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Restoration of minesoil organic matter by cultivation of fiber hemp (*Cannabis sativa* L.) on lignite post-mining areas

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ABSTRACT

We propose here the use of fiber hemp (*Cannabis sativa*) introduced into post-mining area to be a pioneering plant that can be used for reclamation of the soil degraded by opencast lignite mining. Five years experiment carried out on the total surface of 7.5 ha showed usefulness of hemp as a species used for rebuilding the soil organic matter. By plowing in the whole biomass of cultivated plants it was delivered to the topsoil, accelerating the restoration of the humus layer. Organic matter content of the soil increased from 0.87 % to 2.4 %. In the same time the content of important macroelements like phosphorus, potassium, magnesium and manganese reached the levels above minimum for agricultural soil, while heavy metals (Cu, Zn, Fe) did not exceed an acceptable level.

1. Introduction

Lignite is still an imortant source of energy in many countries of the world. Poland (63.7 Mt in 2014) is the second lignite producer in European Union after Germany (178.2 Mt in 2014), and fourth in the world (after Russia and USA with 73 Mt and 70 Mt yearly production respectively). Presently about 30 % of Poland's energy is generated from brown coal (Widera et al., 2016). Lignite mining in Poland covers approximately 16 000 ha while the area of land degraded as a result of open mining activity is over 67 000 ha (Mańkowski et al., 2020).

Opencast mining is the most common technique used for mining of coal and other minerals when they occur close to the surface (Ussiri and Lal, 2005). Surface coal mining causes a lot of disturbances in the ecology of the natural environment. Sometimes, far-reaching geological and ecological changes may even lead to international conflicts and legal disputes (e.g. the intense dispute between Poland and the Czech Republic over the mine in Turów in recent months) (Shipley, 2021). Opencast mining leads to significant geomechanical transformations and degradation of the natural structure of the soil profile and the layers of the natural cover of humus, one of the basic components of soil that determines its fertility. Before the lignite can be excavated by the open-mining method the top layer over the lignite deposit – so called overburden – has to be removed together with all the vegetation and the soil. Surface mining drastically alters soil properties, destabilizes soil organic carbon (SOC) and depletes SOC pools. Carbon is initially lost from mined soils in the same manner that organic C is lost from tilled soils due to the disintegration of soil aggregates that leads to organic matter being decomposed and carbon is ultimately respired (Anderson et al., 2008; Lorenz and Lal, 2007).

After the coal deposit mined with the opencast method is exhausted, a dead excavation remains, which is filled with material from the outlay as the excavation progresses. The surface of such terrain is leveled. The top layer of the open pit fields is characterized by not fully developed soil. The humus content in such a layer is trace, it does not have a biologically active surface layer consisting of mineral and organic particles of varying degrees of disintegration. When natural components of the environment have lost the capability to autoregenerate in a timely manner, their rehabilitation is only possible through anthropogenic correction. Natural processes of soil formation are slow and can take decades or centuries to form new soil. To speed up soil formation processes and to achieve a normal soil productivity level different procedures of land reclamation ale implemented, leading to construction of a new soil. The characteristics of this new soil or minesoil depend on the kinds and sequences of reclamation procedures employed (Favas et al.,

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2018; Welch, 1988).

There are many possible options for the productive uses of reclaimed mine lands. This does not necessarily imply restoring precisely the characteristics of the premine soil and landscape but rather involves the establishment of geological and hydrologically stable landscapes capable of supporting a natural mosaic of ecosystems. The implementation of any one of the land use possibilities is conditioned by technical, economic, social, and environmental aspects (Favas et al., 2018; Feagley and Hossner, 2015).

There are three main directions for the restoration of the post-mining areas. These are agricultural use when arable lands, permanent grassland or orchards are set up, afforestation of reclaimed areas that have a production or protective function (e.g. soil or water protection) and a special direction based on recreational, ecological or aesthetic and protective management. Agricultural reclamation is not the most common. The direction of reclamation in each country is selected for each case separately. In Great Britain for example, as well as in Germany and Hungary, the agricultural approach of reclamation is preferred while in the United States and Turkey the forestry approach dominates. In Poland many disturbed areas are used for recreational purposes (Tymchuk et al., 2021). Among lignite mines in Poland, agricultural reclamation is used on a larger scale by only two mines - "Adamów" and "Konin" (Kasztelewicz, 2014).

Globally, agricultural reclamation is carried out mostly by cultivating a small number of non-food plants, which are then used industrially. In our opinion, this is not the optimal solution. From an industrially degraded area, where the process of creating a humus layer has just begun, biomass is extracted, resulting in low yields of succeeding crops, and the reclamation process is ineffective and extended over time. Devastated soil has a diverse geomechanical composition and deficiencies of some essential nutrients are common, which makes it unsuitable for the production of food or fodder plants. We propose here the use of fiber hemp (*Cannabis sativa* L.) cultivation as a pioneering plant, when all the produced biomass is not removed from the field but is reintroduced into the soil in order to restore the missing humus layer as quickly as possible.

Hemp is an herbaceous plant that can grow from about 1–6 m tall, depending on factors such as cultivar and environmental and agronomic conditions. It can produce high amount of biomass. Some authors reported very high yields of hemp reaching more than 22 tons per hectare (Struik et al., 2000), however more typical values are lower and other authors report yields of fiber hemp on the level of 7−15 tons per hectare (Deleuran and Flengmark, 2006; Fike, 2016; Grabowska et al., 2009). Fibre hemp is a traditional industrial crop in many regions of the world. For many centuries hemp has been cultivated mostly as a source of strong stem fibre and seed oil (Struik et al., 2000). Recently this species gains a lot of attention for its alternative use directions, these include using hemp for biomass and biofuel production. Hemp is a rapidly growing plant that tolerates high planting density and the total biomass of hemp per hectare is similar to other energy crops, including giant miscanthus, poplar or willow. However, hemp may provide a key advantage; its bast fibers contain high amount of cellulose (73–77 %) and low amount of hemicelluloses and lignin (7–9 % and 2–6 % respectively) comparing to other biomass crops. The stem biomass in hemp consists of high cellulose fiber; thus, the ratio of digestible sugars to lignin is higher in hemp than in other similar-yielding biofuel crops (Schluttenhofer and Yuan, 2017). In addition to a high amount of biomass, the plant has a well-developed taproot system, growing into the soil to a depth of about 2 m or more. Hemp's short growing cycle, decreased need for pesticides, and low plant maintenance makes it an ideal candidate for phytoremediation utilization (Husain et al., 2019). *Cannabis sativa* is also plant potentially usable for the detoxification of contaminated soils due to its resistance to soil contamination, its ability to accumulate heavy metals and possibility of cultivation in different climatic conditions (Campbell et al., 2002; Kalousek et al., 2020).

All these unique characteristics of hemp and the awareness that vegetation plays a major role in improving the properties of mine soils, where increased biomass production, root residues and exudates, and the greater activity of microbes following revegetation have positive effects on the accumulation of soil organic matter (Zhang et al., 2020) has encourage us to test the study the usefulness of fibre hemp as a species for experimental reclamation of the 7.5 ha area degraded by previous lignite mining operations.

2. Materials and methods

Field experiments were conducted in years 2014–2018 on the lignite post-mining area close to Kazimierz Biskupi province Wielkopolska, Poland. The research was financially supported by European Comission LIFE + grant LIFE11ENV/PL/445 and by National Fund for Environmental Protection and Water Management in Warsaw granted to the Institute of Natural Fibres and Medicinal Plants.

Before agronomic treatments could be conducted in selected experimental field, they had to be cleared of volunteer weeds and bushes as well as stones. The number of stones made initially the work on the field impossible. After removing the stones, agrotechnical works were carried out, which included disc-harrowing of the field and plowing (Fig. 1C) followed by pre-sowing tillage and application of lime in the dose of 0.25 tons/ha. Liming of the field was carried out only in the first year of the project.

Every year mineral fertilization (with nitrogen, phosphorus and potassium) was carried out in accordance with the fertilization plan: nitrogen fertilization at a dose of 150 kg N/ha, phosphorus fertilization at a dose of 150 kg P_2O_5/ha and potassium fertilization at the dose of 215 kg K/ha. Phosphorus and potassium fertilizers were applied in autumn and nitrogen in spring before sowing of hemp. Hemp was sown every year in April with the sowing rate of 42 kg of seeds per ha. Every year in October hemp was mowed. Mowing was conducted using a mower pulled by the tractor, equipped with three knives cutting the stem into three sections. This facilitated later plowing the biomass down. Working width of the mower was 4 m and it was able to mow 3−4 ha/h. In November, plant residues were plowed with 30 cm deep plowing. The costs of all agronomic treatments were estimated at 660 euro per hectar per year.

Samples for soil tests were collected annually before the commencement of spring agrotechnical treatments with the use of a soil auger. The field was divided into four sections, five samples were taken from each section. Laboratory tests were performed using accepted Polish standards (PN). Phosphorus and potassium were extracted from soil using Egner-Riehm method and then phosphorus was determined by spectrophotometric method (PN-R-04023) and potassium by flame photometry (PN-R-04022). Magnesium was extracted with 0.0125 M $CaCl_2$ solution and determined by atomic absorption spectrometry (PN-R-04020). The soil pH was determined in 1 N KCl. Micronutrients were extracted with 1 N HCl and manganese, zinc and copper were determined by atomic absorption spectrometry (PN93/R-04019, PN92/R-04016 and PN92/R-04017 respectively) while boron by spectrophotometry (PN93/R-04018).

The presented weather pattern data is from the Weather Station in Konin (Table 1). In the years of experiment the average temperatures during hemp growth season differed only a little with the exception of 2018 – the warmest year in the period of plants emergency. Precipitation in 2017 was significantly higher than in the remaining years of the experiment. Especially June and July 2017 were characterized by a lot of rainfall. The reclaimed layer was very wet (Fig. 1J–K) due to its limited water permeability. Frequent rainfall had largely suffocated the cultivated hemp. Cannabis plants died in many places due to the lack of oxygen in the soil layer, which was displaced by water (Fig. 1H). The height of the plants often did not exceed 1 m at that year. Such unfavorable weather conditions led to a reduction in the yield of plants.

The results were evaluated statistically with the R statistical software version 4.0.5 (R Core Team, 2020). ANOVA tests were used to test main

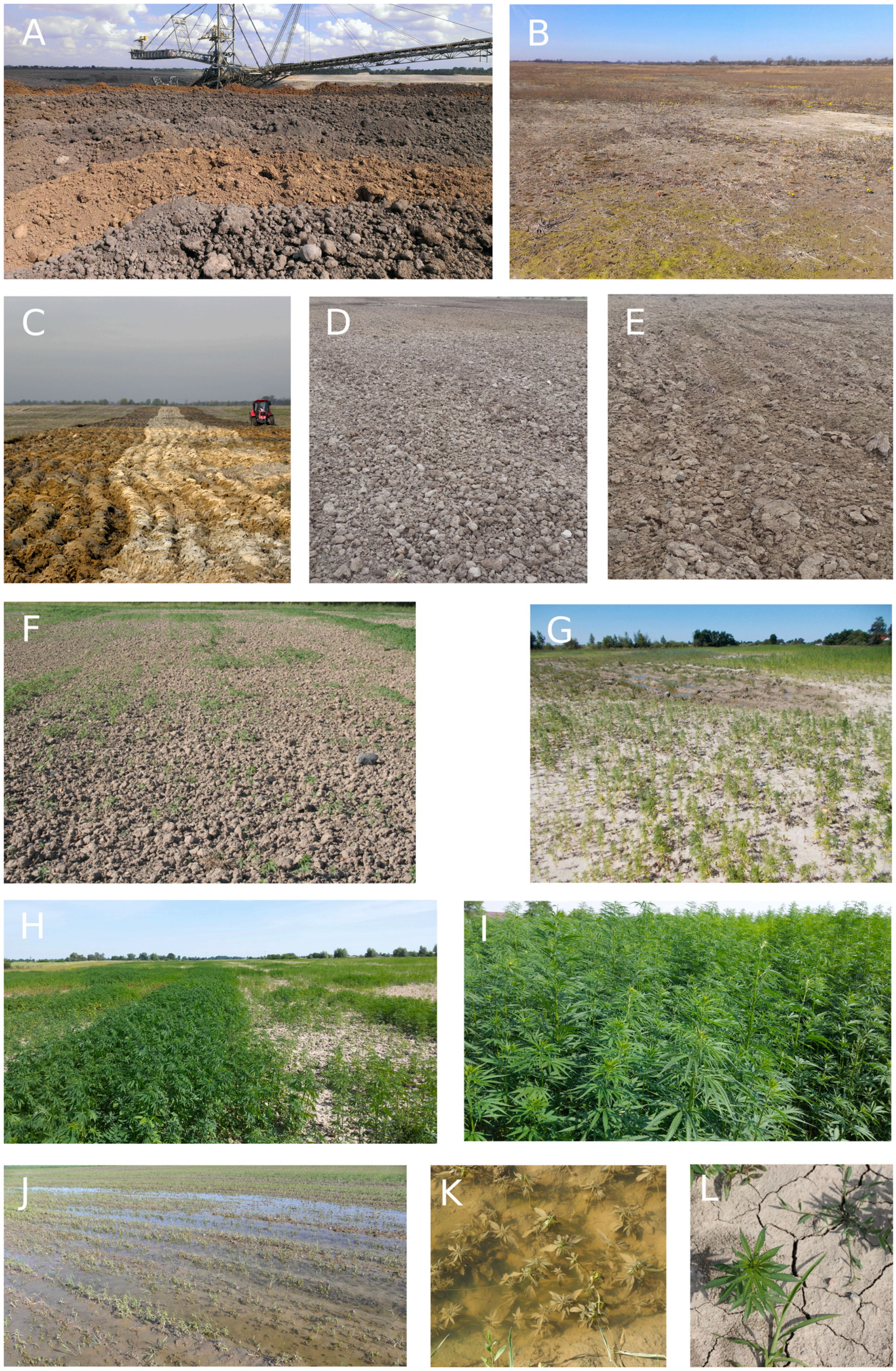

Fig. 1. Stages of degraded land reclamation. (A) filling the excavation with material from the outlay, (B) leveled surface before reclamation, (C) minesoil differences during tillage, (D) minesoil before sowing of hemp, (E) soil after 5 years of hemp cultivation, (F-I) stages of hemp growth on reclaimed area, (J-K) reclaimed area after moderate rain, (L) reclaimed area after several days without rainfall.

effects of recultivation year. The data from all years were combined and analysed post hoc with Fisher's LSD test from agricolae package (de Mendiburu, 2013) at a significance level α = 0.05.

3. Results and discussion

3.1. Hemp yield

Agrotechnical procedures related to reclamation of the experimental field started in 2013. They consisted of clearing the field of stones, sowing lime and PK fertilization. The aforementioned treatments were designed to initiate the plot reconstruction and preparation for the

Table 1
Monthly precipitation [mm] and average air temperatures [°C] during years 2014–2018.

	Average temperatures [°C]						Monthly precipitation [mm]					
	Year						Year					
Months	2014	2015	2016	2017	2018	1991–2020	2014	2015	2016	2017	2018	1991–2020
I	−3.07	1.96	−2.39	−5.04	1	−0.5	45.1	31.9	43	15.3	43	36
II	4.94	1.57	4.45	1.69	−3.71	0.4	4.7	17.7	53.7	27.7	0.7	31.7
III	11.07	7.66	7.33	10.71	0.95	3.6	62.9	29.1	30.7	27.4	26.4	38.7
IV	11.71	12.42	12.65	11.95	14.75	9.2	29.7	19.9	13.2	52.8	40.3	30.4
V	16.58	14.97	16.75	14.81	19.35	14.3	132.4	20.1	38.1	36.1	82.6	57.1
VI	20.08	20.75	22.32	19.97	20.18	17.6	25	30.9	37.3	80.2	43.8	54.5
VII	22.11	23.06	22.32	21.65	21.52	19.7	55.1	86.7	106.9	102.9	101.9	83.1
VIII	19.73	23.44	20.19	23.21	21.57	18.9	65.2	21.1	20.5	56.2	21	55.6
IX	14.9	21	18.26	15.63	16.62	13.9	29.2	23.3	8.4	110.5	32.6	47.4
X	11.51	9.88	10.55	11.5	12.41	8.7	33.5	46.7	120.2	77.8	42.8	38.1
XI	5.46	6.13	5.6	6.1	5.74	4.1	24.3	52.4	48.8	40.8	10.4	36.9
XII	1.39	3.72	2.6	3.79	0.78	0.7	30.9	20.1	48.5	48.9	45.8	37.6
					Yearly sum		538	399.9	569.3	676.6	491.3	544.6

planned vegetation treatment.

The soil depletion with previously conducted industrial activity resulted in low hemp yielding in the first year of the experiment. The average hemp biomass yield was only 1.6 tons/ha (Fig. 2A). Already in the second year of the project, the annual incorporation of biomass from the first year led to the activation of the soil and a jump of the yield of hemp biomass to 5.3 tons/ha (330 % increase), followed by 5.9 tons/ha in 2016. The highest yield of 6.3 tons/ha was obtained in the last year of experiment. This growth was also influenced by favorable weather conditions favoring the development of the plants in 2018.

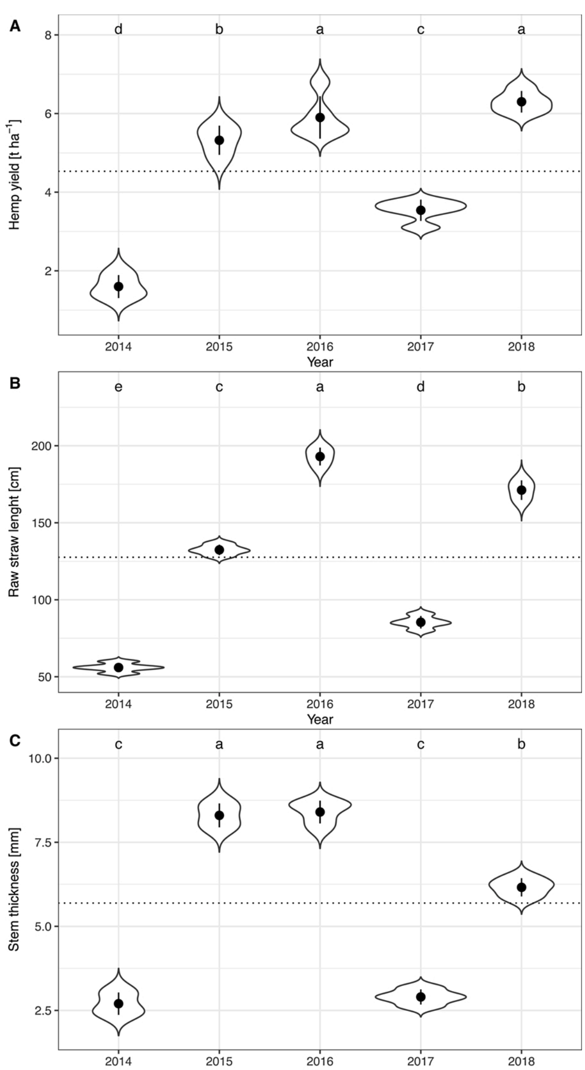

Fig. 2. Hemp yield (A), raw straw lenght (B) and stem thickness (C). Different small case letters (a–d) indicate significant differences between year means according to Fisher's LSD test ($p < 0.05$). Black dots represent the mean values and black vertical lines standard deviations (SD). Dotted line represent grand mean for all years of experiment.

The increase of the hemp yield was the result of the increase of the plants heigh and the straw width (Fig. 2B-C). In the first year of the experiment the average plants heigh was only 56 cm, while on the second year it was higher by 236 % (132 cm) and in 2016 reached the average heigh of 193 cm. The straw widh on the second and third year of experiment was 3 times bigger than in 2014 (8,1 and 2,7 mm respectivelly). In 2017, hemp crop suffered due to long-lasting intense rainfall. A large amount of precipitation in the period immediately after emergence led to the loss of many plants. It was reported that too much available moisture can limit production or cause failure, particularly in low lying and poorly drained fields (Fike, 2016). In the case of the reclaimed minesoil, due to the compact, impermeable recultivated layer, even slight rainfall led to the formation of large water stalls (Fig. 1J–K). The standing water displaced oxygen from the soil which led to the suffocation of many plants. This lead to the low hemp yield of 3,5 tons/ha and low and thin plants.

3.2. Organic matter

Every year, the hemp biomass obtained was plowed in, enriching the soil with nutrients. This affected the level of humus in the reclaimed soil. The 2014 yield after plowing in had an impact on the content of nutrients in the soil, which was tested before the commencement of agrotechnical treatments in 2015. The same applies to all years of research. The annual incorporation of plant biomass resulted in a gradual increase in the level of humus in the reclaimed soil (Fig. 3).

The year 2014 is treated as the starting year in the conducted experiment. In 2015 we did not observe any increase of the organic matter (OM) content in the soil and it remained on a very low level of 0,88 %. It was due to the relatively small amount of plant biomass received and plowed in in 2014. Between 2015 and 2016 the increase of the OM was observed as we noted 10 % increase (from 0,88 to 0,96 %) but is was not statistically significant. A statistically significant increase was observed in 2017. The soil survey carried out in 2017 showed a significant increase in the level of humus in the soil also in relation to the initial data from 0,87 % (2014) to 2.44 %. In the last year of experiment in 2018 we did not observe the further increase of the OM content but the deviations of the measurements decreased. In this year we did not note the large differences between samles analyzed.

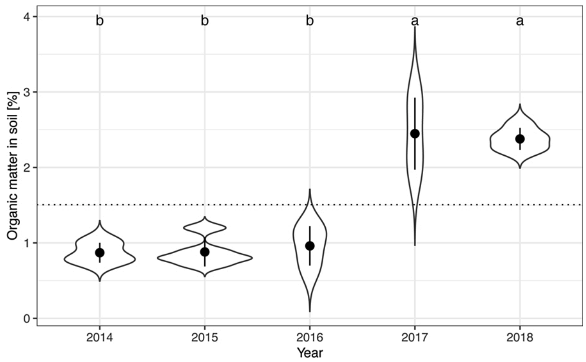

Fig. 3. Organic matter content in the soil.
Different small case letters (a–b) indicate significant differences between year means according to Fisher's LSD test ($p < 0.05$). Black dots represent the mean values and black vertical lines standard deviations (SD). Dotted line represent grand mean for all years of experiment.

It is widely agreed that successful reclamation of lignite mine sites, especially when the topsoil has

been removed, depends on the rapid formation of a surface horizon rich in organic matter (Leirós et al., 1993) Humic substances improve the physical properties of mine soils by favouring aggregation, which facilitates aeration and water transport. They also improve the chemical properties of soil by providing buffering capacity and increasing surface area and ion exchange capacity. As a result soils on reclamation sites can become progressively more productive with time (Gildon and Rimmer, 1993; Oades, 1984). It the case of the presented survey we have observed relatively fast building up of the soil organic matter. Already after four years in the top layer of the studied minesoil the OM reached the level observed in the undisturbed agricultural soils of the region. It is in line with the other authors reporting that reclaimed minesoils develop recognizable horizonation relatively quickly and effectively sequester carbon (Thomas and Jansen, 1985). It was reported that a distinct horizon up to 15 cm thick can develop during first 5 years of reclamation and is distinguished from subsoil by the accumulation of SOM, loose soils due to root growth, and soil structure development (Akala and Lal, 2001; Roberts et al., 1988).

3.3. Roots development

The potential of organic matter sequestration in minesoils depends on biomass productivity but also on root development in the subsoil and changes in minesoil resulting of their development (Haering et al., 1993).

Hemp grown in the optimal soil condition has a well-developed taproot system, growing into the soil to a depth of about 2 m. During

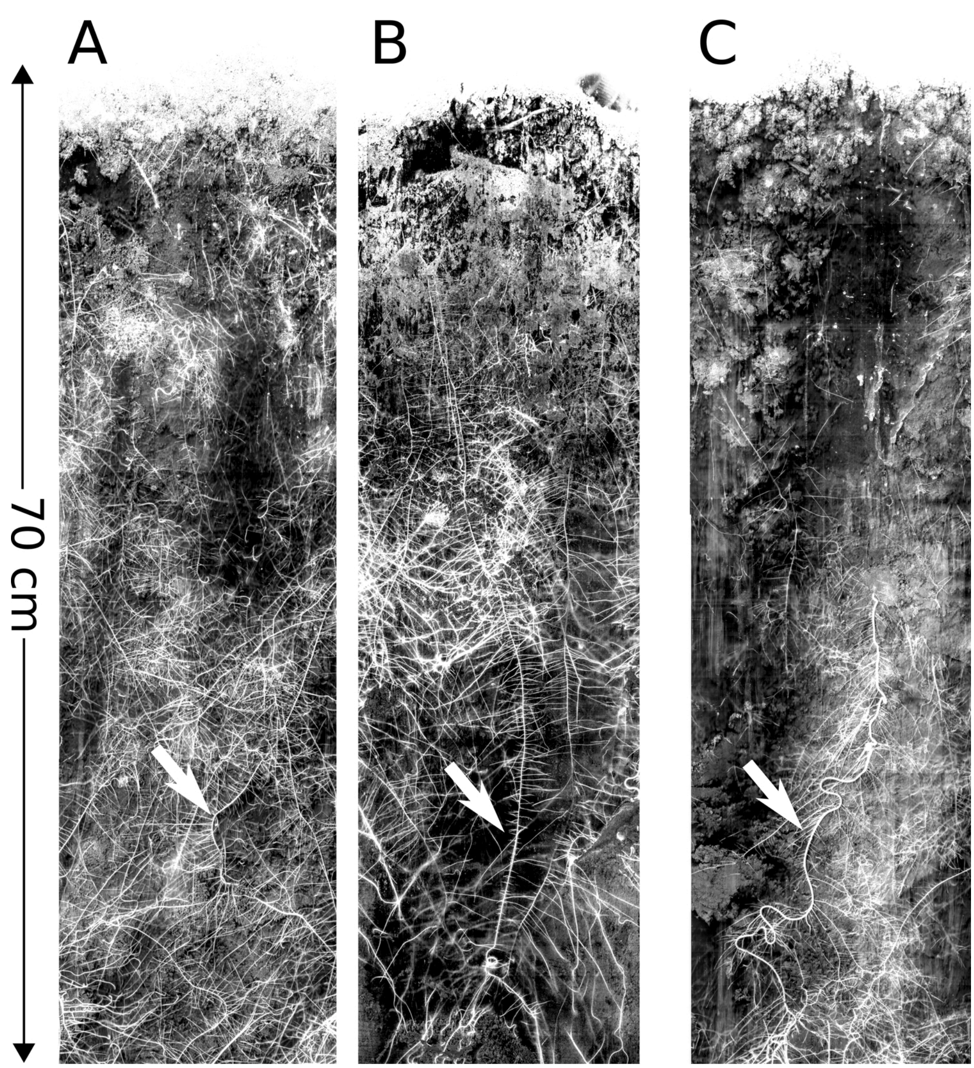

Fig. 4. Hemp roots architecture on recultivated area in 2015 (A), in 2017 (B) and on standard agricultural field (C).
White arrows poin the tap roots.

the course of the experiment we have observed the changes of hemp root architecture (Fig. 4). In the first years the typical tap root was hardly visible. The lateral roots were numerous, but small and thin and outgrown rather the top layer (down to ca. 30 cm) of the minesoil. In later years, the plants began to develop a tap roots, typical for this species, which penetrated well into the soil. The root was still thinner compared to the plants grown on agricultural soils, but the root system looked typical for cannabis.

Roots provide a path for movement of carbon and energy to the deeper horizons of the recultivated minesoil. Therefore, root production have a direct impact on the amount of organic matter present in the soil (Izaurralde et al., 2001). The fine root contributions to SOC range from 33 to 67 percent in forest ecosystems (Grier et al., 1981). Balesdent and Balabane (1996) calculated that corn roots incorporated 58 percent more carbon than combined incorporation by leaves and stalks. From this perspective, the use of hemp, capable of producing a large amount of aboveground biomass and at the same time developing a strong and deeply growing root system, for the rehabilitation of areas poor in organic matter, seems to be justified as deep-rooted plant species have the potential of increasing SOC sequestration by transferring more OM into deeper horizons.

3.4. Soil pH

In many cases reported in the literature the minesoils formed after lignite mining suffer with low or extremly low pH. It was not observed in our case.

During the course of experiment the pH of the minesoil remained alkaline, close to neutral (Fig. 5). We have observed slight increase of the soil pH value during the years. Soil pH is one of the main factors determining soil fertility and it may be affected by crop and residue management. Reports on the effect of organic matter addition on soil pH have been contradictory. Some authors have suggested that accumulation of fresh organic matter may be one of the causes of soil acidification (Šourková et al., 2005) while many other reported soil pH increase after OM incorporation (Butterly et al., 2013; Tang and Yu, 1999). Our observations are in line with the latter reports. The the exception from this trend was observed in the second year (2015) when pH dropped from 7.7 in 2014 to 7.4. This drop was due to the lack of the soil structure typical for the minesoil at the begining of rehabilitation process, resulting with the lack of oxygen in the top layer. These together with the incorporation of the initial amount of the organic matter from the previous year could lead to the anaerobic microbial processes in the soil, production of organic acids and lowering the soil pH.

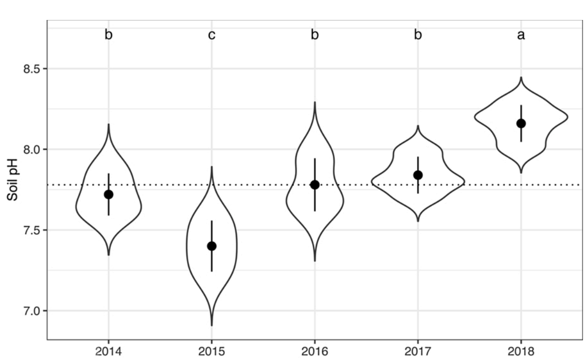

Fig. 5. Recultivated soil pH.
Different small case letters (a–c) indicate significant differences between year means according to Fisher's LSD test ($p < 0.05$). Black dots represent the mean values and black vertical lines standard deviations (SD). Dotted line represent grand mean for all years of experiment.

3.5. Macroelements and microelements

The amount of all four tested macroelements increased during the course of the minesoil reclamation experiment however, the content increase dynamics was different in the case of the analyzed elements (Fig. 6). The content of phosphorus and, to some extent, also potassium increased in proportion to the increase in the content of organic matter (Fig. 3). At the same time, the magnesium content increased linearly in each year of the experiment, and the changes in the manganese content corresponded to the changes in the soil pH (Fig. 5).

3.5.1. Phosphorus

The content of phosphorus in the tested soil increased with the reclamation carried out. This increase was statistically significant. The level of phosphorus in the reclaimed soil was below the norm, ranging from 101 to 150 mg kg of typical agricultural soil. During first two years it was extremely low (54 and 59 mg kg of soil respectively). In the third year (2016) phosphorus level increased by 39 % and in 2017 by next 42 % reaching 117 mg kg. In the last year of the experiment the phosphorus content did not increase anymore (119 mg kg) but in the last two years the soil reached the minimal accepted level of 100 mg kg. The increase of phosphorus in the minesoil was in line with organic matter content increase.

Soil organic matter plays an important role in P sorption as the main constituent of the soil sorption complex which is responsible for binding of anions in the soil material (Debicka et al., 2016). Phosphorus leaching can be significantly affected by soil adsorption-desorption properties, and it has been shown that application of organic fertilizers could significantly improve the soil phosphorus adsorption capacity (Fei et al., 2020). Mengmeng et al. (2021) found, that organic fertilization together with mineral NPK increased available phosphorus by 150 % comparing to NPK alone. Application of organic matter is also supposed to improve the soil phosphate availability by promoting microbial activity (Nobile et al., 2020).

3.5.2. Potassium

The increase in potassium content was slowier than that of phosphorus. During the first three years, this increase was not statistically significant. It was only in 2017 that a statistically significant increase in the potassium content was noted, to the level of 95 mg kg of soil. In the last year of the experiment (2018), the potassium content reached the value within the norm for this element, ranging from 120 to 200 mg, reaching the value of 175 mg kg of soil.

Disturbance to soil by mixing subsoil with topsoi may decrease potassium content (Desserud and Naeth, 2013). In the studied soil the initial amount of K was very low (70 mg kg of soil). On top of that it is known that potassium readily leaches from organic matter as it decomposes. (Christensen, 1985) found, that when staw was left on the field, most of its K content was leached during the first month of storage. That can explain the delayed increase of this element level in the course of soil remediation – even though annual potassium fertilization was used. On the other hand hemp is known to take up potassium when the element is not needed and hemp has a lower requirement for potassium than other crops. Most of the absorbed potassium absorbed by Cannabis is concentrated in the stem (70–75 %) (Finnan and Burke, 2013). That could explain the finally observed increase of the potassium in the studied soil as this part of the plant is particularly resistant to decay due to the high content of celulose and lignins and could store the absorbed amount of potassium.

It is worth noting that the content of phosphorus and potassium reached a value above the lower limit of the norm for these elements only after three and four years of soil rehabilitation respectively, despite the annual intensive fertilization with these elements. This confirms the important role of organic matter in the absorption of potassium and phosphorus in the soil.

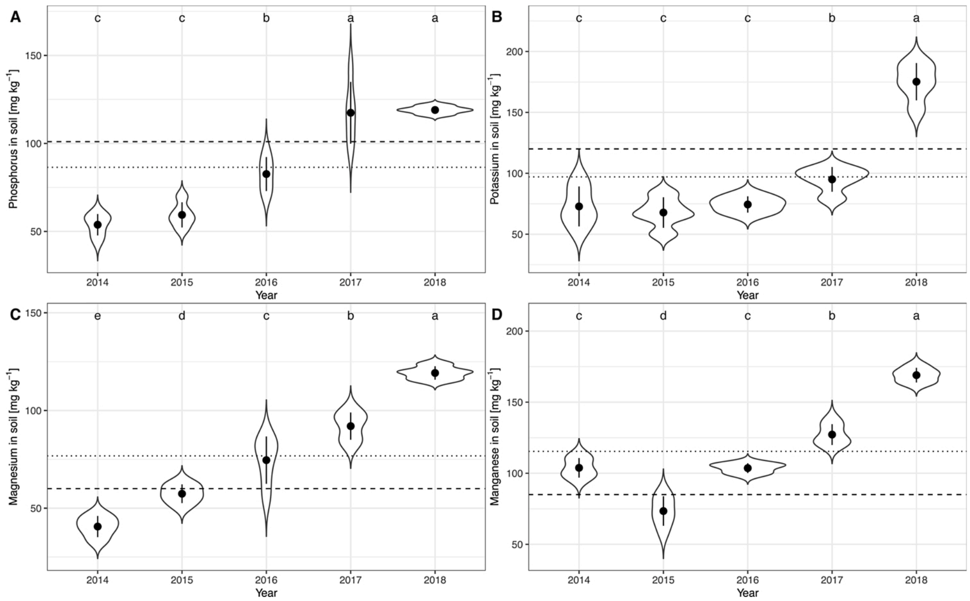

Fig. 6. Macroelemens content in the soil (A) phosphorus, (B) potassium, (C) magnesium, (D) manganese.
Different small case letters (a–e) indicate significant differences between year means according to Fisher's LSD test ($p < 0.05$). Black dots represent the mean values and black vertical lines standard deviations (SD). Dotted line represent grand mean for all years of experiment.

3.5.3. Magnesium

A significant increase was also observed in the case of magnesium content. In the base year, the magnesium content was below normal and amounted to 40.6 mg kg of soil. The level of macronutrient gradually increased and in 2017 it amounted to 92 mg / kg of soil, reaching the value of 119.2 in the last year of the study. The standard for the content of magnesium in the soil is from 61 to 100 mg kg.

The rate of movement of magnesium in soil depends on soil texture, rainfall and soil pH. It is generally believed that it is easy to migrate in neutral to acidic soil and difficult to migrate in alkaline soil (Metson, 1974; Yan and Hou, 2018). That suggests that soil conditions (especially higher soil pH) in the course of the experiment were in favour to limit leaching of this element and as a result progressive absorption within the organic matter delivered into soil.

3.5.4. Manganese

The manganese content in the tested soil increased in the years 2015–2017 as reclamation was carried out and fell within the norm, which is from 85 to 830 mg. This increase was statistically significant. Also, comparing the base year (2014) with 2017, a significant increase in the level of manganese in the studied soil was observed.

It has been reported that soil Mn was primarily found in the exchangeable and organic fractions, regardless of soil pH but solubilization of organic acids under alkaline conditions may result in increased complexation of Mn inhibiting its precipitation in the soil environment (Sims, 1986). It has been also observed that stronger bonding of manganese ions by organic matter was induced by increased soil pH (McBride, 1982). These previous observations well explain our results showing that Mn content in the soil directly followed changes in the soil pH (Figs. 6 and 5).

3.5.5. Boron

The boron content in the soil varied in the studied period (Fig. 7). Its level increased significantly from 0.41 mg/kg of soil in 2014 to 0.99 mg/kg of soil in 2017. There was no significant change in the boron level between the starting year 2014 and 2015. Between 2015 and 2016, a significant increase of this micronutrient content was observed. Despite the increase, the content of this microelement was below the standard for Polish soils, which ranges from 2.2 to 7.2 mg kg of the soil.

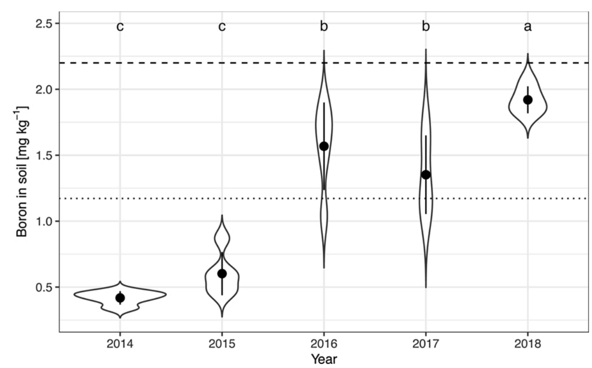

Fig. 7. Boron content in the soil.
Different small case letters (a–c) indicate significant differences between year means according to Fisher's LSD test ($p < 0.05$). Black dots represent the mean values and black vertical lines standard deviations (SD). Dotted line represent grand mean for all years of experiment.

Although many investigations have been performed with the influence of certain constituents on boron behavior in soil, there is no general agreement on the role they play in B adsorption and desorption. There is general belief that organic matter plays an important role in B adsorption and its availability in the soil (Marzadori et al., 1991). Besides organic matter, also soil pH plays an important role in B behaviour in the soil environment. Gu and Lowe (1990) found that B adsorption by humic acids was strongly pH-dependent, being low and relatively constant in the pH range 3.0–6.5, increasing markedly up to a peak at near pH 9.5, and then decreasing at higher pH values. It has been concluded that complexation of B with soil organic matter should only be important at alkaline pH (Evans, 1987). Our results are in agreement with those previous observations. We have noted the increase of B content in the minesoil together with organic matter accumulation and with soil pH increase.

3.6. Heavy metals

We have tested also the soil content of main heavy metals (copper, iron and zinc) (Fig. 8). We wanted to test if together with organic matter

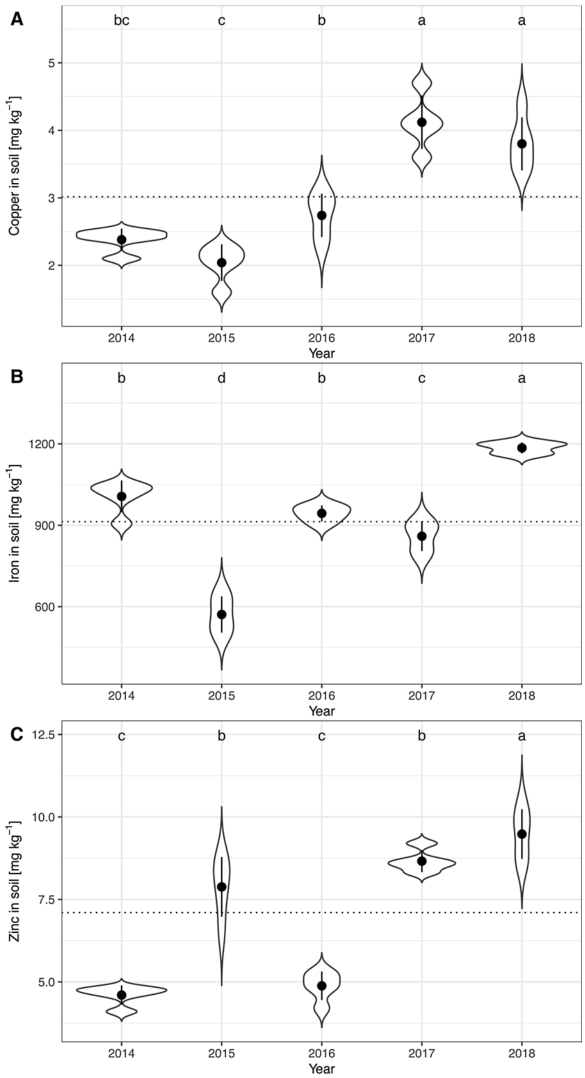

Fig. 8. Heavy metals content in the soil (A) copper, (B) iron, (C) zinc. Different small case letters (a–d) indicate significant differences between year means according to Fisher's LSD test ($p < 0.05$). Black dots represent the mean values and black vertical lines standard deviations (SD). Dotted line represent grand mean for all years of experiment.

deposition from *Cannabis sativa* we would also observe the accumulation of the heavy metals in the reclaimed soil. Hemp is known for its ability to actively take up and accumulate metals to high levels in the above-ground parts, far exceeding those detectable in the soil (Arru et al., 2004). It makes hemp a promising plant for phytomanagement and phytoremediation of the polluted areas (Baraniecki et al., 2001, 1995; Pietrini et al., 2019). But in our experiment, when whole plants were left on the field to build up the organic matter content in the poor minesoil, this hemp potential would be problematic.

Our results show that the content of copper in the soil indeed increased during the course of the remediation experiment but stayed within the norm, which is for Polish soils from 2.3 to 6.7 mg kg of the soil. This increase was statistically significant and followed the increase of the OM in the soil. The iron content increase was statistically significant when comparing the year when the experiment started (2014) and when it was finished (2018) but the increase was on the level of only 17 %. Despite the observed increase, it remained within the lower limits of the norm, which is from 700 to 3800 mg kg of the soil. The level of zinc in the soil varied. Year-by-year changes in individual years were statistically significant. Comparing the starting year with 2018, a significant increase in the level of zinc in the studied soil was observed but it also remained within the normal range, ranging from 4.6 to 20.5 mg kg of the tested soil.

4. Conclusions

The main assumption of the work carried out was that fiber hemp introduced into post-industrial and post-mining areas will prove to be a pioneering plant that can be used in reclamation. The main goal of the project was to rebuild the soil organic matter. By plowing in the biomass of cultivated plants was delivered to the top layer of soil, accelerating the restoration of the humus layer, at the same time well-developed roots, overgrowing the restored humus layer, ventilated and loosened the reclaimed soil. Despite the fact that reclamation is a long-term process, the results from five years are very promising and shows the usefulness of *Cannabis sativa* for the large scale reclamation of industrially degraded lands. As a result of the work carried out, there was a significant increase in the content of humus and selected macro elements in the soil. After the experiment was completed, wheat was sown on the reclaimed field in 2019. Nitrogen fertilization with ammonium nitrate in the amount of 300 kg/ha was applied, and the wheat was harvested in August 2019, yielding 4 tons/ha. This shows that restoring degraded areas for agricultural use by using the method proposed herein can be effective and relatively fast.

CRediT authorship contribution statement

Krzysztof Pudełko: Investigation, Data curation, Writing - original draft, Visualization, Conceptualization. **Jacek Kołodziej:** Investigation, Resources, Visualization, Project administration, Conceptualization. **Jerzy Mańkowski:** Investigation, Funding acquisition, Supervision, Conceptualization.

Declaration of Competing Interest

The authors report no declarations of interest.

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