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Approaches to reducing the carbon footprint of mines within the framework of planned biorecultivation of technogenically disturbed lands

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Abstract

Over the past decade, there has been a rapid increase in coal production and intensity of mining activities, primarily due to the use of the open-pit method. This has led to a corresponding increase in the negative impact on natural ecosystems, which are characterized by a unique biodiversity. Mining is an anthropogenic activity that can have a serious impact on natural components. It is known that active, inactive or abandoned mines can have a significant impact on the soils, flora, fauna, landscape, historical and archaeological heritage, aquatic and atmospheric environments surrounding these territories. To reduce their carbon footprint, it is possible not only to modernize mining technologies, but also to use plants with a high ability to phytoremediation, capable of absorbing carbon dioxide and other pollutants from the soil and air.

Keywords: Coal mining, coal mine, carbon footprint, greenhouse gases, reclamation, biorecultivation

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1. Introduction

The carbon footprint is the amount of carbon emissions into the atmosphere created by all human activities, including the burning of fossil fuels (oil, gas, coal), the production and use of chemicals, automobile traffic and the activities of various industries and agriculture [1]. The carbon footprint also refers to the excess amount of greenhouse gases in the atmosphere, which lead to a change in the Earth's climate [2]. The carbon footprint measure is usually expressed in carbon equivalent (CO_2e) and is used to assess and compare the contribution of various actions and sectors to total carbon emissions [3]. One of the main problems of greenhouse gases is the climate change of the planet. Greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide (N_2O), trap heat in the atmosphere and create a greenhouse effect. This leads to global warming and changes in the weather and climate on Earth [4]. Several approaches can be used to determine the amount of greenhouse gases emitted by consumers or producers of goods and services [5]: emission inventory (collection of statistical data on greenhouse gas emissions during the production of goods and services, both as a result of measurement and as a result of emissions audit), life cycle analysis (LCA - a method for assessing potential environmental risks impacts of a particular product or service from its creation to the end of its life cycle, including production, transportation and disposal), material balance (analysis of calculations of the impact of a particular sector of the economy on climate change based on measuring incoming/outgoing flows of materials and energy), use of databases and models (use of specialized databases and models, which contain information on emissions from various manufacturing and consumer industries), social and economic studies (for a deeper understanding of the causes and factors affecting the consumption of goods and services, social and economic studies can be conducted to help assess the impact of changes in consumer behavior on the carbon footprint). The term "carbon footprint" is usually attributed to Rees [6], who studied ways to quantify impacts on various ecosystems (water, biodiversity, climate). It is considered to be the carbon footprint, which is expressed in the equivalent of carbon dioxide (CO_2e), the totality of all greenhouse gas emissions produced directly or indirectly as a result of human activity [7].

The carbon footprint concept is closely related to the concept of the carbon cycle, interest in which arose in the 90s of the last century, when the policies to reduce the carbon footprint started being developed [8]. The carbon cycle is a summary of all carbon transfers between the biosphere and the atmosphere, as well as greenhouse gas emissions from the use of fossil fuels as an energy source. The human factor has disrupted this cycle, and it has not stopped being in balance. As a result of the burning of fossil fuels, as well as the destruction of carbon-rich forests and their replacement with agricultural land, the concentration of CO_2 is increasing.

The purpose of this research was to study approaches to reducing the carbon footprint in the territories of mine dumps and mines in the process of biorecultivation.

2. Methods

2.1. Objects of research

The research focused on the main methods and technologies for reducing the carbon footprint, primarily on technogenically disturbed lands of mines.

2.2. Research methods

The study was based on a bibliographic search and subsequent critical analysis of online resources and scientific manuscripts dedicated to solving environmental problems and reducing greenhouse gases on the lands of coal mining enterprises and mines. Materials from open Internet sources and the Elibrary and Scopus citation databases were used. Given the relevance of the topic of the carbon footprint impact, the depth of the search was limited mainly by the last five years and the usefulness of quoting some earlier works on specific issues of reducing carbon dioxide in the reclamation of technogenically disturbed lands was determined by the uniqueness and originality of the results presented in them.

Plants use glucose $C_6H_{12}O_6$ as a starting point for a variety of chemical components that make up biomass. Some of these biochemical products are short-lived and decompose in a few days, others are resistant to decomposition and can accumulate as a "carbon reserve" and persist for centuries [9].

During photosynthesis, water is split due to the energy received from sunlight, and oxygen is released into the atmosphere. [9]:

$$\text{Photosynthesis}\rightarrow 6CO_2+12H_2O\Leftrightarrow C_6H_{12}O_6+6CO_2\leftarrow$$
$$\leftarrow \text{breath + fire}$$

The equation of photosynthesis is valid for breathing and fire, but in the opposite direction.

If carbon sources and sinks were in equilibrium, then the concentration of C_2O in the atmosphere would approximately remain constant from year to year. In the modern world, of every ton of CO_2 emitted as a result of anthropogenic impact, some part remains in the atmosphere, another part dissolves in the ocean and is distributed in marine biota, and the third part is distributed in terrestrial biota through photosynthesis.

In most organisms, including plants, carbon makes up about 50% of the dry mass. Ho Ma *et al.* [10] found that for most plants this content is lower (on average 45±5%). Woody plants have a significantly higher carbon content than herbaceous crops, mainly in the range of 48-49%. Wood contains polymer lignin, which is 60% carbon. Non-woody vascular plants contain lignin in small amounts, the main structural material is cellulose, which is only 44% carbon. In this case, cellulose is easily broken down by a number of organisms, unlike lignin. Decay-resistant molecules are found in the cell walls of algae, plant cuticles, as well as in the walls of spores and pollen. These compounds have been preserved for thousands of years and can turn into fossils. The distribution of carbon stocks in terrestrial biosystems is shown in Table 1.

3. Results and discussion

Table 1. Distribution of terrestrial carbon stocks in major biomes

Biome	**Area (10^6 km^2)**	**Global Carbon Stocks (Gt C)**		
		Vegetation	**Soils**	**Total**
Tropical forests	17.6	212	216	428
Temperate forests	10.4	59	100	159
Boreal forests	13.7	88	471	559
Tropical savannas	22.5	66	264	330
Temperate pastures	12.5	9	295	304
Deserts and semi-deserts	30.0	8	191	199
Tundra	9.5	6	121	127
Wetlands	3.5	15	225	240
Arable land	16.0	3	128	131
Total	135.6	466	2011	2477

Source: WBGU (1998). Die Anrechnung biologischer Quellen und Senken im Kyoto-Protokoll: Fortschritt oder Rückschlag für den globalen Umweltschutz. Sondergutachten 1998. Bremerhaven, Germany: WBGU.

The most cost-effective way to extract CO_2 from the atmosphere is to plant trees and/or preserve existing plantings [11]. Currently, approximately 10.4×10^6 km^2 (about 7.7% of the world's land area) is covered by temperate forests. Currently existing forests accumulate ~45% of organic carbon on land in their biomass and soils [12]. In total, existing mature and regenerating forest ecosystems absorb approximately 2 GtC (gigatons of carbon dioxide) annually, contributing significantly to the terrestrial carbon cycle [13]. Recent analysis has shown that an increase in forest plantation area by 0.9 billion ha could result in the sequestration of 205 GtC [14], which is about a third of the total anthropogenic emissions to date (≈ 600 GtC). However, it will take at least 100 years to achieve this [12]. Forest biomass can be preserved by burial, and the transformations caused in this case will lead to the formation of charcoal (biochar), which can be used on agricultural land to increase crop yields. The selection of ecologically sensitive plant species will help optimize ecosystem services in planted forests. The majority (more than 99%) of new plantations in the last half century have been monocultures [15]. Throughout the world, plantations are dominated by a few species of fast-growing trees, such as eucalyptus, pine, and poplar. However, there is evidence to suggest that greater diversity of tree species can contribute to increased carbon sequestration over the long term. Mixtures of different tree species often exhibit faster growth rates and better survival rates [16-19], which together enhance carbon uptake on a forest stand scale. Even in the absence of a significant correlation between species diversity and plant productivity [20-21], polycultures contribute to the development of other desirable ecosystem effects. In particular, greater species richness guarantees carbon capture regardless of annual climatic changes [22], and the landscape's resistance to destruction increases [23]. Species selection is crucial in the context of environmental restoration since previous land use and the identity of planted species interact, affecting the trajectory of restoration of territories, including forests [24]. Furthermore, native tree species have been associated with a higher level of plantation biodiversity compared to exotic species [25]. Examples of successful matching between species and sites can be found in two vastly different economic and geographical contexts: the British Isles (covering 4 million ha, or 10% of the total land area) and China (covering approximately 62 million ha, equivalent to about 1% of the country's land area) [26].

The fate of carbon sequestered by growing trees is an important factor in determining the amount of carbon captured by both natural forests and planted ones [27]. A portion of the carbon stored in tree biomass will eventually become part of the soil through the process of litter and root deposition, where it may remain for decades or even millennia [28]. Soil contains more carbon than both terrestrial vegetation and the atmosphere combined, so even minor changes in the size of this reservoir can have a significant effect on the extent of carbon uptake by forests. Reforestation, forestation, and land restoration efforts in general have been shown to contribute to the accumulation of additional carbon in soils over a period of ten years [29-30]. In this case, planting cultivated and/or wild grasses will increase the stability of carbon in the soil).

It is known that the fate of plant-derived carbon in soils is largely determined by the physiology of decomposer microorganisms and their interaction with soil minerals [31-32]. Carbon (Figure 1) enters the soil in the form of root secretions or as a result of decomposition of root or aboveground biomass; in soil, C is present in root or microbial biomass, in the form of bioavailable labile organic or in the form of more persistent carbon; carbon leaves the soil in the form of direct emissions or through root or microbial respiration, while microbial-mediated soil respiration is the main source of CO_2 from terrestrial ecosystems; carbon is also lost from the ecosystem in the form of volatile organic compounds (VOCs) and methane (CH_4) [33]. Improving soil quality contributes to the accumulation of carbon in it [28]. Fertilizers also affect the circulation and stabilization of organic substances in the soil [34]. Forests are widely recognized as the main carbon sink in terrestrial vegetation due to the absorption of huge amounts of carbon dioxide. It is known that trees and woody biomass play an important role in the global carbon cycle. Forest biomass accounts for more than 45% of terrestrial carbon stocks, while approximately 70% and 30% are contained in aboveground and underground biomass, respectively [35,36]. Woodlands outside forests have a significant distribution, but there is still little information about carbon stocks in these systems or their carbon sequestration potential [37,38]. It is known that when planting even with low density due to the large area occupied, the cumulative carbon accumulation in trees can be significant [39,40]. It is believed that only in aboveground biomass such trees accumulate 3-15 Mg/ha/year [41], which is comparable to other carbon sinks such as soil [42]. It has been established that the use of plantations of tree crops for carbon sequestration also leads to an increase in the level of sustainable development and mitigation of climate change [39,43-48]. In [43], the following carbon sequestration potential by monoplantations of some tree crops was determined: cocoa tree (age 21 years) - 65.0 tC/ha and 3.1 tC/ha/year; oil palm (7) - 21.7 tC/ha and 3.1 tC/ha/year; oil palm (16) - 28.0 tC/ha and 1.8 tC/ha/year; oil palm (23) - 45.3 tC/ha and 2.0 tC/ha/year; rubber tree (12) - 61.5 tC/ha and 5.1 tC/ha/year; rubber tree (44) - 213.6 tC/ha and 4.9 tC/ha/year; orange tree (25) - 76.3 tC/ha and 3.1 tC/ha/year, aboveground and accumulation, respectively. As a rule, the ability of trees and shrubs to absorb and retain carbon is closely related to the accumulation of biomass, the amount of which increases on trees with age. The concept of "carbon uptake by forest plantations" is closely related to the concept of "agroforestry". In any interpretation, agroforestry defines two characteristics of ecosystems [49]: the deliberate cultivation of woody perennial plants on the same unit of land as crops and/or animals, or in any combination; there must be significant interaction between woody and non-woody components of the system, either ecological or economic. Agroforestry is an umbrella term for land use practices and technologies that involve the intentional integration of woody perennial plants (trees, shrubs, palm trees, bamboo, and others) with agricultural crops and/or animal husbandry on the same land, in a specific spatial arrangement or time sequence [49,50]. As a rule, agroforestry includes two or more species of plants (or plants and animals), at least one of which is a woody perennial; the cycle of the agroforestry system always exceeds one year; the agroforestry system always has two or more outputs, and even the simplest agroforestry system is more complex and efficient than the monoculture system [49].

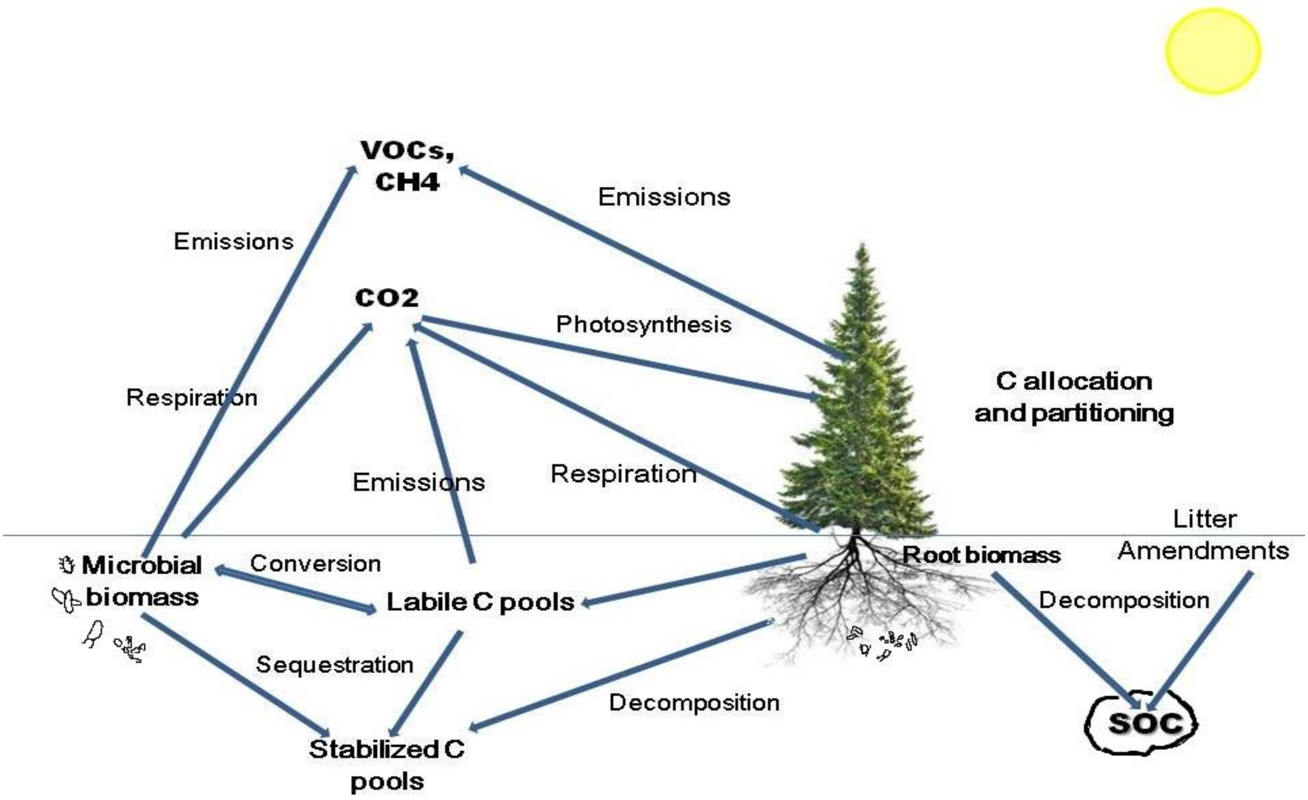

Figure 1. The transfer of atmospheric CO_2 into biotic and soil carbon (C) unites the plant ecosystem.

Source: the figure by the authors, the scheme's idea [33].

Figure 2. The results of biological reclamation (planting in 2014) of the dump of the coal enterprise of the Kemerovo region - Kuzbass (photo from the KemSU collection).

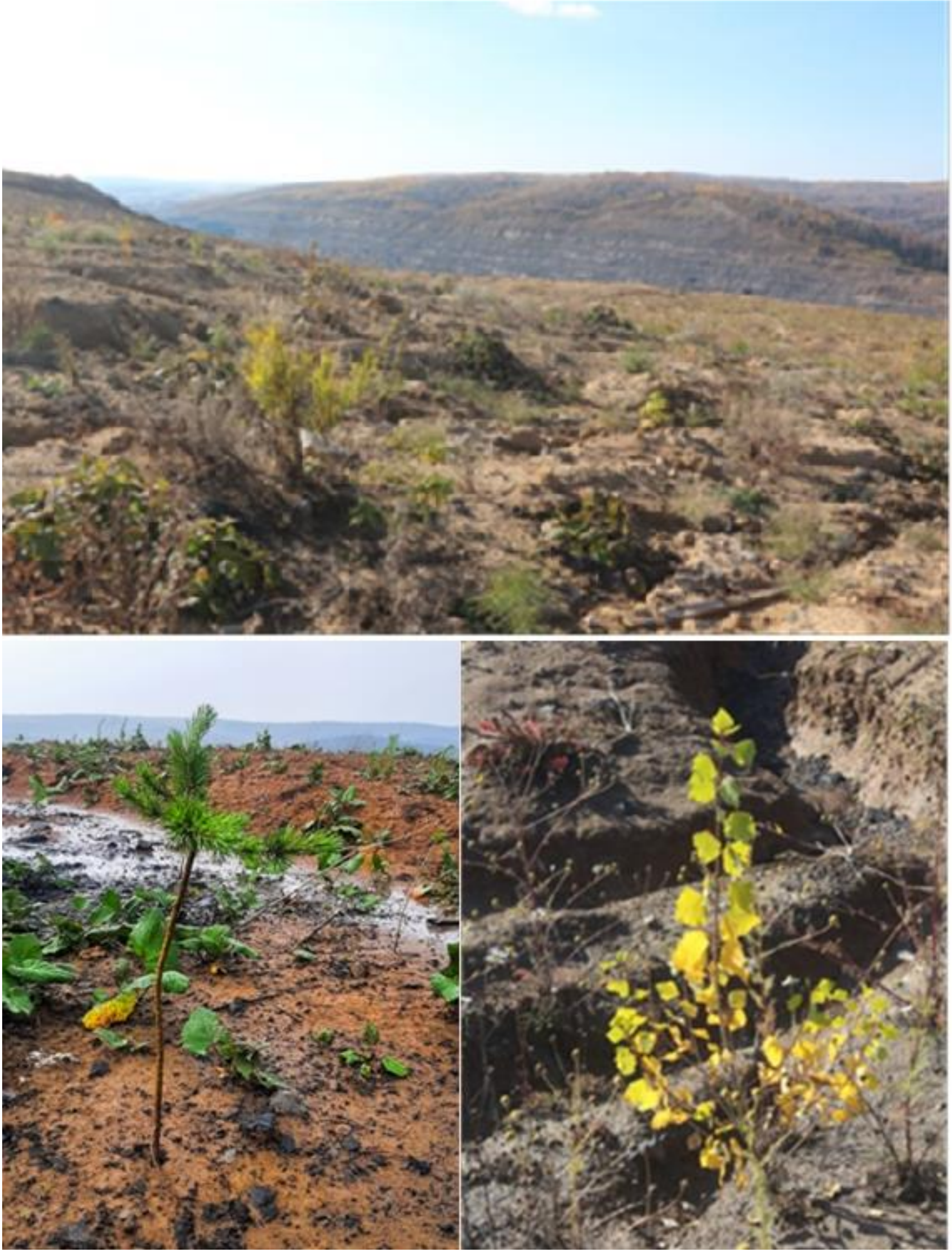

Figure 3. The results of biological reclamation (planting in 2021) of the dump of the coal enterprise of the Kemerovo region - Kuzbass (photo from the KemSU collection).

Table 2. Carbon stocks and sequestration rates in various agroforestry systems of the world

Region	System	Components	Carbon stocks (MG/ha)		Carbon sequestration rate (MG/ha/year)	Sources
			Range	Value		
Africa	Faidherbia albida	-	-	-	0.22–0.77	[51,66]
	Home gardens	-	-	-	0.4–0.8	[51,67]
Brazil	Cocoa with	-	-	-	2.7	[51,68]
Canada	Trees of the protective belt	Deciduous (green ash, Manitoba maple, hybrid poplar and	110–367	-	-	[51,69]
		Coniferous species (white spruce, Scots pine and Colorado	107–186	-	-	[51,69]
		Shrubs (bird cherry, Manchurian lilac, buffalo grape, Caragana,	160–387	-	-	[51,69]
	Tree-based intercropping	Hybrid poplar + barley	-	78.5	-	[70,71]
Chilean Patagonia	Silvopastoral	-	-	224	-	[51,72]
Claveria, Philippines	The small-scale farming system	Ground	3.9 - 159.7	0.3–17.9	-	[51]
Costa Rica	Alley cropping system	*Erythrina poeppigiana* (Walp.) O. F. Cook + maize and bean	-	162	-	[70,73]
Eastern Tanzania	The system of rotational forest	-	18–26	2.32–5.10	-	[51,74]
Europe	Pinus radiata	-	40.8–102.4	-	-	[51,75]
	Dehesa system	-	-	27–50	-	[71,76]
India	Agri-silviculture	*Populus deltoides*	-	-	12.0	[77,78]
	Agri-silviculture	*Dendrocalamus hamiltonii*	-	-	15.9	[77,79]
	Plantation	*Eucalyptus hybrid*	-	-	7.88	[77,80]
	Alley cropping	*Leucaena leucocephala*	-	-	3.4	[77,81]
USA	Coastal buffers	Ground	7.5–269	123	2.6	[51,82]
		Underground	2.0–14.4	4.6	-	
		Soil	1.8–5.5	3.6	-	
	Alley	Ground	0.05–96.5	26.8	3.4	
		Soil	0.05–25	6.9	-	
	Wooded meadows	Ground	1.17–12.2	4.9	6.9	
		Soil	1.03–1.38	1.21	-	
	Windbreaks	Ground	0.68–105	-	-	
		Soil	23.1	-	6.4	
		Hybrid poplar	-	367.0	0.73	
		White spruce	-	186.0	-	

In most cases, dwarf trees and shrubs predominate on degraded lands [51], which have little ecological and economic value; therefore, plantations of local and superior tree species are usually preferable on such lands to increase biomass production and higher carbon uptake, which is the ultimate goal of solving the problem of climate change [51,52]. The selection of suitable tree species is an important criterion that greatly affects the success of tree species plantings (afforestation). Evaluating the effectiveness of species in terms of growth, biomass production, and carbon stocks is also necessary for a successful plantation plan. It is known that *Azadirachta indica*, *Acacia catechu* and *Emblica officinalis* produced higher biomass and carbon reserves on dry degraded lands [53,54]. Thus, afforestation has the potential to produce more biomass, contributing to an increase in carbon stocks on degraded lands. On the contrary, land degradation reduces the carbon stock in vegetation due to poor survival and low biomass of tree species. Therefore, afforestation of degraded lands can potentially lead to an increase in the carbon concentration in the atmosphere and can become the main sink of CO_2 if their potential is effectively used [55]. Kumar et al. [56] call for the development of agroforestry is essential for increasing resilience to climate change and promoting carbon sequestration in heavily degraded gorges/mines. Continuous annual efforts to selectively plant species and implement sustainable practices on degraded lands can balance and manage the global carbon cycle [51,57-59]. Tree planting is a viable option in situations where soils affected by salinization cannot be restored by conventional methods. In soils subject to salinization, due to lower plant growth, the carbon intake into the soil is very low, which is the main reason for the lower nutrient content in soils subject to salinization [60]. Some promising species for agroforestry are mesquite, acacia, *Tamarix articulata* and *Casuarina equisetifolia*. In soils with a high pH level, a forest pasture system based on *P. juliflora-Leptochloa fusca* has been recognized as promising for the sustainable production of fuelwood and feed [61]. Appropriate planting methods have been standardized for growing tree plantations on saline (subsurface planting, ridge-trench method, subsurface planting and furrow irrigation system) and sodic (ridge-trench method, auger method, quarry-auger method, quarry-augermethod and furrow method) soils. Various agroforestry systems based on fruit trees and shrubs, bush beans and barley as auxiliary components have been recognized as feasible and profitable [62]. Table 2 provides information on carbon sequestration by plants in different regions. It is known [63] that the conversion of agricultural lands and pastures into agroforestry increases the organic carbon content in the soil by 34% (0-100 cm) and 10% (0-30 cm), respectively. Woody systems have a huge potential for biomass production and carbon storage compared to systems without woody perennials. Forests accumulate more carbon in their biomass than agroforestry systems and meadows, the stock of soil carbon in forest soils is higher than in pastures or agroforestry. Forests and agroforestry can accumulate carbon in the range from 1.5 to 3.5 MG/ha/year [64-65]. In semi-arid, subhumid, humid and temperate regions, the average carbon uptake by agroforestry methods is estimated as 9, 21, 50 and 63 MG/ha. In addition, agroforestry retains carbon reserves in the range of 213.8–220.8 tons of carbon/ha in Central America [66]. Thus, agroforest lands can be effective carbon sinks, provided they are properly designed and managed. Biomass, carbon stocks in biomass and in soil vary depending on vegetation type, age, density, soil type, soil organic carbon, topography, soil and climatic conditions of land use systems.

When choosing plants that will absorb a larger volume of carbon dioxide, rapid growth is taken into account (high intensity of biomass accumulation); large leaves (large interaction surface allows to absorb large amounts of carbon dioxide from the air); high concentration of chlorophyll, which is responsible for photosynthesis; woody plants (large leaf surface, long life cycle allows to absorb significant amounts of carbon dioxide from the air); aquatic plants (algae, phytoplankton and marine plants absorb large amounts of carbon dioxide from the environment. The inclusion of such plants in an eco-environment with plantations can help increase the absorption of CO_2. Examples of plants that absorb carbon dioxide well include oak and birch trees, fast-growing acacia and maple species, and bamboo. However, for specific plantations, experts in agriculture or botany should be contacted to determine the most suitable plants for a particular climate and conditions.

For effective land reclamation, in addition to the formation of a plant biome, it is necessary to maintain the ecosystem as a whole, i.e. the formation of microbiota and fauna in the territories. To achieve maximum results in improving the ecological situation of the region, it is important to use a combination of land reclamation methods. The modern approach is based on the formation of stable self-sustaining woody-grass biota with high biological diversity and biological features of forest vegetation in the foreground that are maximally adapted to the conditions of man-made territories. Forest plantations are formed from a wide range of species of trees and shrubs from the composition of the belt vegetation. In addition to coniferous and deciduous crops, shade-tolerant species such as mountain ash (*Sorbus sibirica)*, elderberry (*Sambucus sibirica)*, acacia (*Caragana arborescens*), etc., forming the undergrowth of local tree species, are used as shrub layer. To activate the soil-forming process, it is recommended to plant perennial cereals, legumes, and complex-colored grasses during the formation of young plants [83]. Moreover, at the state level, forestry as a whole is considered as a technology to mitigate the effects of climate change.

Currently, reforestation is the leading direction for the restoration of lands disturbed by the coal industry in the Kemerovo region – Kuzbass (Western Siberia, Russia). This area is the most economical and easiest to implement, and forest communities are the best at converting disturbed lands into productive habitats (Figures 2-3). The impact on the ecosystem through reforestation, the creation of plant communities on landfills is an important criterion for the restoration of technogenically disturbed lands [84]. Modern recommendations on forest reclamation are focused on the creation of monocultures that are insufficiently stable, do not create a nature-like structure of plant communities and are not stable for a long period of time [85]. The main forest-forming species on coal dumps are *Betula pendula, Pinus sylvestris* and *Populus tremula*. Related species are *Acer negundo, Crataegus sanguinea, Hippophaë rhamnoides, Lonicera tatarica, Malus baccata, Padus avium, Rosa acicularis, Salix cinerea, Sambucus sibirica, Swidina alba* and *Ulmus pumila*. More successful reforestation is achieved under favorable environmental conditions (lowlands, northern slopes with a steepness of less than 15° or flat areas with a well-defined microrelief). Birch planting in general can be considered satisfactory on almost all dumps of the southern forest-steppe of the Kemerovo region. The abundance of renewal of the invasive species *Acer negundo* is maintained due to the constant introduction of seeds into landfills (most seedlings and young undergrowth of the plant die before reaching generative age) [84-88].

4. Conclusions

The best way to capture carbon is to plant trees on abandoned lands avoiding grassy areas where there is a native biota that can be disturbed. Trees absorb carbon from the atmosphere during their growth and perform the function of draining harmful emissions. The disturbed territories of mines are perfect for this. Carbon farming efforts, such as nature restoration projects, can be more effective if monoculture is avoided and the focus on restoring biodiversity while absorbing carbon is made.

The described decarbonization measures largely coincide with the measures of biorecultivation of technogenically disturbed lands of coal mines. The exception is aquatic plants that could be used in the flooding of spent quarries, which is not practiced in the coal mines of the Kemerovo region – Kuzbass. When choosing a planting material for coal dumps, as well as cultivated and wild plants for growing in experimental fields, traditional recommendations for the use of plants in biorecultivation were taken into account in combination with recommendations for measures to absorb carbon from the atmosphere.

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