Soil Carbon Sequestration

Subjects: Soil Science

Contributor: Amisalu Milkias

Carbon sequestration is the process of capturing, securing, and storing carbon dioxide from the atmosphere. Carbon is sequestered in soil by plants through photosynthesis and can be stored as soil organic carbon (SOC). The amount of SOC accumulated in RMS was mostly influenced by the restoration age, vegetation type, and substrate or type of reclamation used.

mining sites novel ecosystem soil carbon

1. Introduction

In the Anthropocene, human activities, such as mining, have caused large-scale ecosystem disruptions and changes to the earth's surface [1][2]. Human activities have also altered global element cycles, including carbon, while the gradual increase in carbon dioxide content in the atmosphere continues to be a driving factor for climate change.

The removal of vegetation cover and topsoil causes a severe decrease in soil organic carbon (SOC) content, making mining one of the most significant human impacts on the environment [3][4]. Shrestha and Lal [5] found that SOC in reclaimed mine soils decreased by up to 83% when compared with undisturbed sites. Land productivity is also diminished as a result of soil profile disturbance during mining [6]. The exposed or deposited post-mining substrates become the parent rock of the developing soils called reclaimed mine soils (RMS) or Technosols [7][8][9]. These substrates typically display a lack of SOM, nutrient deficiency (mainly of nitrogen and phosphorus) and disturbed nutrient ratios, low pH-values, and unfavorable air–water properties [2][9][10].

When it comes to restoring the ecological function of mining sites after exploitation, two basic questions should be considered: succession or reclamation [11]? Succession does not always allow for the restoration of soil function and plant communities in a timely manner. As a result, anthropological intervention through reclamation stimulates the long-term process of succession in post-mining sites [10][12]. The reclamation of mining sites improves the productivity of the sites as well as the sequestration of lost carbon (C) and the reduction in CO_2 emissions [7]. For example, Pietrzykowski and Socha [13] revealed that Scots pine (*Pinus sylvestris* L.) productivity in post-mining ecosystems was comparable with that of a managed forest on a natural pine site. As a result, mine heap rehabilitation is critical for the restoration of ecosystem services [14][15]. The goal of reclamation (how it will be used later); natural conditions, such as climate, the availability of soil substrates, and water balance; technical (mining) management, including management of rock overburden; and the relief of the site designed for reclamation all influence the design and detailed planning of reclamation treatments [9][11][13]. In areas with a well-formed landscape, favorable hydrological conditions, and potentially productive soils, reclamation may entail using biological methods such as agricultural practices, mineral fertilization, and the introduction of appropriate humus-forming vegetation to target and skillfully accelerate soil formation processes. In places with barren or phytotoxic soils (e.g., the acidic and sulfurous Miocene sands, etc.), the basic restoration technique, in addition to appropriate landscape formation and hydrological condition regulation, consists of sealing and neutralization, followed by biological reclamation [16].

Planting vegetation is the most popular biological restoration approach for mining sites [10][17]. Mining constrains the establishment of vegetation by affecting essential soil components for plant growth, such as organic matter, microbial activity, and water, as well as by increasing bulk density and heavy metals [17][18][19][20]. Reclaiming a rehabilitation site with various methods such as topsoiling (i.e., respreading of salvaged topsoil or spreading of uppermost soil layer from surrounding arable fields), green manure such as lupine and alfalfa, biochar, inclusion of plant litters, fertilizer treatment, and planting of grass and leguminous shrubs aids in the growth of vegetation [21][22][23]. Planting vegetation at a mining site plays a crucial role in the production of organic matter, which supports soil biota and releases carbon and essential nutrients into the soil [15][24][25][26][27][28]. Improved soil organic matter may also improve the soil moisture-holding capacity and soil cation exchange, which are vital in the restoration of degraded mining soils [29]. Evaluating a mine site after restoration is vital to ensuring successful restoration. Among the reclamation quality indicators, SOC is very reliable, and evaluating its’ status over time shows the quality of the reclaimed land [4][28][30][31][32].

The accumulation rate of SOC in a reclaimed site is affected by different driving factors, such as the age of the stand, the type of vegetation, treatments applied before restoration, the approach of rehabilitation, and agro-climate [13][28][33]. Litterfall from the planted vegetation is one of the major sources of SOC in reclaimed sites, and its accumulation over time has a direct relationship with SOC. The findings of Barliza et al. [34] in spoil heap reclaimed from an opencast coal mine in Colombia indicates that the highest fine litterfall recorded in the 21-year-old site (2.3 Mg ha^{-1} $year^{-1}$) was more than double that recorded in the 7-year-old site (1.1 Mg ha^{-1} $year^{-1}$) and concluded the enriching role of litterfall on soil organic matter content and nutrient status with the increasing age of the stand. An increase in the age of the stand also increases the microbial community [35], which results in the decomposition of organic matter and increases the amount of carbon in the soil with increasing age. Mukhopadhyay et al. [36] also concluded that age of reclamation has a significant effect on the nutritional and microbial properties of the mine soils.

Since the beginning of the history of mining, many studies have been conducted on reclamation methods for degraded mining sites to minimize its environmental impact and to enhance ecosystem services in the changing climate. Several studies have evaluated the effects of mining site reclamation on carbon sequestration [33][37][38][39][40][41].

2. Factors Affecting Carbon Accumulation in RMS

The restoration of mining sites often contributes to SOC accumulation, but its rate may be affected by different factors such as the reclamation method, the age of restoration, the climate, soil properties, soil moisture, and vegetation [17][28][33][37][42][43] (**Table 1**).

Table 1. The effect of age on soil organic carbon accumulation.

Tree Species	Age of the Plantation	SOC Total Stock (Mg ha^{-1})	SOC Accumulation Rate (Mg ha^{-1} Year^{-1})	Soil Depth (cm)	MAP(mm)	MAT (°C)	Reclaimed Mine Soil Substrate Type	General Reclamation Techniques	References
Mixed Forest	5	9.11	1.82	0–20	1000	26	Coal	Top soil with mixed forest	[28]
	10	19.89	1.99						
	25	41.37	1.65						
Quercus liaotungensis	11	32.59	1.59	0–30	431.1	10.0	Coal	Leveling and top soiling	[44]
Pinus tabuliformis		16.04	0.37						
Mixed *Acacia auriculiformis, Sennasiamea, Acacia catechu* and *Dalbergia sissoo*	3	1.83	0.61	0–15	1375	25.7	Coal	Regrading of spoil materials and plantation of tree species	[8]
	7	3.65	0.52						
	10	5.82	0.58						
	15	7.60	0.51						
Prosopis juliflora	2	8.1	4.05	0–60	975	27.5	Coal	Regrading and top soiling	[33]
	3	12.6	4.20						
	4	17	4.25						
	5	19.2	3.84						
	6	27.5	4.58						
	7	32.8	4.69						
	8	45.4	5.68						
Robinia pseudoacacia L.	2	11.7	4	0–30	569	9.4	Lignite	NK fertilization, and spread of a mixture	[45]
	14	59.8							

Tree Species	Age of the Plantation	SOC Total Stock (Mg ha^{-1})	SOC Accumulation Rate (Mg ha^{-1} Year^{-1})	Soil Depth (cm)	MAP(mm)	MAT (°C)	Reclaimed Mine Soil Substrate Type	General Reclamation Techniques	References
								of rye and alfalfa	
Dalbergia sissoo	2	1.1	0.55	0–15	1308	27	Coal	Top soiling, farm yard manure, and NPK fertilizers	[46]
	16	8.91	0.56						
Mixed Forest	5	7.02	1.40	0–25	1230	16.2	Coal	Loose-graded, hydroseeded, and NPK	[47]
	11	13.52	1.23						
	21	21.35	1.02						
Alder (*Alnus glutinosa*)	28	33.49	1.20	0–20	650	6.8	Coal	n/a *	[48][49]
Lime (*Tilia cordata*)	31	34.51	1.12						
Oak (*Quercus robur*)	28	15.01	0.54						
Spruce (*Picea* sp.)	27	8.46	0.32						
Pine (*Pinus* sp.)	22	8.80	0.40						
Casuarina equisetifolia	6	3.19	0.53	0–30	1228	21.7	Heavy mineral	Topsoil with a seed mixture of short-lived annual species	[50]
	9	3.75	0.42						
	12	9.35	0.78						
	15	11.55	0.77						
Mixed Forest	2	5.4	2.70	0–30	975	23	Coal	Only backfilled dumps	[51]
	8	16.4	2.05						
	14	26.4	1.89						
Scots pines and giant	n/a	33	n/a	0–20	n/a	n/a	Lignite	Sewage sludge	[52]

Tree Species	Age of the Plantation	SOC Total Stock (Mg ha^{-1})	SOC Accumulation Rate (Mg ha^{-1} Year^{-1})	Soil Depth (cm)	MAP(mm)	MAT (°C)	Reclaimed Mine Soil Substrate Type	General Reclamation Techniques	References
miscanthus plants.		45	n/a					Compost	
Scots pines	25	27.2	1.1	O to C2 horizon	n/a	n/a	Lignite	Liming and NPK fertilizers	[53]
		37.4	1.50					NPK fertilizers	
Scots pines	12	63.1	5.20	0–110	580	7.6	Lignite	Liming, NPK fertilization and sowing a mixture of grasses and leguminous plants	[8][28][47][50][51]
	17	45.9	2.70						
	21	22.6	1.08	0–110	700	8	Sand	Top soiling, NPK fertilization, and lupine as green manure	[54]
	23	16.8	0.73						
	30	65.0	2.17	0–110	650	7	Sulfur	Leguminous and grass crop with NPK fertilization	
	30	34.4	1.15						
Pasture land	25	36.7	1.47	0–30	n/a	n/a	Coal	Grading and application of stored top and subsoils	[55]
Forest land		37.1	1.48						

tree species showed a rate of SOC accumulation in the range of 1.2–2.8 Mg SOC ha^{-1} year^{-1}. As indicated in **Table 1**, the annual SOC ranged from approximately 0.32 Mg ha^{-1} [48][49] to 5.0 Mg ha^{-1} [33][54]; the calculated average annual increment was 1.84 Mg ha^{-1}; and the variation in the annual increment may be due to tree species, climate, and reclamation methods [33][37][42]. Similarly, Pietrzykowski and Krzaklewski [60] also reported SOC accumulation at a rate of 1.5 Mg C ha^{-1} year^{-1} in mine soil in Poland. The findings of Stahl et al. [61] revealed increased SOC content with age and the 22-year-old and 32-year-old reclaimed soils had higher mean SOC contents than the undisturbed soil. This indicates that the age of restoration has a significant impact on the accumulation of SOC in RMS.

2.2. The Effect of Vegetation Types on SOC Accumulation

In the case of restoration by afforestation, the success of reclamation mainly depends on the type of plant species selected for revegetation for the particular site and climate [28]. The most common vegetations types used for restoration are mixed forest, deciduous, ever green, legumes, and grass [4][62][63]. Different tree species play different roles in amending mine soil properties even in the same climate [38][64][65][66]. Field experiment studies indicated significant differences in the SOC stocks under different afforested trees on the same soil substrate, which may be due to the amount of litter, the decomposition of dead roots, and the elemental composition of the individual biomass [37][67]. The decomposition of leaf litter releases the bound nutrients into the soil, which increases the SOC concentration of mine soils over time [62]. Ahirwal and Maiti [59] stated that the increase in SOC concentration is due to the accumulation of leaf litter and its subsequent decomposition to humus. Yan et al. [44] recommended Quercus liaotungensis compared with Rhus typhina and Pinus tabuliformis is associated with its significantly higher organic carbon sequestration rate (1.59 t ha^{-1} yr^{-1}) for reclamation management of degraded mining lands in China. Frouz et al. [48] also observed significantly different SOC accumulation rates among different tree species, ranging from 0.15 to 1.28 t ha^{-1} yr^{-1} in post-mining sites in the Czech Republic.

References

1. Bell, F.G.; Donnelly, L.J. Mining and Its Impact on the Environment; Taylor & Francis: London, UK; New York, NY, USA, 2006.
2. Feng, Y.; Wang, J.; Bai, Z.; Reading, L. Effects of surface coal mining and land reclamation on soil properties: A review. Earth-Sci. Rev. 2019, 191, 12–25.
3. Wick, A.F.; Stahl, P.D.; Ingram, L.J.; Vicklund, L. Soil aggregation and organic carbon in short-term stockpiles. Soil Use Manag. 2009, 25, 311–319.
4. Mukhopadhyay, S.; Masto, R.E.; Yadav, A.; George, J.; Ram, L.C.; Shukla, S.P. Soil quality index for evaluation of reclaimed coal mine spoil. Sci. Total Environ. 2016, 542, 540–550.
5. Shrestha, R.K.; Lal, R. Changes in physical and chemical properties of soil after surface mining and reclamation. Geoderma 2011, 3–4, 168–176.
6. Maiti, S.K. Ecorestoration of the Coalmine Degraded Lands; Springer: New Delhi, India, 2013.
7. Ussiri, D.A.N.; Lal, R. Carbon sequestration in reclaimed mine soils. Crit. Rev. Plant Sci. 2005, 24, 151–165.
8. Ahirwal, J.; Kumar, A.; Pietrzykowski, M.; Maiti, S.K. Reclamation of coal mine spoil and its effect on Technosol quality and carbon sequestration: A case study from India. Environ. Sci. Pollut. Res. 2018, 25, 27992–28003.
9. Pietrzykowski, M. Soil quality index as a tool for Scots pine (Pinus sylvestris) monoculture conversion planning on afforested, reclaimed mine land. J. For. Res. 2014, 25, 63–74.
10. Macdonald, S.E.; Landhäusser, S.M.; Skousen, J.; Franklin, J.; Frouz, J.; Hall, S.; Jacobs, D.F.; Quideau, S. Forest restoration following surface mining disturbance: Challenges and solutions. New For. 2015, 46, 703–732.

11. Bradshaw, A. The use of natural processes in reclamation- advantages and difficulties. Landsc. Urban Plan. 2000, 51, 89–100.
12. Pietrzykowski, M. Soil and plant communities development and ecological effectiveness of reclamation on a sand mine cast. J. For. Sci. 2008, 54, 554–565.
13. Pietrzykowski, M.; Socha, J. An estimation of Scots pine (Pinus sylvestris L.) ecosystem productivity on reclaimed post-mining sites in Poland (central Europe) using of allometric equations. Ecol. Eng. 2011, 37, 381–386.
14. Asensio, V.; Vega, F.A.; Andrade, M.L.; Covelo, E.F. Tree vegetation and waste amendments to improve the physical condition of copper mine soils. Chemosphere 2013, 90, 603–610.
15. Srivastava, N.K.; Ram, L.C.; Masto, R.E. Reclamation of overburden and lowland in coal mining area with fly ash and selective plantation: A sustainable ecological approach. Ecol. Eng. 2014, 71, 479–489.
16. Pietrzykowski, M.; Krzaklewski, W. Reclamation of Mine Lands in Poland. In Bio-Geotechnologies for Mine Site Rehabilitation; Elsevier: Amsterdam, The Netherlands, 2018; pp. 493–513.
17. Pietrzykowski, M.; Woś, B.; Haus, N. Scots pine needles macronutrient (N, P, K, CA, MG, and S) supply at different reclaimed mine soil substrates as an indicator of the stability of developed forest ecosystems Environ. Monit. Assess. 2013, 185, 7445–7457.
18. Wanga, D.; Zhanga, B.; Zhua, L.; Yang, Y.; Li, M. Soil and vegetation development along a 10-year restoration chronosequence in tailing dams in the Xiaoqinling gold region of Central China. Catena 2018, 167, 250–256.
19. Maharana, K.J.; Patel, K.A. Microbial biomass, microbial respiration and organic carbon indicates nutrient cycling in a chronosequence coal mine overburden spoil. IJES 2013, 4, 171–184.
20. Shrestha, R.K.; Lal, R. Carbon and nitrogen pools in reclaimed land under forest and pasture ecosystems in Ohio, USA. Geoderma 2010, 157, 196–205.
21. Pietrzykowski, M.; Gruba, P.; Sproull, G. The effectiveness of Yellow lupine (Lupinus luteus L.) green manure cropping in sand mine cast reclamation. Ecol. Eng. 2017, 102, 72–79.
22. Otremba, K.; Kozłowski, M.; Tatusko-Krygier, N.; Pająk, M.; Kołodziej, B.; Bryk, M. Impact of alfalfa and NPK fertilization in agricultural reclamation on the transformation of Technosols in an area following lignite mining. Land Degrad. Dev. 2020, 32, 1179–1191.
23. Reverchon, F.; Yang, H.; Ho, T.Y.; Yan, G.; Wang, J.; Xu, Z.; Zhang, D. A preliminary assessment of the potential of using an acacia—biochar system for spent mine site rehabilitation. Environ. Sci. Pollut. Res. 2014, 22, 2138–2144.
24. Moghimian, N.; Hosseini, S.M.; Kooch, Y.; Darki, B.Z. Impacts of changes in land use/cover on soil microbial and enzyme activities. Catena 2017, 157, 407–414.

25. León, J.D.; Castellanos, J.; Casamitjana, M.; Osorio, N.W.; Loaiza, J.C. Alluvial gold-mining degraded soils reclamation using Acacia mangium Wild. plantations: An evaluation from biogeochemistry. In Plantations Biodiversity, Carbon Sequestration and Restoration; Hai, R., Ed.; Nova Sci Publishers: New York, NY, USA, 2013; pp. 155–176.
26. Josa, R.; Jorba, M.; Vallejo, V.R. Opencast mine restoration in a Mediterranean semiarid environment: Failure of some common practices. Ecol. Eng. 2012, 42, 183–191.
27. Zhao, Z.; Bai, Z.; Zhang, Z.; Guo, D.; Li, J.; Xu, Z.; Pan, Z. Population structure and spatial distributions patterns of 17 years old plantation in a reclaimed spoil of Pingshuo opencast mine, China. Ecol. Eng. 2012, 44, 147–151.
28. Bandyopadhyay, S.; Novo, L.A.B.; Pietrzykowski, M.; Maiti, S.K. Assessment of Forest Ecosystem Development in Coal Mine Degraded Land by Using Integrated Mine Soil Quality Index (IMSQI): The Evidence from India. Forests 2020, 11, 1310.
29. Restrepo, M.F.; Flórez, C.P.; Osorio, N.W.; León, J.D. Passive and active restoration strategies to activate soil biogeochemical nutrient cycles in a degraded tropical dry land. Int. Sch. Res. Not. 2013, 1–6.
30. Chaudhuri, S.; McDonald, L.M.; Skousen, J.; Pena-Yewtukhiw, E.M. Soil organic carbon molecular properties: Effects of time since reclamation in a mine soil chronosequence. Land Degrad. Dev. 2013, 26, 237–248.
31. Wick, A.F.; Daniels, W.L.; Orndorff, Z.W.; Alley, M.M. Organic matter accumulation post-mineral sands mining. Soil Use Manag. 2013, 29, 354–364.
32. Bodlák, L.; Krováková, K.; Kobesová, M.; Brom, J.; Stastny, J.; Pecharová, E. SOC content—An appropriate tool for evaluating the soil quality in a reclaimed post-mining landscape. Ecol. Eng. 2012, 43, 53–59.
33. Ahirwal, J.; Maiti, S.K.; Reddy, M.S. Development of carbon, nitrogen and phosphate stocks of reclaimed coal mine soil within 8 years after forestation with Prosopis juliflora (Sw.) Dc. Catena 2017, 156, 42–50.
34. Barlizaa, C.J.; Rodrígueza, B.O.; León Peláeza, D.J.; Chávez, F.L. Planted forests for open coal mine spoils rehabilitation in Colombian drylands: Contributions of fine litterfall through an age chronosequence. Ecol. Eng. 2019, 138, 180–187.
35. Ivanova, E.; Pershina, E.; Karpova, D.; Rogova, O.; Abakumov, E.; Andronov, E. Soil microbiome in chronosequence of spoil heaps of Kursk Magnetic Anomaly. Biol. Commun. 2019, 64, 219–225.
36. Mukhopadhyaya, S.; Maiti, S.K.; Masto, R.E. Development of mine soil quality index (MSQI) for evaluation of reclamation success: A chronosequence study. Ecol. Eng. 2014, 71, 10–20.

37. Akala, V.A.; Lal, R. Soil organic carbon pools and sequestration rates in reclaimed minesoils in Ohio. J. Environ. Qual. 2001, 30, 2098–2104.

38. Juwarkar, A.A.; Mehrotra, K.L.; Nair, R.; Wanjari, T.; Singh, S.K.; Chakrabarti, T. Carbon sequestration in reclaimed manganese mine land at Gumgaon, India. Environ. Monit. Assess. 2010, 160, 457–464.

39. Ussiri, D.A.N.; Lal, R.; Jacinthe, P.A. Soil Properties and Carbon Sequestration of Afforested Pastures in Reclaimed Minesoils of Ohio. J. Soil Sci. Soc. Am. 2006, 70, 1797–1806.

40. Zhang, P.P.; Zhang, Y.L.; Jia, J.C.; Cui, Y.X.; Wang, X.; Zhang, X.C.; Wang, Y.Q. Revegetation pattern affecting accumulation of organic carbon and total nitrogen in reclaimed mine soils. Peer J. 2020, 8, e8563.

41. Shrestha, R.K.; Lal, R.; Jacinthe, P.A. Enhancing Carbon and Nitrogen Sequestration in Reclaimed Soils through Organic Amendments and Chiseling. J. Soil Sci. Soc. Am. 2009, 73, 1004–1011.

42. Parajuli, P.B.; Duffy, S. Evaluation of Soil Organic Carbon and Soil Moisture Content from Agricultural Fileds in Mississipi. J. Soil Sci. 2013, 3, 81–90.

43. Hobley, E.U.; Wilson, B. The depth distribution of organic carbon in the soils of eastern Australia. Ecosphere 2016, 7, 1–21.

44. Yan, M.; Fan, L.; Wang, L. Restoration of soil carbon with different tree species in a post-mining land in eastern Loess Plateau, China. Ecol. Eng. 2020, 158, 106025.

45. Matos, E.S.; Freese, D.; Böhm, C.; Quinkenstein, A.; Hüttl, R.F. Organic matter dynamics in reclaimed lignite mine soils under Robinia pseudoacacia L. plantations of different ages in Germany. Commun. Soil Sci. Plant Anal. 2012, 43, 745–755.

46. Mukhopadhyay, S.; Masto, R.E. Carbon storage in coal mine spoil by Dalbergia sissoo Roxb. Geoderma 2016, 284, 204–213.

47. Avera, B.N.; Strahm, B.D.; Burger, J.A.; Zipper, C.E. Development of ecosystem structure and function on reforested surface-mined lands in the Central Appalachian Coal Basin of the United States. New For. 2015, 46, 683–702.

48. Frouz, J.; Pižl, V.; Cienciala, E.; Kalčík, J. Carbon storage in post-mining forest soil, the role of tree biomass and soil bioturbation. Biogeochemistry 2009, 94, 111–121.

49. Vindušková, O.; Frouz, J. Soil carbon accumulation after open-cast coal and oil shale mining in Northern Hemisphere: A quantitative review. Environ. Earth Sci. 2013, 69, 1685–1698.

50. Van Rooyen, M.W.; Van Rooyen, N.; Stoffberg, G.H. Carbon sequestration potential of post-mining reforestation activities on the KwaZulu-Natal coast, South Africa. Forestry 2013, 86, 211–223.

51. Ahirwal, J.; Maiti, S.K. Assessment of carbon sequestration potential of revegetated coal mine overburden dumps: A chronosequence study from dry tropical climate. J. Environ. Manag. 2017, 201, 369–377.

52. Placek-Lapaja, A.; Grobelaka, A.; Fijalkowskia, K.; Singhb, B.R.; Almåsb, A.R.; Kacprzak, M. Post—Mining soil as carbon storehouse under polish conditions. J. Environ. Manag. 2019, 238, 307–314.

53. Greinert, A.; Drab, M.; Śliwińska, A. Storage Capacity of Organic Carbon in the Reclaimed Post-Mining Technosols. Environ. Prot. Eng. 2018, 44, 117–127.

54. Pietrzykowski, M.; Daniels, W.L. Estimation of carbon sequestration by pine (Pinus sylvestris L.) ecosystems developed on reforested post-mining sites in Poland on differing mine soil substrates. Ecol. Eng. 2014, 73, 209–218.

55. Akala, V.A.; Lal, R. Potential of mine land reclamation for soil organic carbon sequestration in Ohio. Land Degrad. Dev. 2000, 11, 289–297.

56. Sperow, M. Carbon Sequestration Potential in Reclaimed Mine Sites in Seven East-Central States. J. Environ. Qual. 2006, 35, 1428.

57. Filcheva, E.; Noustorova, M.; Gentcheva-Kostadinova, S.; Haigh, M.J. Organic accumulation and microbial action in surface coal-mine spoils. Pernik, Bulgaria. Ecol. Eng. 2000, 15, 1–15.

58. Adeli, A.; Brooks, J.P.; Read, J.J.; McGrew, R.; Jenkins, J.N. Post-reclamation age effects on soil physical properties and microbial activity under forest and pasture ecosystems. Commun. Soil Sci. Plant Anal. 2018, 50, 20–34.

59. Ahirwal, J.; Maiti, S.K. Development of Technosol properties and recovery of carbon stock after 16 years of revegetation on coal mine degraded lands, India. Catena 2018, 166, 114–123.

60. Pietrzykowski, M.; Krzaklewski, W. Potential for carbon sequestration in reclaimed mine soil on reforested surface mining areas in Poland. Nat. Sci. 2010, 2, 1015–1021.

61. Stahl, P.D.; Anderson, J.D.; Ingram, L.J.; Schuman, G.E.; Mummey, D.L. Accumulation of Organic Carbon in Reclaimed Coal Mine Soils of Wyoming. In Proceedings of the National Meeting of the American Society of Mining and Reclamation and the 9th Billings Land Reclamation Symposium, Billings, MT, USA, 3–6 June 2003.

62. Kumari, S.; Maiti, S.K. Reclamation of coalmine spoils with topsoil, grass, and legume: A case study from India. Environ. Earth Sci. 2019, 78, 429.

63. Li, C.; Gao, S.; Zhang, J.; Zhao, L.; Wang, L. Moisture effect on soil humus characteristics in a laboratory incuba-tion experiment. Soil Water Res. 2016, 11, 37–43.

64. Mukhopadhyay, S.; Maiti, S.K.; Masto, R.E. Use of Reclaimed Mine Soil Index (RMSI) for screening of tree species for reclamation of coal mine degraded land. Ecol. Eng. 2013, 57, 133–

142.

65. Mukhopadhyay, S.; Maiti, S.K. Trace metal accumulation and natural mycorrhizal colonisation in an afforested coalmine overburden dump—a case study from India. Int. J. Min. Reclam. Environ. 2011, 25, 187–207.
66. Mendes Filho, P.F.; Vasconcellos, R.L.F.; de Paula, A.M.; Cardoso, E.J.B.N. Evaluating the potential of forest species under microbial management for the restoration of degraded mining areas. Water Air Soil Poll. 2010, 208, 79–89.
67. Ahirwal, J.; Kumar, A.; Maiti, S.K. Effect of Fast-Growing Trees on Soil Properties and Carbon Storage in an Afforested Coal Mine Land (India). Minerals 2020, 10, 840.