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ENHANCEMENT OF CARBON DIOXIDE SEQUESTRATION BY FOREST

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Abstract
The potential of CO_2 sequestration by forests is characterized. It was shown on the example of Poland that it is possible to increase the CO_2 sequestration by forest through afforestation of poor soils that do not guarantee profitable agricultural production, fertilisation with mineral fertilisers to increase photosynthesis process and by growing catch crops cultivated between the rows of trees. It would allow to increase in Poland the CO_2 sequestration from 26.2 mln t CO_2 yr^{-1} to about 314.4 mln t CO_2 yr^{-1}.

***Keywords**: Climate change mitigation; CO_2 sequestration by forest; Forest fertilization; Intercrops*

Introduction

Energy generation from fossil fuels is responsible for the main part of CO_2 emissions. The global CO_2 emissions from energy related sources were 31.5 $GtCO_2$ yr^{-1} in 2020.

In Poland, forests occupy 9.7 million ha i.e. cover 29.5% of Polish territory [1] and they absorb from 4 to 17 t CO_2 ha^{-1} depending on tree stand age and species [2]. The 100 year old tree stand absorbs from 1288 kg CO_2 in the case of oak to 553 kg CO_2 in the case of pine. On average, Polish forests absorb 3.3 t CO_2 ha^{-1} (from 30 to 35 t CO_2 ha^{-1}) [3, 4].

There are further possibilities to increase the forest area in Poland through afforestation of marginal land (2.3 million ha) and thus increase the CO_2 sequestration by about 20.5 million t CO_2 yr^{-1} [5].

Another possibility to increase the CO_2 sequestration by forests is fertilization of forest soil. It would allow to increase the CO_2 sequestration by forests in Poland for about 8.5% [6-9].

Forest is one of the major ecosystems playing an important role in controlling the CO_2 content in atmosphere. It covers 31% of the Earth's land surface (4.06 billion ha) and absorbs 15.8 Gt CO_2 yr^{-1} (data for 2020) through the photosynthesis process, simultaneously emitting 8.1 $GtCO_2$ yr^{-1} through respiration and dead biomass decomposition processes [10]. It means that the net CO_2 sink was 7.6 Gt CO_2 yr^{-1} in 2020 (24.1% energy related emissions).

There are four reservoirs of carbon in the forest ecosystems: living biomass (44%), dead wood (4%), litter (4%) and soil organic carbon (45%).

The CO_2 absorption in 2020 by Polish forests and as well potential increase by afforestation, fertilization and cultivation of intercrops growing between the trees rows have

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been estimated. It is possible to increase the CO_2 absorption through the techniques presented in this paper.

In recent years, agroforestry has been steadily gaining importance. This is manifested, among others, by the cultivation of intercrops in the rows between trees, which is a popular practice in Indonesia and Thailand. Such intercrop species should be resistant to the lack of light. The biomass of intercrops, subjected to the decomposition processes, constitutes an additional nutrient for forest trees [11-16]. Moreover, intercrops contribute to the increased CO_2 sequestration by forests and "storage" of carbon in soil [17, 18]. Mineral fertilization of forests, which can be combined with the cultivation of intercrops, is also increasingly common. The organic carbon in soils constitutes an important input into the total carbon balance [19-21]. Its total share in soils is estimated at 1500 Gt and is greater than biocenosis reserves.

Taking into account the information above, it was assumed that the cultivation of intercrops (undersown crops) in the rows between trees, as well as mineral fertilization will increase the carbon content in forest soils. It was also assumed that the enhancement of carbon sequestration will be greater in the young forest (10-15 year old), especially in the case of the intercrop biomass, as compared to the old forest (20-25 year old). Due to the large area of agricultural marginal lands and soils of poor quality, it was assumed that the area of forests in Poland can be increased by approximately 20%. This would contribute to a substantial enhancement of the CO_2 sequestration by forests.

This work was aimed at evaluating the current structure of forest areas in Poland and species of forest trees, as well as assessing the scale of CO_2 sequestration by forests. An attempt was also made to analyze the potential increase in the forest area in Poland on the CO_2 sequestration potential by dominant tree species in Polish forests. Moreover, the influence of intercrops (red clover, serradella) sown in younger forests and mineral fertilization of forests with nitrogen and phosphorus on increasing the organic C content in forest soil was studied.

Methods

Determination of the area and type of forests in Poland

The studies on CO_2 sequestration by forests were conducted in 2020 on the example of 50 forests located in the Lublin Province, Poland. The studies were carried out in various age groups of forests. The source documents concerning the total area of forests and individual tree stands in Poland [1] were analyzed as well.

The biomass of merchantable/large timber and smallwood of most important tree species in Polish forests was assessed and a biometric analysis of more important tree species was carried out (percent and weight share of particular tree parts (roots, trunk – below- and above-ground part, branches – thick and thin, needles/leaves).

CO_2 sequestration by forests

The CO_2 sequestration by forest trees was assessed on the basis of the measurement data reported by Gaj [22]. Using the known share of the above-ground biomass in carbon retention, a model for estimating annual CO_2 absorption by forest per 1ha (without accounting for the lower layers of a forest ecosystem), depending on the forest age, was created [23].

The CO_2 sequestration by forests was estimated on the basis of the data from literature studies and own calculations, taking into account the current area of particular tree stands in Poland, as well as the potential CO_2 sequestration by forests with area increased by 20%, i.e. through afforestation of agricultural marginal lands.

Studies on the role of intercrops and mineral fertilization with N and P in increasing the organic C content in forest soils

The experiment was conducted in 2019-2021 on 10-15 and 20-25 year old forests located in Malinowszczyzna (51°30′N; 22°26′E – Lublin Province, Poland). Pine forests grow on sandy soil belonging to the poor rye complex (V soil valuation class). Pine forests were selected for the study, because they are dominant in Poland. At the initial stage of the study, 5×4m (20m^2) research plots were established in three repetitions in the split-plot arrangement. Each plot was fenced off with garden mesh in order to protect the sown intercrops against forest animals.

Four methods of increasing the organic C content in forest soils between rows of trees were distinguished: intercrop sowing – serradella, intercrop sowing – red clover, mineral fertilization with N (100%), mineral fertilization with P (100%), and mineral fertilization with N + P (50% + 50%).

The intercrop seeds were sown on the forest litter, which was cleared of leaves, by means of a manual seeder with a press wheel (seeds were only pressed into the soils and left without a cover). Intercrops were sown in the amount: 14 kg ha^{-1} (serradella) and 16 kg ha^{-1} (red clover) in the third decade of April 2020. In order to accelerate the growth of intercrops, the plots were watered twice (directly after sowing and after 10 days). At the same time (third decade of April), mineral fertilizers were applied on the test plots. Fertilization with nitrogen (N; ammonium nitrate NH_4NO_3) was applied in the amount of 60kg·ha^{-1}. Fertilization with phosphorus (P; granular triple superphosphate $Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$) also amounted to 60kg·ha^{-1}. In the case of mixed fertilization (N + P), the applied amounts were: 30kg·ha^{-1} N + 30kg·ha^{-1} P. The plots on which mineral fertilization was applied were not watered. The intercrop biomass was harvested in the third decade of September and left on the surface between tree rows as mulch, which was subject to gradual mineralization. The effect of intercrop biomass was determined in the spring of 2021 (by collecting the forest soil samples in the second decade of April 2021) by referring to the organic C content in forest soil in 2019, prior to sowing the intercrops and applying N and P mineral fertilizers on test plots. The samples were collected from the soil layer with a depth of 0-20cm using a soil cylinder from the area of 0.20m^2 in three repetitions per plot. The organic C content in soil was determined using a TOC analyzer and expressed in g·kg^{-1} of soil.

Statistical analysis

Analysis of variance (ANOVA) was used to statistically analyze the results by employing Statistica PL 13.3, while Tukey's test was applied to determine HSD (Honest Significant Difference) values at $p < 0.05$. For the resulting data presented in Tables 2, 3 and 4, the following were calculated: SD – standard deviation.

Results and discussion

The shares of particular tree species in the total area of forests in Poland are presented in Table 1.

Table 1. Area of particular tree species in Polish forests [1, 23]

Species	Area (%)
Pine	63.9
Other conifers	9.3
Oak	6.2
Other leafed	20.6
Total	100

The data presented in Table 1 indicate that the pine forests are dominant in Poland (63.9% of total area), much smaller area is covered by deciduous forests (26.8%, including oak – 6.2%) and other conifers (9.3%).

Assuming pine as so-called "model tree" in the conducted studies, it was established that an 80-100 year old pine – growing in soil with average soil valuation class (quality) can reach the height of 24–26m, diameter at breast height (DBH) of 29–34 and thickness of large timber reaching approximately 0.9–1.0m^3. The volume of roots along with the below-ground mass of the stump constitutes 18–25% of the above-ground thickness of a tree. The average share of bark in the thickness of pine trunk amounts to 11-12%, in the case of beech – 5-6%, spruce – 9-10%, and as much as 20-21% for larch. In the case of a pine with DBH of 30–35 cm, the mass of particular tree parts (averaged and simplified) is as follows: mass of fresh needles – 30-35 kg, small twigs – 120-150kg, thick branches – 80-90kg, bark – 76-80kg, roots and below-ground mass of the stump – 150-160kg, trunk (large timber) directly after felling – 730-760kg (at the timber humidity of approximately 90%). This means that the entire model tree has about 1200kg of fresh mass, almost 800kg of which, i.e. 65% is harvested (large timber: trunk and branches), and the remaining 35% of biomass remains in the forest as organic substance decomposed by numerous organisms, mainly fungi. The above-mentioned calculations are comparable to the estimates reported by *Grzywacz* [24]. Table 2 shows the biomass of large and small timber of most important tree species in Polish forests under the conditions of IV and II soil valuation class. The table shows that better soil conditions have a significant effect on biometric parameters (biomass) of all considered forest tree species. In turn, this suggests that fertilization of forests (mineral fertilization with N and P or intercrop mulch) may improve the soil quality in the forests located on soils of lower valuation classes, and indirectly affect the biomass of forest trees. Increased tree biomass will enhance the CO_2 sequestration by forest ecosystems.

Table 2. Large timber and smallwood in 80-100 years old dominant tree stands in Poland (in m^3)** in rich and poor soils

Soil valuation class	Pine	Spruce	Larch	Beech	Oak	Birch
II	365 ±14*	510 ±21	387 ±16	352 ±11	316 ±13	293 ±12
IV	195 ±7	392 ±18	308 ±16	251 ±10	202 ±9	167 ±6
$HSD_{(0.05)}$	42.3	54.2	34.6	31.2	28.9	24.1

**According to yield and volume tables of tree stands [25], *SD – standard deviation

Taking into account the above-ground biomass of the investigated species of trees, the CO_2 sequestration by forests was estimated. The data presented in Table 3 indicate that the greatest amounts of CO_2 (156.9 mln t CO_2 yr^{-1}) are absorbed through the photosynthesis by pine forests, followed by deciduous forests (79.4 mln t CO_2 yr^{-1}) and other conifers (25.7 t CO_2 yr^{-1}). In total, the forests in Poland absorb 262 mln t CO_2 yr^{-1}, while increasing the forest area by 20% by afforestration of marginal lands in Poland would enhance the CO_2 sequestration by trees to approximately 314.4 mln t CO_2 yr^{-1}.

The performed estimations [22] indicate that Polish forests emit about 151 mln t CO_2 yr^{-1} through respiration and decomposition processes of dead biomass. This means that the net CO_2 absorption by Polish forests equals 111 mln t CO_2 yr^{-1}, i.e. 31.3% energy related CO_2 emissions (which was given estimated on 322.63 mln t CO_2 yr^{-1} [26]).

Afforestation of agricultural marginal lands could increase the CO_2 absorption by 20%, i.e. about 52 mln t CO_2 yr^{-1}, which corresponds to net CO_2 absorption of 20 mln t CO_2 yr^{-1}. This would enable to increase the net CO_2 absorption by Polish forests to 121 mln t CO_2 yt^{-1}, i.e. to 37.5% of energy related CO_2 emissions.

Table 3. Current and forecast CO_2 sequestration by Polish forests

Species	Area of forest in 2020 (mln ha)	CO_2 absorption		
		t CO_2 $halyr^{-1}$	mln t CO_2 yr^{-1} *	mln t CO_2 yr^{-1} **
Pine	6.2	25.3 ±7.61***	156.9 ±21.5	188.2 ±25.3
Other conifers	0.9	28.5 ±8.15	25.7 ±6.3	30.7 ±7.6
Oak	0.6	35.4 ±9.64	21.2 ±3.8	25.4 ±4.2
Other leafed	2.0	29.1 ±8.35	58.2 ±9.3	69.8 ±10.8
Total	9.7	118.3 ±28.7	262.0 ±38.6	314.3 ±43.2
$HSD_{(0.05)}$	0.32	3.11	4.12	5.26

*from the total area of forests in Poland; **asssuming the forecasted 20% increase in forest acreage in Poland; ***SD – standard deviation

Cultivation of intercrops and mineral fertilization had a significant influence on the organic C content in soil (Table 4).

Table 4. Carbon content in soil of 10-15 and 20-25 years old pine forests depending on age, type of catch crops and fertilization

Specification	**Carbon content in pine forest soil (g kg^{-1} soil)**			
	Forest 10-15 years old		**Forest 20-25 years old**	
	2019	2021	2019	2021
Intercrop (serradela)	18.5 ±1.6*	32.3 ±3.7	17.7 ±1.4	24.4 ±2.5
Intercrop (red clover)	18.3 ±1.2	31.1 ±3.2	18.2 ±1.2	22.9 ±2.1
Mineral fertilization N	18.5 ±1.3	21.3 ±2.7	17.9 ±1.3	19.7 ±1.9
Mineral fertilization P	18.1 ±1.1	21.7 ±2.6	20.0 ±1.1	18.1 ±1.4
Mineral fertilization N + P	18.6 ±1.4	25.3 ±2.9	21.4 ±1.8	18.0 ±1.3
$HSD_{(0.05)}$	n.s.	3.92	n.s.	1.82

*SD – standard deviation

Compared to the control objects (without intercrops or mineral fertilization, 2019), increased organic C content was observed in forest soil (2021). Especially advantageous (statistically significant) influence on the C content in forest soil was found in the case of serradella cultivation, followed by red clover, and combined mineral fertilization N + P (both in a 10-15 and 20-25 year old forests). Application of individual fertilizers (N or P) also had a significant (but smaller) beneficial effect on increasing the carbon content in soil.

It was found that significantly better effect of intercrops cultivation on the carbon content in forest soil is observed in the case of 10-15 year old forests, compared to older ones. This results from the better access to sunlight in the case of young forests, which affect the intensity of photosynthesis. For instance, mean yield of serradella in a 10-15 year old forest was 0.96 t biomass ha^{-1}, and in a 20-25 year old forest – 0.68 t biomass ha^{-1}. In the case of red clover, the yield of biomass in a 10-15 year old forest was 0.87 t biomass ha^{-1}, whereas in a 20-25 year old forest – 0.59 t biomass ha^{-1}.

In own studies, an attempt was made to assess the influence of forest fertilization (mineral fertilization with N and P) and the fertilizing effect of intercrop biomass (seradella, red clover) on the increased biomass of forest trees. This is pioneering research; no such studies have been conducted in the world so far (there are no scientific publications on this topic). The effect of fertilization and intercrops on the biomass of forest trees will be possible to determine after 3-5 years of studies. The studies conducted thus far over a period of 2 years enabled only to obtain the data pertaining to the influence of these factors on the organic matter (organic C) content in forest soil.

Other studies [27] indicate that a number of nutrients from the biomass of intercrops left on the surface of soil as mulch are gradually mineralized and absorbed by soil. For instance, in intercrop biomass (legume mixture of faba bean + spring vetch), the content of macronutrients amounts to ($g \cdot kg^{-1}$ DM): N = 45.4, P = 4.4, K = 34.6, Ca = 10.0, Mg = 2.4; whereas the content of micronutrients is ($mg \cdot kg^{-1}$ DM): Cu = 7.5, Zn = 84.4, Mn = 132.0, Fe = 506.0).

In the performed studies, the content of macronutrients in serradella biomass was ($g \cdot kg^{-1}$ DM): N = 36.2, P = 3.7, K = 30.1, Ca = 9.2, Mg = 2.0; while the content of micronutrients amounted to (mg kg^{-1} DM): Cu = 6.5, Zn = 79.4, Mn = 118.5, Fe = 487.2. In turn, the content of macronutrients in the biomass of red clover was ($g \cdot kg^{-1}$ DM): N = 35.6, P = 3.4, K = 28.7, Ca = 9.0, Mg = 1.8; whereas the content of micronutrients was ($mg \cdot kg^{-1}$ DM): Cu = 6.2, Zn = 74.7, Mn = 120.1, Fe = 475.3. Therefore, the fertilization effect of the studied intercrops (serradella, red clover) on forest soils was comparable.

Forests in temperate zones constitute another essential ecosystem. They contain 314.9 Gt of carbon. These forests are characterized by high carbon content, ranging from 150 to 320 tonnes of carbon per hectare. The area of forests in North America and Europe constantly increases. Currently, the European temperate forests absorb 7-12% of CO_2 emitted from anthropogenic sources [4, 28].

The world's forests have absorbed as much as 30% (2 petagrams of carbon per year; Pg C yr^{-1}) of annual global anthropogenic CO_2 emissions (8.0 ± 0.8 Pg C yr^{-1}) – about the same amount as the oceans [20, 29].

In the forest environment, carbon is accumulated in living aboveground biomass, dead standing trees, dead lying wood, and in soil organic matter, which consists of humus (endogenous and exogenous), plant roots, and soil organisms. It is an extremely dynamic system that undergoes constant transformations. Globally, forests sequester 1240 Pg of carbon [30]. The amount of carbon accumulated in biomass and soil depends on geographical zone (Table 5).

Table 5. Carbon stock in individual biomes of the world [31]

Biome	Carbon stock (in Pg)		
	Vegetation	**Soil**	**Total**
Tundra	8	97	105
Taiga	88	471	559
Temperate forests	59	100	159
Tropics	212	216	428
Wetlands	6	202	208
Total	373	1086	1459

The average annual carbon sequestration in biomass of European forests over the period 2005-2015 was 719 million tonnes of CO_2 [31]. Forest aboveground carbon stocks in Europe are lowest in its central part and they increase in the south-western and north-eastern directions. The FAO reports that forests can sequester an amount of carbon equivalent to 10% of global carbon dioxide emissions [32].

The greatest amount of CO_2, i.e. 547.8 Gt C, is found in tropical and subtropical forests and peatlands [33, 34, 35, 36]. Out of this amount, 406 Gt C is contained in tropical forests (190 Gt C in plant biomass on the surface and 226 Gt C in soil). Tropical forests are one of the most important terrestrial ecosystems, which absorb approximately net 1.3 Gt C yr^{-1}: 0.6 Gt C yr^{-1} in Central and South America, 0.4 Gt C yr^{-1} in Africa, and 0.25 Gt C yr^{-1} in Asia [37, 38]. One hectare of tropical forests contains 90 to 200 tonnes of carbon [7].

It should be expected that further forestation and appropriate management of forestry may become one of the main CO_2 sequestration mechanisms. The boreal forests in Russia, Alaska, and Scandinavian countries also contain huge amounts of carbon (approximately 384.2 Gt). Due to low temperatures, decomposition of dead biomass in these forests occurs slowly; thus, soil is rich in carbon (116-343 $t \cdot ha^{-1}$). They are an important element of CO_2 sequestration. One should bear in mind that net CO_2 absorption occurs only in young forests. It is suspected that mature forests balance the absorption and emission of CO_2, which means that old forests do not contribute to net CO_2 absorption [7].

Contrary to the common notion that living plant biomass is predominantly responsible for carbon accumulation, a much larger part of carbon accumulated in a forest ecosystem is located in soil. The amount of carbon in soil is dependent on the supply of organic matter to it and on the conditions for organic matter transformations, which affect the intensity of mineralization and humification processes. Environmental conditions (bedrock type, terrain features, and the related air and water regime) and climate conditions (mainly temperature and precipitation levels) determine the above-mentioned factors. Taking into account different land uses, it is estimated that the amount of carbon in soil is 2-3 times greater than its amount in aboveground plant biomass, and this amount can be about 1500 Pg [31].

It is estimated that the carbon stock in the ectohumus horizon can be from 1.3 to 70.8 tonnes of carbon per hectare, while in the 20 cm mineral topsoil layer from 11.3 to 126.3 tonnes of carbon per hectare [39]. These authors also note significant differences in carbon concentration between cultivated and forest soils, indicating the enormous importance of the latter in the accumulation of this element.

The data contained in Table 6 show that the CO_2 absorption rates for Polish forests vary depending on tree stand age and type. The data comparison demonstrates that the CO_2 absorption rate is more favorable in the case of younger forests (about 50-year old) than for 80-100-year old tree stands. When considering CO_2 absorption by specific tree species, we note that oak is characterized by the highest rate, followed by beech and spruce, while the rate is lowest for pine.

Table 6. CO_2 absorption rates for Polish forests on a yearly basis

Type of tree stand	Type of rate	Unit	Rate value	References
80-year old spruce tree stand	Gross	$t \cdot ha^{-1}$	35.0	[40]
100-year old tree stand:	Gross	kg $tree^{-1}$		[8]
- pine			553.2	
- spruce			868.3	
- oak			1287.8	
- beech			899.2	
54-year pine	Net (assimilation minus respiration)	$t \cdot ha^{-1}$	30.0	[41]
Total Polish forests	Net (it includes management of forest products and their decomposition)	$t \cdot ha^{-1}$	3.3	[11]
Total Polish forests	Net	$t \cdot ha^{-1}$	5.9 – 17.0	[2]
Total Polish forests	Net (methodology based on ecosystem carbon balance)	$g \cdot m^{-2}$ $t \cdot ha^{-1}$	117.3 4.0	[12]

However, it should be stressed that pine tree stands are most common in Poland – if the total CO_2 absorption rate for all tree stands is averaged, it is this species that largely determines the value of the carbon dioxide assimilation rate. A study by Chojnicki [41] reveals that a 54-year old pine tree stand absorbs about 30 tonnes CO_2 $ha^{-1} \cdot yr^{-1}$, taking into account net assimilation (assimilation minus respiration).

The average net absorption of Polish forests is estimated to be between 4 and 17t CO_2 $ha^{-1} \cdot yr^{-1}$. Such large variance in the data arises from the adoption of different methodologies for calculating the carbon balance in forest ecosystems as well as from variations in tree stand age and species [2, 12].

In Poland, the total pool of carbon in pine forests, which are the most common, is $148 t \cdot ha^{-1}$ [41], out of which 91t is attributed to phytomass, while carbon accumulated in soil amounts to 57t. A carbon balance assessment shows that 1.3t C ha^{-1} per year is sequestered by an ecosystem in dendromass and mineral soil, which accounts for 13% of gross primary production. This means that a large majority of carbon dioxide taken up by a forest from the atmosphere is returned to it during respiration processes. In natural tropical forests, the value of carbon pool is substantially higher and $200\text{-}250 t \cdot ha^{-1}$ [42].

According to the most recent data, scientists estimate that 1 ha of pine forest (the most popular forest in Poland) is able to absorb about 20-30t of CO_2 yr^{-1}. Research reveals that a young forest of the same species can emit more CO_2 than it can absorb, while an over 50-year old forest absorbs the most CO_2. In Poland, there are more than 2 million hectares of poor soils that do not guarantee profitable agricultural production and they would be ideally suitable for planting trees in order to balance CO_2 emissions [1, 8].

As demonstrated in an inventory report prepared by the National Centre for Emissions Management [8], in 2013 forestry in Poland was the largest net absorber of CO_2 (41, 421 and 753t CO_2) among the land use categories distinguished in the LULUCF sector, while the other absorbers – cropland and grassland, contributed to the removal of carbon dioxide from the atmosphere to a much lesser extent, respectively 435,678 and 348,425t CO_2. Taking into account the surface areas of the individual land use categories, it proves that the absorption of carbon dioxide by Polish forests, expressed on a unit area basis, is highest compared to other categories of land use, and reaches nearly 4.5t·ha^{-1} (Table 7).

Table 7. Carbon dioxide emissions and absorption levels in Poland by land use category [8]

Land use category	Emissions / absorption t CO_2 yr^{-1}	Area ha	Absorption / unit emissions t CO_2 ha^{-1} yr^{-1}
Forests	- 41,421,753	9,369,403	- 4.42
Cropland	- 435,678	14,103,689	- 0.03
Grassland	- 348,425	4,162,123	- 0.08
Wetlands	4,316,309	1,370,864	3.15
Settlements	262,232	2,163,440	0.12

The sign "-" means CO_2 absorption

During the current emissions trading period, which covers the years 2013-2020, the forestry sector is accounted for based on emission and absorption volumes calculated according to the IPCC methodology [43]. Emissions and absorption of greenhouse gases generated as a result of afforestation, reforestation, and deforestation are accounted for separately, while those that are generated as a result of forest management are also calculated separately.

The CO_2 sequestration by terrestrial ecosystems is an essential, albeit not fully utilized method of mitigating the CO_2 emissions to the atmosphere. It would make sense to perform an in-depth analysis of the existing and prospective possibilities of CO_2 sequestration by terrestrial ecosystems in Poland. One of possible ways to increase CO_2 sequestration by forests is their fertilization. It would allow for a further reduction of anthropogenic CO_2 emissions in Poland by additional 8.5% [6, 7].

It is estimated that temperate and boreal forests are a net carbon absorber at a level of about 0.7 ± 0.2 Pg·yr^{-1}. This means that they have already compensated for a part of fossil fuel emissions. On average, temperate and boreal forests are composed of relatively young tree stands with quite high growth rates (and hence high carbon dioxide sequestration rates).
Nevertheless, there is a specific time during which net carbon absorption can occur and after that forests reach a steady-state level [38]. Some scientists think that the current carbon dioxide absorber in European forests may disappear within 50 to 100 years and even suggest that forests may need hundreds of years to reach a constant level of carbon in all their components, including soil [23, 34, 37, 44].

The potential future role of forests – the major objectives for managing forest lands generally include the following: industrial wood production, fuelwood production, production of non-wood forest products, protection of natural resources (e.g. biological diversity, water and soil), wildlife management, recreation, rehabilitation of degraded lands, and the like. Carbon conservation and sequestration resulting from forest management and the pursuit of the above-mentioned objectives will be an added benefit because these activities reduce the atmospheric concentrations of CO_2 and thus mitigate climate change. Forest management practices for mitigating climate change can be grouped into three categories: management for carbon conservation, carbon storage, and carbon substitution [44-46].

Conclusions

Forests can contribute to the mitigation of climate change through their impact on the global carbon cycle. They store 1.15×10^3Gt C (equivalent to 4.22×10^3Gt CO_2). Annually, the world forest absorbs through photosynthesis about 16 Gt CO_2 and emits through respiration and decomposition of dead biomass 8.1Gt CO_2. Net global annual CO_2 absorption by forest is 7.9Gt CO_2 yr^{-1}.

Polish forests absorb 262mln t CO_2 yr^{-1} in the photosynthesis process as well as emit 151mln t CO_2 yr^{-1} in the respiration processes and decomposition of dead matter. Therefore, net absorption equals 111mln t CO_2 yr^{-1}. This means that the forests in Poland neutralize ca. 34% of the energy related CO_2 emissions.

The conducted studies show that it is possible to increase the CO_2 absorption by forests by 20% through afforestation. Cultivation of intercrops and mineral fertilization may significantly increase the CO_2 absorption by forests.

The performed research indicates that it is possible to increase the area of forests in Poland. Afforestation with pine (which is tolerant even to poor soils) has the greatest potential. Forests constitute one of the main means for global warming mitigation. Assuming that the area of Polish forests is increased by 20%, the annual CO_2 absorption by forests can be estimated at over 314mln t yr^{-1}. There is a potential in the cultivation of intercrops (however, mainly in young, 10-15 year old forests) and mineral fertilization of forests with nitrogen and phosphorus – which contributes to increased organic carbon content in forests soils, and in the long term, increased biomass of trees and enhanced total CO_2 sequestration by forests. These studies should be further continued in order to confirm the initial results pertaining to the role of intercrops and fertilization in improving the carbon balance in forest soils.

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