00	4.50	33.1	8.00
Quercus robur, 150	5.3	3.18	11.66	4.77	35.1	8.48
Quercus robur, 200	10.5	6.30	23.11	9.45	69.6	16.81
Eastern Beskids mountain zone						
Abies alba, 100	4.0	2.40	8.80	3.60	26.5	6.40
Abies alba, 150	6.0	3.60	13.20	5.40	39.8	9.60
Abies alba, 200	9.0	5.40	19.81	8.10	59.6	14.41
Fagus sylvatica, 100	2.0	1.20	4.40	1.80	13.3	3.20
Fagus sylvatica, 150	3.0	1.80	6.60	2.70	19.9	4.80
Fagus sylvatica, 200	6.0	3.60	13.20	5.40	39.8	9.60

Z_{st} – standing forest volume, Z_c – deposited carbon volume, E_{ph} – photosynthesis energy studied by us have average 699 trees per ha, including more than 20% large trees (H≈28-48 m, DBH≈40-114 cm). These trees form the upper canopy and about 60% of the growing stock. The average total growing stock of such stands is 732 $m^3 \cdot ha^{-1}$ (Chernevyy, 2014).

To calculate the total stand phytomass volume (Z_{ph} – total, including besides trunk wood the volume of branches and stems, bark, and roots, also leaf mass) we used the conversion factor 2. This multiplier is justified in Vasylyshyn *et al.* (2012). To calculate dry mass increase (Z_{dr}) the average density ($kg \cdot m^{-3}$) of dry wood was used (oak – 655, beech – 650, hornbeam – 760, birch – 620, spruce – 420, pine – 480). Therefore, for our calculations we used the average value of dry wood mass of 600 $kg \cdot m^{-3}$. The content of deposited carbon in the dry phytomass (Z_c) in the amount of 50% was applied (Pretzsch, 2009). That is, 2 tons of dry wood contain 1 ton of carbon.

These indicators (values of Z_{st} and Z_c) are shown in Tables 3 and 6. Intermediate values of Z_{ph} and Z_{dr}, are not shown in these tables, because they are calculated taking into account the above constant coefficients: $Z_{ph}=2 \cdot Z_{st}$; $Z_{dr}=0.6 \cdot Z_{ph}$; $Z_c=0.5 \cdot Z_{dr}$.

However, the full energy support of the forest phytomass increase (E_g) can be presented as the sum of at least four components:

$$E_g = E_{ph} + E_{tr} + E_v + E_{aa} \ldots$$

where:

E_{ph} – photosynthesis energy,
E_{tr} – transpiration energy,
E_v – energy of vascular transport of water and minerals,
E_{aa} – active root absorption energy.

Energy costs for transpiration are equal to:

$$E_{tr} = m_{tr} \times L$$

where:

m_{tr} – water transpiration mass,
L – specific vaporization heat at 20°C (2,453 $k_j \cdot kg^{-1}$ or 0.681 $kWh \cdot kg^{-1}$).

$$m_{tr} = Z_{dr} \times k_{tr}$$

where:

Z_{dr} – the dry phytomass increment, k_{tr} – the transpiration coefficient.

Conventionally let's take for ktr the average value 600 $kg \cdot kg^{-1}$, which is equal to the total annual evaporation (physical evaporation and plant transpiration) volume (ET), and the maximum value of 1,000 $kg \cdot kg^{-1}$, which is characteristic of broad-leaved trees (Arkley, 1963; Kowalik and Scalenghe, 2009; Lewak, 2009).

The energy for lifting fluids by transport tissue (root pressure) is equal to:

$$E_{gr} = m_{tr} \times g \times h$$

where:

g – the gravitational acceleration, h – the trees height.

If m_{tr}=1,000 kg, h=30 m and g=9.8 $m \cdot s^{-2}$ then E_{gr}=0.082 kWh energy.

The active root absorption energy (Eaa) is the energy potential of the active process of water and mineral absorption by the roots. It ensures their movement through the root tissues, and also creates the root pressure necessary to raise these substances to the treetops. This requires a significant expenditure of metabolic energy. However, data for this energy value are lacking (Chavarria and Pessoa, 2012). Therefore, we conditionally assume that $E_{aa}=E_{gr}$.

We assume that during the movement of aqueous solutions of minerals in xylem there is an energy loss of 30% in E_g volume. Therefore, we accept that $E_{aa}=1.3\ E_{gr}$.

The corresponding calculations of the energy needs of the stand increments are presented in Tables 4 and 7.

Therefore, in general, energy consumption is proportional to the increase in phytomass (dry substance) and, respectively, to the deposited carbon amount. When calculating energy costs, we use the proportion:

$$1\ \text{MWh}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1} = 0.1\ \text{KWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1} = 0.0114\ \text{Wh}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$$

The cooling effect is calculated for the air layer between the ground surface and 30 m height. This corresponds to the average height of a 100-years-old stand. The calculations were performed in accordance with the proportions presented above. The results are shown in Tables 5 and 8.

Results

The highest average annual increment values are observed in forests in Central and Western Europe, as well as in Poland. These growth increments determine the highest indicators of deposited carbon and produced oxygen (Table 3) and quantity of moisture transpired to the atmosphere, which is almost 7-8.5 kilotons of water per hectare per year (Table 4), equal to 700--850 mm of annual precipitation. Given the maximum energy consumption, the boundary 30-meter layer of air should be cooled by 4.5-5.5°C (Table 5). In other parts of Europe and in Ukraine these indicators are almost 50% lower.

Prospective calculations of model stands, containing 100 old trees, show the available reserves to increase forest productivity, and to generate moisturizing and cooling effects on the surface air layer. The presented materials (Tables 6, 7, 8) show that in the Ukrainian Carpathians the presence of 100 old *Abies alba* Mill. trees per ha can increase oxygen production and moisture transpiration 2-3 times, as well as cool the 30-meter boundary layer air by 5-14°C. Also, older trees of other species can significantly influence the local climate: *Fagus sylvatica* L. and *Quercus robur* L. at the age of 100 and 200 years, respectively.

Ratio of maximum to average indicators of air evaporation and cooling are important. Maximum values are approximately 65% higher than average evaporation rates in the local situation. Accordingly, in the maximum case, air cooling is greater, as well as oxygen supply.

Discussion

The results obtained reflect the fundamental impact of the forest vegetation phytomass increment on surface air layer climate changes. This connection is based on the powerful material and energy exchange caused by photosynthesis and transpiration. In contrast to the greenhouse effect caused by air carbon dioxide, the matter and energy exchange between vegetation and the boundary atmosphere layer has a corresponding quantitative representation. After all, the carbon removal from the air still has no such argumentation. Existing fundamental publications affirm only a certain correlation between the carbon dioxide concentration in the atmosphere and the average air temperature increase above the ground surface (OECD/IEA, 2015).

The results presented in this article can be interpreted from a geo-ecological point of view. Taking into account the above proportions of the values of stand increment and the correspon-

Table 7.

Perspective annual volume of water transpiration and energy consumption as a photosynthesis and transpiration result of the Ukrainian Carpathians forests, which 100 older trees per hectare in stands contain

Tree species, trees age [years]	Z_{dr} [t·ha^{-1}]	E_{ph} [MWh·ha^{-1}]	m_{tr} [kt·ha^{-1}]		E_{tr} [MWh·ha^{-1}]		E_v [MWh·ha^{-1}]		E_{aa} [MWh·ha^{-1}]		E_g [MWh·ha^{-1}]	
			A	*M*	*A*	*M*	*A*	*M*	*A*	*M*	*A*	*M*
Carpathian Foothills												
Abies alba, 100	19.80	109.3	11.88	19.80	8.090	13.484	0.974	1.624	0.974	1.624	8,201	13,597
Abies alba, 140	6.00	33.1	3.60	6.00	2,452	4,086	0.295	0.492	0.295	0.492	2,486	4,120
Fagus sylvatica, 75	10.80	59.6	6.48	10.80	4,413	7,355	0.531	0.886	0.531	0.886	4,474	7,416
Fagus sylvatica, 100	6.00	33.1	3.60	6.00	2,452	4.086	0.295	0.492	0.295	0.492	2,486	4,120
Quercus robur, 100	6.36	35.1	3.82	6.36	2,599	4,331	0.313	0.522	0.313	0.522	2,635	4,367
Quercus robur, 150	12.60	69.6	7.56	12.60	5,148	8,581	0.620	1.033	0.620	1.033	5,219	8,653
Eastern Beskids mountain zone												
Abies alba, 100	4.80	26.5	2.88	4.80	1,961	3,269	0.236	0.394	0.236	0.394	1,988	3,296
Abies alba, 150	7.20	39.8	4.32	7.20	2,942	4,903	0.354	0.590	0.354	0.590	2,982	4,944
Abies alba, 200	10.80	59.6	6.48	10.80	4,413	7,355	0.531	0.886	0.531	0.886	4,474	7,416
Fagus sylvatica, 100	2.40	13.3	1.44	2.40	981	1,634	0.118	0.197	0.118	0.197	994	1,648
Fagus sylvatica, 150	3.60	19.9	2.16	3.60	1,471	2,452	0.177	0.295	0.177	0.295	1,491	2,472
Fagus sylvatica, 200	7.20	39.8	4.32	7.20	2,942	4,903	0.354	0.590	0.354	0.590	2,982	4,944

Z_{dr} – dry substance volume, m_{tr} – annual transpired water volume, E_{tr} – transpiration energy consumption, E_v – vascular upward fluid transport energy, E_{aa} – roots active absorption energy, E_g, – consumed energy total amount or forest increment energy support, *A* – average value, *M* – maximum value

Table 8.
Expected forest increment energy consumed (E_g) and cooling temperature gradient (ΔT) of the boundary 30 m air layer in stands containing 100 older trees per hectare, in the Ukrainian Carpathians

Tree species, trees age [years]	E_g [MWh·ha^{-1}·yr^{-1}] A	E_g [MWh·ha^{-1}·yr^{-1}] M	E_g [KWh·m^{-2}·h^{-1}] A	E_g [KWh·m^{-2}·h^{-1}] M	ΔT [°C] A	ΔT [°C] M
			Carpathian Foothills			
Abies alba, 100	5,965	9,888	68.05	112.82	–6.31	–10.47
Abies alba, 140	8,201	1,3597	93.56	155.14	–8.68	–14.39
Fagus sylvatica, 75	2,486	4,120	28.36	47.00	–2.63	–4.36
Fagus sylvatica, 100	4,474	7,416	51.03	84.65	–4.73	–7.85
Quercus robur, 100	2,486	4,120	28.36	47.00	–2.63	–4.36
Quercus robur, 150	2,635	4,367	30.06	49.85	–2.79	–4.62
Quercus robur, 200	5,219	8,653	59.54	98.68	–5.52	–9.15
			Eastern Beskids mountain zone			
Abies alba, 100	1,988	3,296	22.68	37.65	–2.10	–3.49
Abies alba, 150	2,982	4,944	34.02	56.35	–3.16	–5.23
Abies alba, 200	4,474	7,416	51.03	84.65	–4.73	–7.85
Fagus sylvatica, 100	994	1,648	11.34	18.82	–1.05	–1.75
Fagus sylvatica, 150	1,491	2,472	17.01	28.18	–1.58	–2.61
Fagus sylvatica, 200	2,982	4,944	34.02	56.35	–3.16	–5.23

A – average value, M – maximum value

ding values of material and energy consumption and production, the following can be stated. The forests of Central and Eastern Europe cover 44.5 million ha, or 27.1% of the total land area. Taking into account the indicators of Table 3 (Z_{st}=4.1 m^3·ha^{-1}, Z_c= 2.46 t·ha^{-1}, CO_2=9.02 t·ha^{-1}, O_2=3.52 t·ha^{-1}) we can calculate the following consequences. In general, these forests from the atmosphere annually consume approximately 401 million tons of carbon dioxide and deposit 109 megatons of carbon. At the same time, forests produce 292 megatons of oxygen to the atmosphere. Also, taking into account the indicators of Table 4 (m_{tr}=2.95 and 4.92 kt·ha^{-1}, E_g=2.04 and 3.38 MWh·ha^{-1}) we obtain the following results. In total these forests produce throughout the year 131.28-218.94 Gt of water vapour. For these processes, forests generally consume 90.78-150.4 TWh of energy. As a result, a 30-meter air layer can be cooled by 2.2-3.6°C (Table 5).

It is clear that the atmosphere is an open physical system, and therefore this thermal energy consumption is largely compensated by heat exchange with neighbouring air masses.

Polish forests, which occupy 9.2 million hectares with an annual growing stock increment of 5.7 m^3·ha^{-1}, generate a total of 37.8-63.0 Gt of water vapour and consume 26.1-43.2 TWh of energy. This is 32% of the volume of these indicators in Central and Eastern Europe as a whole. Ukraine's forests occupy 9.6 million hectares and an annual growing stock increment of 3.9 m^3·ha^{-1}. They generate a total of 27.0-44.9 Gt of water vapour and consume 18.6-30.8 TWh of energy. This is 23% of the volume of these indicators in Central and Eastern Europe as a whole. Accordingly, the influence of forests on the cooling of the 30-meter layer of air in these countries differs, in Poland 3-5°C, and in Ukraine 2-3.4°C (Table 5).

It is clear that the influence of forests on the matter and energy balance of the lower air layer has geographical specificity. The lowest values of annual increment of stands are typical for South-West Europe (2.2 m^3·ha^{-1}), South-East Europe (2.4 m^3·ha^{-1}) and North Europe (3.5 m^3·ha^{-1}). These values are much less than the annual growing stock increment in the EU-28 as a whole

(4.5 $m^3 \cdot ha^{-1}$). However, the annual growing stock increment in Central and Western Europe is the largest and reaches 7.2 $m^3 \cdot ha^{-1}$, although the forest cover in this region is only 27.6% (Table 3, 4, 5). Thus, the highest value of forest productivity is probably caused not only by natural factors but is significantly achieved by local forestry actions. Under these circumstances, the ecological role of forests in the formation of gas composition and temperature regime of the boundary air layer on these parts of Europe is particularly significant.

Thus, within the European space forest vegetation productivity has a significant political and geo-ecological significance. Therefore, not only carbon balance, but also indicators of oxygen production and water transpiration and energy consumption should be reflected in the final report about the state of forests in Europe and separate countries.

In contrast to forests, the productivity of transpiration of agricultural vegetation is lower, is about 75-50%. Since the period of active growth of most crops is 60-100 days, their impact on the matter and energy balance in the air is about half that of the forest vegetation. Therefore, the role of the forests in local climate is significant and can be confirmed by mathematically models specific to the forests' areas and their productivity (Tretyak and Chernevyy, 2018; Tretiak and Chernevyi, 2020).

The net annual growing stock increment in the Ukrainian Carpathians is estimated as 5.0 $m^3 \cdot ha^{-1}$ (Publichnyy…, 2020). However, our research has shown that locally the net annual increment of stands can reach even 10-20 $m^3 \cdot ha^{-1}$ (Tretiak and Chernevyy, 2012; Tretiak and Czernevyy, 2013; Tretyak and Czernevyy, 2018; Tretyak and Chernevyy, 2018).

Obviously, it is possible to achieve high values of stand increment by modelling their structure on the basis of the researched analogues. The examples are the old-aged stands growing in the Skole Beskids (Tretyak and Czernevyy, 2018). The research has shown in such mixed (*Abies alba – Picea abies – Fagus sylvatica*) stands, which grow on moist soils of medium fertility, the average growing stock reaches 732 ±205 $m^3 \cdot ha^{-1}$, the basal area is 54.7 ±13 $m^2 \cdot ha^{-1}$, and the number of tree trunks is 699 ±258. The relative number of *Abies alba* trees averages 25.9 ±22.4%, and their relative volume in the stand is only 15.3 ±8.8% (Chernevyy, 2014).

Thus, according to the results of Table 6, it is recommended to double the relative volume of *Abies alba* trees within the stands. This can be done by growing the available number of trees of this species to 150 rather than 100 years old.

Similarly, we recommend that *Quercus robur* be grown on the foothills in mixed stands up to 200 rather than 100 years Under this condition, the annual increment of such stands will increase, in the case of *Abies alba* by 4 $m^3 \cdot ha^{-1}$, and *Quercus robur* by 5 $m^3 \cdot ha^{-1}$. These will double the ecological effect of such stands.

Such highly productive forests grew recently in the Carpathian part of the Dniester River basin. They can be found in our online database (Tretyak *et al.*, 2016). For example, stands of growing stocks in excess of 1,000 $m^3 \cdot ha^{-1}$ grew on 133 plots and together occupied 797 ha. So, if they were natural forests or created by foresters of the 19^{th} and the first half of the 20^{th} century, they can be reproduced. But it will take at least 100 years.

Conclusions

- The forest's phytomass increment is a significant factor influencing the gas composition and air temperature of the boundary air layer. The intensity of photosynthesis determines not only the proportional phytomass increase and the carbon dioxide absorption from the air, but also the concomitant transpiration. These processes consume a lot of thermal energy from the environment. This leads to significant cooling of the air, as well as to its powerful enrichment with oxygen and moisture. This leads to significant air cooling, as well as powerful oxygen and moisture enrichment. These processes have been properly confirmed.

- The annual growing stock increment of 4.1 $m^3 \cdot ha^{-1}$ in forests in Central and Eastern Europe provides not only the deposition of 2.46 $t \cdot ha^{-1}$ of carbon due to photosynthesis, but it is accompanied by moisture transpiration of 35 $kt \cdot ha^{-1}$. This process requires the consumption from 2.0-3.4 $GWh \cdot ha^{-1}$ energy. In total, these forests produce throughout the year 131.28--218.94 Gt of water vapour. For these processes, forests generally consume 90.78-150.4 TWh of energy. As a result, a 30-meter air layer can be cooled by 2.2-3.6°C.
- Increasing transpiration impacts on local climate change is possible in the case of enhanced forest productivity. These can be different-aged mixed forests of varying ages, which, for example, contain 100 *Quercus robur* or *Abies alba* per ha, at 150-200 years old. This will the increase annual growing stock increment by 4-5 $m^3 \cdot ha^{-1}$ and could double the regional forest's average productivity. Accordingly, their impact on the gas composition of the air and its cooling will be twice as large.

Authors' contributions

P.T. – concept development, manuscript planning, data collection, analysis and interpretation, final text editing; Y.Ch. – literary review, analytical procedures, tables construction, draft manuscript preparation.

Conflicts of interest

The authors declare no conflicts of interest regarding the publication of this paper.

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STRESZCZENIE

Wpływ wzrostu biomasy leśnej na intensywność parowania i możliwe zmiany klimatyczne

Przyrost fitomasy lasu jest istotnym czynnikiem wpływającym na skład gazowy nadziemnej warstwy powietrza. Intensywność fotosyntezy determinuje nie tylko proporcjonalny wzrost fitomasy i absorpcję dwutlenku węgla z powietrza, ale wzbogaca nadziemną warstwę powietrza w tlen i wilgoć, głównie dzięki towarzyszącej transpiracji. Intensywne parowanie wymaga pobierania ze środowiska dużej ilości energii cieplnej, co powoduje ochłodzenie otaczającego powietrza. Na tych podstawach pojęciowych i odpowiadającym im prawach fizycznych opracowano metodę obliczeń transferu substancji oraz energii pomiędzy roślinnością leśną a 30-metrową niższą warstwą powietrza (tab. 1, 2).

Do badań wykorzystano oficjalne dane statystyczne o przyroście lasów w regionie europejskim oraz w Polsce i Ukrainie. Modelowanie perspektywiczne przeprowadzono na podstawie wyników własnych badań biometrycznych.

Obliczenia (tab. 3, 4, 5) dowiodły, że roczny przyrost zasobów roślinnych 4,1 $m^3 \cdot ha^{-1}$ w lasach Europy Środkowo-Wschodniej zapewnia nie tylko depozycję 2,46 $t \cdot ha^{-1}$ węgla w wyniku fotosyntezy, ale towarzyszy mu także transpiracja wilgoci w ilości od 3 do 5 tys. $t \cdot ha^{-1}$. Wymaga to zużycia od 2,0 do 3,4 $GWh \cdot ha^{-1}$ energii. W sumie lasy te produkują w ciągu roku od 131,28 do 218,94 Gt pary wodnej. Na te procesy lasy zużywają na ogół od 90,78 do 150,4 TWh energii. Dzięki temu 30-metrową warstwę powietrza można schłodzić o 2,2-3,6°C. W Polsce ten wskaźnik wpływu roślinności leśnej na chłodzenie powietrza powinien wynosić od 3 do 5°C, a w Ukrainie – od 2 do 3,4°C.

Obliczenia perspektywiczne drzewostanów modelowych, składających się ze 100 starych drzew, wykazały dostępne rezerwy dla zwiększenia produktywności lasu oraz działania nawilżającego i chłodzącego na powierzchniową warstwę powietrza. Z przedstawionych materiałów (tab. 6, 7, 8) wynika, że w Karpatach Ukraińskich obecność 100 starych drzew *Abies alba* w drzewostanach na powierzchni 1 ha może zwiększyć produkcję tlenu i transpirację wilgoci 2-3 razy, a 30-metrową warstwę graniczną powietrza schłodzić o 5-14°C. Również starsze drzewa innych gatunków mogą znacząco wpływać na kształtowanie się tutejszego klimatu. Są to *Fagus sylvatica* i *Quercus robur* w wieku 100 i 200 lat.

Zwiększenie wpływu transpiracji na lokalne zmiany klimatu jest możliwe w przypadku wzrostu produktywności lasów. Mogą to być lasy mieszane w różnym wieku, w których na powierzchni 1 ha znajduje się 100 starych drzew *Quercus robur* lub *Abies alba* w wieku 150-200 lat.

Spowoduje to roczny przyrost miąższości drzewostanów o 4-5 $m^3 \cdot ha^{-1}$. Mogłoby to podwoić średnią produktywność lasów w regionie, a ich wpływ na skład gazowy powietrza i jego chłodzenie byłby dwukrotnie większy.