JOURNAL OF FOREST SCIENCE, *54*, 2008 (6): 273–280

Forest reclamation of dumpsites of coal combustion by-products (CCB)

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ABSTRACT: The present paper describes the reclamation of dumpsites of coal ash – coal combustion by-products (CCB) generated by the burning of brown coal in thermal power plants. It evaluates the soil properties of formed Anthroposols and growth vitality of the forest tree species *Quercus robur* L., *Quercus rubra* L., *Pinus sylvestris* L., *Betula verrucosa* Ehrh., *Populus tremula* L., *Populus nigra* L., *Salix fragilis* L., *Salix alba* L., *Alnus glutinosa* (L.) Gaertn. The best growth vitality at these sites was reached in tree species of seed origin from the vegetation series of primary succession. Deformations of the taproot (taproot laterals) in trees under 10 years of age were observed on Anthroposol from coal ash in *Salix alba* L., *Salix fragilis* L., *Populus tremula* L., *Populus nigra* L. and *Populus alba* L. and in the overlaying of the compacted stabilizate with a layer of reclaimable soil up to 0.5 m in *Pinus sylvestris* L., *Alnus glutinosa* (L.) Gaertn. and *Quercus rubra* L.

Keywords: forest reclamation; Anthroposol; coal-ash dumpsite; coal combustion by-products; soil properties; growth vitality; root system

The reclamation of coal ash before reforestation coming from the combustion of different types of coal in thermal power stations and deposited in settling pits by hydraulic sluicing was most frequently done in the Czech Republic before 1990 by the overlaying of its surface with suitable reclaimable soils (topsoil, pressmud) 5–10 cm in thickness and by grassing down. Taxa (Špiřík 1973; Malý, Špiřík 1975) usable on all types of coal ash coming from black and brown coal including lignite were considered as "suitable" tree species with higher ameliorative effects. This group most frequently comprised *Alnus incana* (L.) Moench., *Alnus glutinosa* (L.) Gaertn., *Populus tremula* L., *Populus alba* L., *Tilia cordata* Mill., *Robinia pseudoacacia* L., *Salix fragilis* L., *Acer negundo* L., *Crataegus oxyacantha* L., *Ligustrum vulgare* L., *Physocarpus opulifolius* Maxim., *Hippophaë rhamnoides* L., *Caragana arborescens* Lam. The second group was composed of "partly suitable" tree species but of greater economic importance; their growth on coal ash was not always convincing but they were also usable if other ameliorative measures (green manuring, topsoil application to the hole before outplanting, additional application of mineral fertilizers, mulching around plants) were parallelly taken in the course of reforestation of these localities. *Quercus robur* L., *Quercus rubra* L., *Acer pseudoplatanus* L., *Acer platanoides* L., *Ulmus laevis* Pall., *Fraxinus excelsior* L., *Larix decidua* Mill., *Pinus sylvestris* L., *Pinus nigra* Arn., *Spirea salicifolia* L., *Cornus sanguinea* L., *Lonicera tataricum* L. were included in this group most frequently. Another technique of reforestation of these localities consisted in the planting of tree species with high ameliorative effects – *Alnus glutinosa* (L.) Gaertn. or *Alnus incana* (L.) Moench., and only after on-site conditions had improved (after 10–15 years), the planting of tree species of greater economic importance was envisaged. Adequate reclamation technologies on similar types of recent

Supported by the Ministry of Agriculture of the Czech Republic, Project No. 0002704901.

formations are currently recommended also in other countries (Juwarkar et al. 1993; Dobson, Moffat 1993; Srivastava et al. 1995; Alonso et al. 2002; Athy et al. 2006).

The experience with reclamations of new dumpsites of coal combustion by-products (hereinafter CCB), deposited in a dry state after 1995 in connection with the introduction of other technologies of desulphurization of thermal power stations in the CR, is scarce. Particularly a compacted stabilizate and the proposal of a suitable physiological depth for the development of tree taxa are reclamation problems whereas the knowledge acquired by studying the coal ash of several meter thickness deposited by hydraulic sluicing with similar profile chemical and physical properties can be applied only partly. Currently, projects solving the problem of CCB most frequently recommend the application of technologies when they are overlaid with soils of different pedological quality and of maximum thickness 0.7 m, in practice usually max. 0.5 m.

To test suitable reclamation methods for these dumpsites a field trial with the planting of *Pinus sylvestris* L. and *Quercus robur* L. was conducted already in 1996 on sluiced coal ash treated with additive-containing agglomerate (CaO) and with agglomerate without additives (Herynek 1997, 1998) in the area of the power station Mělník in Panský les locality. Another experimental object for the evaluation of the condition of reforested coal ash settling pits in the CR (Minx 2003) was established in the area of the power station in Chvaletice (Čermák, Kohel 2005) that has been studied continually and where reclamation variants of Anthroposol formation for forestry purposes have been evaluated: besides the conventional method of the overlaying of the compacted stabilizate with soil layer (up to 0.5 m in thickness) the overlaying with different reclamation substrates up to 1.5 m in thickness has been tested.

MATERIAL AND METHOD

Coal combustion by-products (CCB, certified products) currently originate from power-station treated fly ash from coal burning in thermal power stations: they are used in the building industry or they are deposited on dumpsites in a dry state and used for reclamation purposes:

Agglomerate – fly ash without additives, treated with mixing water (ca 25% proportion). Chemical and physical properties of this product are similar to those of coal ash deposited by hydraulic sluicing.

Stabilizate – a mixture of fly ash treated with 1–2% CaO, 25% water, slag and FDG gypsum. Chemical and physical properties contribute to the origination of an adverse soil environment (high alkalinity, cementing effects).

FDG* (*flue gas desulphurization*) *gypsum (dihydrate of calcium sulphate) – a product of flue-gas scrubbing by wet limestone washing. Chemical and physical properties contribute to the origination of an adverse soil environment (high alkalinity, cementing effects, high content of sulphates and chlorides).

On-site characteristics of evaluated coal ash dumpsites

Panský les locality is situated in the area with annual precipitation amount of 489 mm and vegetation precipitation amount of 339 mm. An experimental plot for the testing of coal combustion by-products for forest reclamation purposes (reclamation variant "B") was established on coal ash deposited by hydraulic sluicing while two technologies were used to treat its surface. Compacted stabilizate 0.5 m in thickness (reclamation variant "C"), which would reduce the seepage of precipitation waters into the subsoil, and agglomerate without additives were applied to one part of this plot whereas the other part of this plot was treated only with agglomerate without additives 0.50 m in thickness. The final treatment of the surface of the entire experimental plot before reforestation consisted in the application of a cover layer composed of pressmud and cellulose sludge 5–10 cm in thickness that would reduce evapotranspiration, surface overheating and dustiness. The entire plot was reforested with bare-rooted planting material (2/0) and containerized planting material (2/1) grown in removable PVC containers, and the plants were set out into dug holes. *Quercus robur* L. and *Pinus sylvestris* L. were used for reforestation. The evaluated tree species of seed origin (primary succession) in this locality are individuals occurring at a site with hydraulically sluiced coal ash where its surface was covered (to prevent dustiness) with a geotextile only (reclamation variant "D").

Chvaletice locality is situated in the area with annual precipitation amount of 593 mm and vegetation precipitation amount of 378 mm. The dumpsite is the space of a former quarry for manganese-pyrite slates that was filled in 1980–1995 with coal ash from the combustion of brown coal in a thermal power station and after 1995 only compacted stabilizate was deposited in a dry state to the level of the terrain that corresponded to the original landscape before

the extraction of slates. An experimental plot for the testing of coal combustion by-products for forest reclamation purposes was established on compacted stabilizate (reclamation variant "C") using the technology of stabilizate overlaying with reclaimable soil 0.4–0.5 m in thickness (reclamation variant "A"). The entire plot was reforested with bare-rooted planting material (2/0) that was outplanted with a trench planter. *Pinus sylvestris* L. (more than 60%) was mostly used for reforestation, other tree species were *Alnus glutinosa* (L.) Gaertn., *Quercus rubra* L., *Larix decidua* Mill., *Betula verrucosa* Ehrh., *Acer pseudoplatanus* L. and *Populus tremula* L. The evaluated tree species of seed origin (primary succession) in this locality are again individuals occurring at a site with hydraulically sluiced coal ash where its surface was covered (to prevent dustiness) with a geotextile only (reclamation variant "D").

Method of evaluation of the development stage of forest tree species and soil properties

In **Panský les locality** (reclamation variant "B") the forest tree species were evaluated at the age of 7 years while in **Chvaletice locality** (reclamation variant "A") the age of the evaluated forest tree species was 5 years. As for the tree species of seed origin (reclamation variant "C") the individuals at both localities were max. 10 years old (the time since the termination of coal ash sluicing). The tree species were evaluated for their health status (damage caused by biotic and abiotic factors) and shoot length; after the trees were lifted from the soil profile either by hand or by an excavator, we evaluated the characteristics of the spatial distribution of horizontal skeletal roots, presence of anchor roots, taproot (lateral taproots) and fine roots (less than 1 mm in diameter), width and depth of root penetration into the soil profile, root system deformations (spiral coiling of roots – knob, changes in the vertical orientation of taproot growth). The transversal transect – the wall denuding the root system in the formed soil profile of Anthroposol was an auxiliary method used to evaluate the root system development in the tree species in Chvaletice locality (reclamation variant "A").The determination of soil properties of evaluated Anthroposols (texture, soil reaction, sorption properties, content of carbonates, total nitrogen, organic matters and available nutrients – P, K, Mg, Ca) and of the nutrient status of assimilatory tissues in some tree species taxa in connection with the evaluated soil condition was a part of these investigations.

RESULTS AND DISCUSSION

Soil properties of evaluated Anthroposols

From the aspect of the particle-size composition Anthroposols composed solely of coal ash without additives represent a similar soil condition, i.e. they are in the category of the sandy to loam-sandy texture. An exception is the variant of Anthroposol formed on the compacted stabilizate with reclaimable soil where the overlaying stratum can be classified as sandy-loam. The content of particle-size category I (< 0.01 mm) in the overlaying stratum composed of reclaimable soil ranged at the level of variance 20–29% (sd 3.263), in coal ash deposited by hydraulic sluicing at the level of variance 6–15% (sd 2.764), in the agglomerate at the level of variance 6–12% (sd 2.147) and in the stabilizate at the level of variance 7–13% (sd 2.052). In Anthroposols composed only of coal ash particularly the total content of nitrogen and organic matters is considered as low and sorption properties as unsuitable from the aspect of reclamation. On the contrary, this variant has a higher content of phosphorus, potassium and magnesium compared to the overlaying with soil layer and is also characterized by some specific physical properties such as high porosity (62–67%) and low bulk density (0.6–0.7 g/cm^3). Reclaiming material and uncompacted stabilizate are interesting from the aspect of reclamation; they cause a marked initial increase in soil alkalinity (8.0–8.5) compared to the agglomerate but they also positively influence sorption properties. Table 1 shows

Table 1. Chemical and other properties of soil

Reclamation state	pH KCl	$CaCO_3$ (%)	N_t (%)	C_{ox} (%)	CEC (cmol$^+$/kg)	Content of available nutrients (mg/kg)			
						P	K	Mg	Ca
"A"	6.3–6.8	< 0.1–0.7	0.05–0.07	0.4–0.5	< 5.0–12.8	1–9	43–121	113–348	2,655–2,958
"B"	6.8–7.0	< 0.1	< 0.05	0.3–0.4	< 5.0	28–40	164–243	429–703	624–1,050
"C"	7.9–8.1	1.2–2.8	< 0.05	0.3–0.7	13.9–19.3	33–38	194–221	515–712	13,112–13,920
"D"	5.3–6.0	< 0.1	0.05–0.06	1.4–2.5	< 5.0–5.8	14–26	122–163	113–230	920–1,536

Fig. 1. The root system of *Betula verrucosa* Ehrh. of seed origin in a coal-ash settling pit

Fig. 3. The root system of *Pinus sylvestris* L. of seed origin in a coal-ash settling pit

the determined soil properties of evaluated reclamation variants.

Evaluation of growth vitality of forest tree species

Betula verrucosa Ehr.: a taxon of very high reclamation importance, little damaged by biotic factors. Rhizological characterization (Fig. 1) of individual trees of seed origin at the age under 10 years on Anthroposol formed from coal ash only shows the system of uniformly distributed horizontal roots, placed in the surface soil horizon to 0.1 m and penetrating into the total soil-profile width of 7 m, which are complemented by numerous vertical anchor roots penetrating into the soil profile to the total depth of 0.4 m.

Salix alba L.: a taxon of very high reclamation importance, little damaged by biotic factors. Rhizological characterization (Fig. 2) of individual trees of seed origin at the age under 10 years on Anthroposol formed from coal ash only shows the formation of the uniformly distributed or one-sided system of horizontal roots reaching the total width of root penetration into the soil profile 10 m, numerous vertical anchor roots and the taproot (taproot laterals) which is bent into a horizontal position in 80% of individuals at a depth of 0.4–0.7 m, is branching and some

Fig. 2. The root system of *Salix alba* L. of seed origin in a coal-ash settling pit

Fig. 4. Development of the root system in the bare-rooted planting material of *Pinus sylvestris* L. at a site with the overlaying of the compacted stabilizate with soil layer

Fig. 5. Characterization of the density of terminal rootlets in the central part of the root system of *Populus nigra* L. of seed origin

Fig. 6. Development of the root system in the bare-rooted planting material of *Alnus glutinosa* (L.) Gaertn. at a site with the overlaying of the compacted stabilizate with soil layer

roots continue to grow in a vertical direction. The total depth of root penetration into the soil profile is up to 1.2 m. The performance and characteristics of the root system formation in *Salix fragilis* L. of seed origin can be evaluated at these sites in a similar way.

Populus tremula L.: a taxon of very high reclamation importance, little damaged by biotic factors. Rhizological characterization of individual trees of seed origin at the age under 10 years on Anthroposol formed from coal ash only shows the formation of the uniformly distributed or one-sided system of horizontal roots penetrating into the soil-profile width of 7 m, numerous vertical anchor roots and the shorter taproot (taproot laterals), which is bent, similarly like in *Salix alba* L., to a horizontal position at a depth of more than 0.4 m in the majority of the trees. *Populus nigra* L. and *Populus alba* L. are of the same reclamation importance at this site and have the same rhizological characteristics.

Table 2. Characteristics of forest tree species development

Locality (reclamation state)	Tree species	No. of individuals	Root width (cm)			Root depth (cm)			Shoots (cm)		
			max.	min.	average	max.	min.	average	max.	min.	average
Panský les ("B")	*Quercus robur* L.	6	120	70	98	50	30	38	118	40	66
Panský les ("D")	*Betula verrucosa* Ehrh.	3	350	250	293	45	15	27	390	220	303
	Populus tremula L.	4	385	150	383	100	50	80	420	350	383
	Salix fragilis L.	2	250	110	180	80	50	65	430	245	338
Chvaletice ("D")	*Betula verrucosa* Ehrh.	20	730	410	549	55	40	43	455	190	316
	Salix alba L.	16	950	260	543	115	50	69	350	65	217
	Populus nigra L.	3	800	650	717	90	50	63	620	500	523
Chvaletice ("A")	*Quercus rubra* L.	10	135	105	118	40	35	38	145	115	125
	Alnus glutinosa (L.) Gaertn.	13	425	330	372	40	35	38	345	280	311
	Robinia pseudoacacia L.	7	425	350	390	40	35	37	385	280	318

Table 3. Significance of differences in the rating development of *Pinus sylvestris* L. for the evaluated Anthroposols

Variant comparison	Shoots (cm) average	Dispersion	Value *P*	Value *F*	Difference	Root width (cm), average	Dispersion	Value *P*	Value *F*	Difference	Root depth (cm), average	Dispersion	Value *P*	Value *F*	Difference
Panský les ("D") natural seeding	188	5,240	0.619	0.26	inconclusive	284	5,160	0.108	2.86	inconclusive	41	110	0.001	15.22	highly conclusive
Panský les ("B") container	200	394				226	6,824				24	84			
Panský les ("D") natural seeding	188	5,240	0.153	2.23	inconclusive	284	5,160	0.029	5.58	conclusive	41	110	0.001	24.96	highly conclusive
Panský les ("B") bare-rooted	153	413				218	2,768				20	67			
Panský les ("D") natural seeding	188	5,240	0.987	0.0003	inconclusive	284	5,160	0.005	10.18	conclusive	41	110	0.052	4.33	conclusive
Chvaletice ("D") natural seeding	189	3,350				412	10,929				52	145			
Chvaletice ("D") natural seeding	189	3,350	0.582	0.314	inconclusive	412	10,929	0.001	42.96	highly conclusive	52	144	0.001	14.32	highly conclusive
Chvaletice ("A") bare-rooted	200	861				191	491				37	4			

$F_{crit.} = 4.41$, $\alpha = 0.05$

Pinus sylvestris L.: a taxon of high reclamation importance; the rhizological characterization (Fig. 3) of individual trees of seed origin (90% of them) at the age under 10 years on Anthroposols formed from coal ash only shows the formation of the uniformly distributed system of horizontal roots penetrating into the soil-profile width of 5 m and the taproot (taproot laterals) 0.7 m in length. 100% deformations of the taproot (Fig. 4) were observed on Anthroposol with the overlaying of the compacted stabilizate with soil layer up to 0.50 m in thickness and more than 50% deformations of the taproot are typical of the container-grown planting material (removable PVC containers) used for the reforestation of the agglomerate without additives. Greater damage by *Lophodermium seditiosum* (Schrad.) Chev. and *Acantholida hieroglyfica* Christ. was recorded both in bare-rooted and container-grown planting material for reforestation and the scorch of the root collar as a result of surface overheating on coal ash is rather a serious problem.

Quercus robur L.: a less vital taxon on Anthroposols formed from coal ash only, with the initial formation of the marked taproot (taproot laterals), rather significantly damaged by the scorch of the root collar, by game browsing, murine rodents, *Microsphaera alphitoides* Griff. et Maubl. and *Altica quercetorum* Foudr. *Quercus rubra* L. can be considered as a taxon of higher reclamation importance with better performance on the compacted stabilizate overlaid with soil.

Alnus glutinosa (L.) Gaertn. is also considered as a taxon of high reclamation importance with good initial performance on Anthroposols formed from coal ash only. At the age of 5 years 100% deformations of taproot laterals (Fig. 6) were observed on Anthroposol with the overlaying of the compacted stabilizate with soil layer to 0.5 m in thickness; this species along with *Populus tremula* L. reaches the highest stand height in the stand structure, its damage by the feeding of *Agelastica alni* (L.) is negligible, but height increment stagnation and premature fertility already become evident. Tables 2 and 3 show the observed growth vitality of evaluated tree species taxa on Anthroposols.

CONCLUSION

Coal ash from the combustion of brown coal in thermal power stations and deposited on

Table 4. Contents of basal nutrients in the assimilatory tissues of forest tree species

Locality (reclamation state)	Tree species	Content (% of dry matter)				
		P	Ca	Mg	K	N
Chvaletice ("A")	*Pinus sylvestris* L.	0.12	0.45	0.17	0.52	1.57
	Populus tremula L.	0.20	2.07	0.34	0.82	2.35
	Betula verrucosa Ehrh.	0.24	0.93	0.40	1.03	2.51
Chvaletice ("D")	*Pinus sylvestris* L.	0.18	0.20	0.99	0.87	1.85
	Populus tremula L.	0.20	1.21	0.28	1.95	2.40
	Betula verrucosa Ehrh.	0.28	0.84	0.36	0.84	2.88
Mineral contents in plants (Beneš 1992)	*Pinus sylvestris* L.	0.14–0.30	0.20–0.60	0.10–0.20	0.40–0.80	1.10–1.70
	Populus tremula L.	0.18–0.30	0.30–1.50	0.20–0.30	1.20–1.80	1.80–2.50
	Betula verrucosa Ehrh.	0.15–0.30	0.30–1.50	0.15–0.30	1.00–1.50	2.50–4.00

dumpsites without additives (CaO) can be considered as a material that can be used for forestry purposes without taking any complicated measures, which is also confirmed by the nutrient status (Table 4) recorded on coal ash deposited by hydraulic sluicing and on Anthroposol with the overlaying of the compacted stabilizate with soil layer and which corresponds to the status reported for natural soils (Beneš 1994). A rhizological problem of Anthroposols formed from coal ash only is that the specific physical properties of soil (high porosity, low bulk density) are invariable in the whole profile (in contrast with natural soils), which could be the cause of rather frequent windthrows in some tree species taxa at older age; at sites with the overlaying of the compacted stabilizate with soil layer up to 0.5 m in thickness the problem is deformations of the vertical part of the root system at the age of 5 years (roots change the direction of their growth to the horizontal one in the contact area composed of the stabilizate). It will also be necessary to apply the knowledge of the growth of tree species of seed origin to this problem of the root system development on such Anthroposol because the presented characterization is information acquired from reforestation with a trench planter. Especially *Robinia pseudoacacia* L., *Betula verrucosa* Ehrh., *Salix alba* L., *Salix fragilis* L., *Populus tremula* L., *Populus nigra* L., *Populus alba* L., and also *Pinus sylvestris* L. can be considered as the tree species taxa of very high reclamation importance characterized by good performance already in the first vegetation series of primary succession on Anthroposols formed from coal ash only. Their typical rhizological trait at the age under ten years is the high density of terminal rootlets in the central part (Fig. 5, shown in *Populus nigra* L.) and the formation of the sizeable system of horizontal roots that is complemented by numerous vertical anchor roots in *Salix alba* L., *Salix fragilis* L., *Populus tremula* L., *Populus nigra* L., *Populus alba* L. and the taproot which changes the direction of growth to a horizontal one at a depth of 0.7 m in more than 80% of individuals and the taproot in *Pinus sylvestris* L. which does not show any marked deformations to the depth of 0.6 m in 90% of evaluated individuals.

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Received for publication February 4, 2008
Accepted after corrections April 14, 2008

Lesnická rekultivace složišť vedlejších energetických produktů (VEP)

ABSTRAKT: Je popsána problematika rekultivace složišť popelovin – vedlejších energetických produktů (VEP), pocházejících ze spalování hnědého uhlí v tepelných elektrárnách. Hodnotí se půdní vlastnosti vytvářených antropozemí a růstová vitalita dřevin – *Quercus robur* L., *Quercus rubra* L., *Pinus sylvestris* L., *Betula verrucosa* Ehrh., *Populus tremula* L., *Populus nigra* L., *Salix fragilis* L., *Salix alba* L., *Alnus glutinosa* (L.) Gaertn. Nejlepší růstovou vitalitou na těchto stanovištích disponují dřeviny semenného původu z garnitury vegetace primární sukcese. Deformace kůlového kořene (postranních kůlových kořenů) ve stáří do 10 let byla zjištěna na antropozemi z popelovin u *Salix alba* L., *Salix fragilis* L., *Populus tremula* L., *Populus nigra* L. a *Populus alba* L. a na překryvu zhutněného stabilizátu zúrodnitelnou zeminou do 0,5 m u *Pinus sylvestris* L., *Alnus glutinosa* (L.) Gaertn. a *Quercus rubra* L.

Klíčová slova: lesnická rekultivace; antropozem; složiště popelovin; vedlejší energetické produkty; půdní vlastnosti; růstová vitalita; kořenový systém

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