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POSSIBILITY OF CARBON DIOXIDE SEQUESTRATION BY CATCH CROPS

MOŻLIWOŚĆ SEKWESTRACJI DITLENKU WĘGLA PRZEZ MIĘDZYPLONY

Abstract: The global fluxes of carbon in the ecosystem of Earth, with particular attention drawn to the cycle of CO_2 were characterised. The sequestration of carbon dioxide in the biomass of plants, especially the ones which can be cultivated as catch crops is described. It was shown that the cultivation of catch crops may play an important role in the mitigation of CO_2 emissions.

Keywords: mitigation of carbon dioxide emissions, climate change, absorption of carbon dioxide by catch crops

Introduction

According to the reports by Intergovernmental Panel for Climate Change [1-3], the emission of greenhouse gases causes a climate change with negative consequences for earth ecosystems.

One of the reasons is the growing emission of CO_2 produced during the combustion of fossil fuels and cement production, which has been on increase since the Industrial Revolution that started in 1769 with the modernization of a steam engine by James Watt, originally built in 1712 by Thomas Newcomen. The second ground-breaking invention was the replacement of charcoal used in metallurgy by coke in 1735 [4]. Since than the intense consumption of fossil fuels has been observed, resulting in a growing emission of CO_2 from their combustion. Until 1760, the global emission of CO_2 amounted to 11 Tg CO_2/yr (0.011 Gt CO_2/yr). Since then, the emission of CO_2 from anthropogenic sources started to increase. An especially dramatic growth in the CO_2 emission occurred after 1956, reaching the value of 36.8 Pg CO_2/yr in 2017 (see Table 1).

Simultaneously, changes in land use, mainly caused by deforestation, also contributed to the growth of CO_2 emission (Table 1).

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Table 1

Global CO_2 emission from anthropogenic sources [5]

Year	Industrial emissions [Pg CO_2/yr]	Land use change emissions [Pg CO_2/yr]
before 1760	0.011	-
1880	0.28	-
1956	7.98	-
1960-1969	11.37	5.50
1970-1979	17.23	4.77
1980-1989	20.17	5.13
1990-1999	23.47	5.87
2000-2009	28.60	3.67
2005-2014	33.00	3.3
2014	35.93	4.03
2015	36.30	4.77
2016	36.20	4.77
2017	36.8	-

An increase in the CO_2 emission to the atmosphere led to its increased concentration in atmosphere from 280 ppm prior to the Industrial Revolution to 313.7 ppm in the critical year 1956; since then, its concentration grew rapidly reaching 404.0 ppm in 2017 (see Table 2). According to IPCC reports [1-3], such high increase in the atmospheric CO_2 concentration leads to the warming of the climate, which causes serious disruption in the earth ecosystems.

Table 2

Concentration of CO_2 in atmosphere [6, 7]

Year	CO_2 [ppm]
before 1780	< 280.0
1860	286.0
1890	292.0
1930	307.1
1950	312.0
1956	313.7
1966	320.6
1976	331.2
1986	345.7
1996	362.6
2006	381.9
2016	404.2
2017	406.6
2018	408.5

In order to prevent the adverse climate changes, actions are taken to mitigate the CO_2 emission to prevent a rise in temperature by more than 1.5 °C [8]. One of the directions is reduction of the combustion of fossil fuels and reduction of CO_2 emission by technical solutions [9, 10] on the one hand, and sequestering CO_2 on the other [11].

Two major fluxes should be distinguished in the global CO_2 cycle within the Earth ecosystem:

- absorption of CO_2 by terrestrial ecosystems in the photosynthesis process, which equals 450 Pg CO_2/yr. Simultaneously, respiration of plant and soil organisms and fires emit 435 Pg CO_2/yr into the atmosphere [2];
- absorption of CO_2 by surface waters, mostly oceans, which amounts to 293 Pg CO_2/yr. Simultaneously, 284 Pg CO_2/yr is emitted into the atmosphere as a result of degassing.

These systems are responsible for the removal of a certain amount of CO_2 from the atmosphere.

The greatest possibilities of removing CO_2 from the atmosphere are connected with an appropriate control of the CO_2 exchange between the atmosphere and terrestrial ecosystems. For instance, it would be sufficient to increase the absorption of CO_2 in the photosynthesis processes by 8.2 % to completely mitigate the emission from the combustion of fossil fuels and cement production processes.

Taking into account the current trends of development, reduction the CO_2 emission is not easy. It is inextricably connected with the supply of energy, which drives the development of our civilization [12]. Therefore, it is necessary to seek more efficient CO_2 sinks. The natural ones include the absorption in ocean waters and terrestrial absorption in biomass and geological strata. It was observed that the net amount of the CO_2 absorbed in oceans increased from 3.7 Pg CO_2/yr in 1960-1969 to 9.5 Pg CO_2/yr in 2016 [5]. However, it is predicted that the share of this sink will decrease with time, as a result of ocean water acidification. The studies carried out by Le Quere et al. [5] shows that starting from the 1960s, the share of another important sink, i.e. net absorption of CO_2 by plants, is on the increase. It grows from 5.1 Pg CO_2/yr in 1960-69 to 11.0 Pg CO_2/yr in 2007-2016, reaching 8.9 Pg CO_2/yr in 1970-1979, 9.2 Pg CO_2/yr in 1990-1999 and 10.6 Pg CO_2/yr in 2000-2009. In 2016, its value reached at 9.9 Pg CO_2/yr, which was lower than the average from the previous decade.

There are further possibilities of enhancing the CO_2 sequestration, both by terrestrial, as well as aquatic ecosystems. In the case of the terrestrial ecosystems, the greatest possibilities of enhancing sequestration lie in increasing the absorption of carbon dioxide by plants in the photosynthesis process and mitigating the emission of CO_2 from soil, by slowing down the oxidation of organic compounds in soils, e.g. by applying no tillage practice.

It is predicted that the increased CO_2 content in ocean water will lead to its acidification and result in a decreased CO_2 dissolution. Within the period from 1751 to 1994, the pH of ocean water dropped from 8.24 to 8.14 [13]. A decrease in the pH of ocean water negatively influences the ocean ecosystem, among others negative impact on coral reefs. Attempts are made to mitigate this phenomenon by enhancing the absorption of CO_2 by algae in the photosynthesis process, carried out by fertilization of ocean waters with Fe ions. Intensification of algae growth enhances the absorption of CO_2 by ocean waters and has a beneficial effect on fishing [14].

Mitigation of climate changes by enhanced CO_2 absorption in biomass

Despite the negative changes connected with the accumulation of CO_2 in the atmosphere, positive effects of increased CO_2 concentration in the atmosphere, leading to increased biomass production, are observed as well. Many years of research conducted on various species of photosynthesizing organisms indicate that the increased CO_2 concentration in the atmosphere intensifies the photosynthesis process [15, 16]. A 10 %

increase of mean relative growth rate of seedlings of *Betula pubescens* in the 35-day greenhouse experiment, followed up by the increase of CO_2 concentration in the atmospheric air from 350 to 560 μmol mol^{-1}, was observed by Mortensen [15]. Increased biomass production in the atmosphere containing 700 μmol mol^{-1} of CO_2 was also observed in the case of grasses (*Lolium perenne*, *Cynosurus cristatus*, *Holcus lanatus* and *Agrostis capillaris*) in an 8-month experiment with the open-top chamber [15]. Moreover, the researchers stated that the particular grass species varied in their response to elevated CO_2, not only in terms of biomass growth but also in species composition. Significant influence of elevated CO_2 concentration was observed by Wang et al. [17] also in the case of rice. They stated that CO_2 concertation in the range of 600-699 ppm enhanced the rice yield by 20 % as compared to atmospheric conditions. According to Leakey [18] direct enhancement of photosynthesis by elevated CO_2 concentration in the atmosphere is evident for the crops with C_3 photosynthetic pathway. In the case of the crops with C_4 pathway (mainly grasses and sedges), the direct stimulation of their growth by high CO_2 concentration was not observed. However, such conditions positively influence the plant growth in the case of drought stress that was as a result of lower stomatal conductance and greater amount of intercellular CO_2. Thus, C_4 crops can only be benefited by elevated CO_2 in the periods or the places with drought stress.

Intensification of biomass growth under the influence of increased CO_2 concentration in the atmosphere can be considered as a factor contributing to the mitigation of climate changes. However, it should be remembered that not all plants react the same to an elevated concentration of CO_2, and the growth of plants is dependent not only on the availability of CO_2, but also a range of other factors, such as the content of N, P, K and other biogenic elements, as well as the access to water. If a single factor is at an inappropriate level, the increased CO_2 concentration will not contribute to a raise in the biomass production.

On the other hand, at higher temperatures, dead organic matter will undergo faster mineralization in soil, which in turn will lead to an increased emission of CO_2 from soils. Accelerated decomposition of organic compounds accumulated in soils, as a result of warming was observed by Cheng et al. [19]. They found that the microbial communities in warmed soils had higher relative abundance of key functional genes involved in the degradation of organic materials than those in the control soils. Thus, warming can enhance decomposition soil organic matter, which can significantly increase the CO_2 flux to the atmosphere [20].

Increasing the retention of carbon in the biomass in soil will be possible through the intensification of the biomass production and slowing the rate of soil organic matter mineralization, for instance through the application of thick vegetation cover, mulching and no tillage practices.

Enhancement of carbon sequestration constitutes one of the main tasks of regenerative (and sustainable) agriculture, also known as agro ecological farming. The aim of regenerative farming systems is to increase the soil quality and biodiversity in farmland while ensuring the profitable production [21]. It encompasses a range of techniques, i.e. non-tillage, avoidance of leaving soil uncovered, integrating livestock and cropping operations on the land [22]. These actions aim at reconstructing and maintaining soil fertility as well as sequestering of carbon. One of the common practices is the application of catch crops, which enhance the CO_2 absorption themselves and additionally constitute a layer covering soil [23]. The application of catch crops enables to increase the biomass production per unit of agricultural field. The biomass produced in such way may be left on the field as a green manure, which constitutes a source of nutrients and humus. Transformation of the organic compounds forming biomass into long-lasting humic compounds, characterized by high resistance to biodegradation, not only improves the physicochemical properties of soil, but also constitutes a method of carbon sequestration.

Moreover, the biomass of catch crops can be utilized for the production of biofuels, including the biogas produced in the methane fermentation process or syngas, bio-oil and biochar produced in the gasification and pyrolysis processes. These products constitute renewable sources of energy, which enable to reduce the consumption of fossil fuels [24]. This influences the mitigation of CO_2 emission, because the carbon contained in the biomass used for biofuels production is captured from the atmosphere [25], and not extracted from deep geological strata. Therefore, it does not add new load of carbon to the global fluxes.

Residues from the biogas and syngas production, may also have a beneficial influence on the carbon cycle, if introduced to soil. They are a valuable fertilizer which improve the quality of soil and greatly contribute to permanent carbon sequestration in soil environment. The results of the studies carried out by Cayuela et al. [26] show the importance of this phenomenon. They analysed the fate of ten by-products from energy production from the biomass, such as digestate from anaerobic digestion of manure, first generation biofuel by-products (rapeseed meal, distilled dried grains), second-generation biofuel by-products (nonfermentables from hydrolysis of different lignocellulosic materials) and biochars. Each of the residues was added to a sandy soil in the same dose calculated on the basis of N rate (150 kg N ha^{-1}). The soils were incubated at 20 °C. The time-dependent loss of carbon in soil was measured for 60 days. The lowest losses of carbon, ranging between 0.5 % and 5.8 % of total added carbon were observed in the case of biochars, a 40 % loss was noted for digestates, and for remaining residues, the losses ranged from 60 to 80 %. The loss of nitrogen from soils was also investigated. The nitrous oxide released from soil as a result of denitrification is an important greenhouse gas, with the GWP (Global Warming Potential) amounting to 265 for 100-year time horizon [2].

Characterization of catch crops cultivation

Catch cropping and intercropping is consider as an efficient strategy to deal with the climate changes [23]. Catch crops are the plants cultivated in pure or mixed sowing, in a period between two main crops [27]. Intercrops and catch crops mainly include the plants with a short vegetation period [28]. Many practical benefits for farmers, such as stable yields, limitation of weeds, pest and plant diseases, increase of protein content in cereals or decrease of nitrogen leaching can be achieved by catch crops and intercrops cultivation [23, 29]. But the appropriate selection of crops species due to the climate and soil conditions is a basic element of an effective counteracting the climate changes and to obtain the benefits for agriculture.

Depending on the sowing time, three types of catch crops can be distinguished:

- Stubble crops - seeds are sown in summer, while the crops are harvested in autumn for green forage, mowed and filched or plowed without mowing. After mowing, plants may be also left for winter in the form of mulch. The plants which are most commonly cultivated as this type of crops include brassicas (white mustard, black mustard, rapeseed, oilseed radish, stubble turnip, *Brassica oleracea* var. *medullosa)*, legumes (horse bean, yellow lupin, narrowleaf lupin, sugarsnap peas, field peas, spring vetch, serradella), and other species (blue tansy, sunflower, oat). While composing mixes, one should not include more than 2-4 plant species. At least one of these species should be adapted to the local habitat conditions and constitute 50-70 % of the sowing rate. The mixture should comprise the species with similar length of the vegetation period and application [28].

- Undersown crops - spring cereals sown in spring or, rarely, sown with winter cereals. They are used similarly to stubble crops in autumn (fodder, green forage biomass, mulch). The most common undersown crops include: small seeded Fabaceae (red clover, white clover, black medick, serradella), their mixtures with grasses, as well as grasses alone (*Lolium westerwoldicum*, orchard grass, perennial ryegrass, annual ryegrass, tall oat-grass).
- Winter catch crops - sown at the break of August and September and harvested in spring of the next year. The plants cultivated after their harvest are called secondary crops (e.g. potato, corn). Winter catch crops are categorized in accordance to their harvest period: early (winter agrimony, winter rapeseed), intermediate (winter rye, winter rye + hairy vetch, winter rye + hairy vetch + crimson clover), late (*Lolium westerwoldicum*, crimson clover, perennial ryegrass + winter vetch + crimson clover, annual ryegrass + winter vetch + crimson clover, perennial ryegrass + winter vetch, winter wheat + winter vetch) [27, 28].

The average yield of biomass (dry mass - d.m.) of the plants cultivated as catch crops in central Lubelskie Voivodeship, which is situated in temperate climate zone, with greater precipitation than evaporation, characterized by the average annual ambient temperature of *ca* 7.6 °C, and mean precipitation of 540 mm [30] ranges from 2.64 to 4.26 Mg d.m./ha (Table 3). White mustard presented the highest biomass yield per hectare. Carbon constitutes approximately 43 % of the dry biomass in the above-ground parts of the plants presented in Table 3. This carbon can be contained for a longer time in a soil ecosystem, provided that biomass is used as green manure. The amount of carbon that remains in soil permanently and will not be released into the atmosphere in the form of CO_2 depends mainly on the soil and climate conditions, such as porosity, humidity, temperature, etc.; these factors are also decisive in terms of what part of the root biomass remaining in soil will be transformed into humic compounds.

Table 3

Mean yield of catch crops air dry mass [t/ha] obtained under the soil and climate conditions of central Lubelskie Voivodeship [31-33]

Species	**Biomass [Mg/ha]**	**Carbon included in the biomass [Mg CO_2/ha]**
White mustard	4.26	6.64
Spring rapeseed	3.40	5.32
Blue tansy	3.98	6.23
Red clover	2.69	4.22
Serradella	3.05	4.77
Spring vetch + field pea	3.46	5.39
Narrow-leaf lupin + field pea	2.64	4.11
Oats + spring vetch + pea	3.22	5.02
Winter rye	4.07	6.34

Due to the beneficial effect on the environment, catch crops and intercrops can be treated as environmentally friendly agriculture [34]. In the last years, the interest in growing these crops has been on the constant increase among farmers.

Assessment of catch crops role in terms of mitigation of carbon dioxide emissions in Poland

Approximately 7.5 million hectares of cereals are cultivated in Poland [35]. This area is suitable for catch crops cultivation. Therefore, if catch crops were cultivated over the entire area, it would be possible to increase the annual absorption of CO_2 from 30.8 Tg CO_2/year to 49.8 Tg CO_2/yr, achieving the biomass production ranging from 19.8 Tg d.m./yr to 32.0 Tg d.m./yr (assuming the biomass yield given in Table 3).

The biomass can be used as a substrate for green energy production. The studies on methane fermentation process indicated that the efficiency of methane generation ranged from 222 to 450 m^3/Mg of volatile solids (VS), depending on the catch crop species [36, 37]. Assuming the average total solid and VS contents equal to 25 and 90 % respectively, the VS mass of the crops ranged from 17.8 to 28.8 Tg/yr. This amount of the biomass would be sufficient to produce from $4.0 \cdot 10^9$ to $13.0 \cdot 10^9$ m^3 of the methane per year. The methane yield of raw biomass is estimated at 50 to 101 m^3/Mg and the methane yields per hectare at 685 to 1384 m^3/ha.

The produced biomass can also be utilized for other purposes, e.g. production of biochar and syngas in the pyrolysis or gasification processes. Assuming the average biomass conversion during slow pyrolysis to biochar, bio-oil, and syngas at 30, 40 and 30 %, respectively [38] the catch crops produced in Poland biomass could be converted to about 5.9-9.6 Tg of biochar, 7.9-12.8 Tg of bio-oil and 5.9-9.6 Tg of syngas. The syngas and bio-oil can be converted to energy and the biochar can be applied to soils, which enables long-term carbon sequestration, estimated even at 200 years [39], what would help to mitigate climate changes. These changes make a serious global problem, which can be alleviated only by developing multidimensional solutions [40, 41].

Conclusions

Cultivation of catch crops enables to increase the sequestration of CO_2 in the agriculture sector. Assuming that all the surface area used for cereals cultivation in Poland, which equals 7.5 million hectares, will be allocated for catch cropping, from 4.11 to 6.64 Mg CO_2/yr can be absorbed per one hectare of the cultivated crops, depending on the plant species. Simultaneously, catch crops cultivation allows producing from 4.46 to 7.20 Tg/yr of biomass, which may be used for green energy production, either by the generation of biogas in the anaerobic digestion process or syngas in thermochemical processes. Additionally, the residues obtained in these processes, such as digestate and biochar can be applied as valuable fertilizers or soil conditioners.

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