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ORIGINAL ARTICLE

Soil improvement with coal ash and sewage sludge: a field experiment

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Abstract A field experimental study was carried out successfully to improve the quality of the sandy soil by adding coal ash and sewage sludge. One ha of barren sandy soil field was chosen for the experiment in Shanghe County, Shandong Province, China. For soil amelioration and tree planting, two formulas of the mixture:coal ash, sewage sludge and soil, in ratios of 20:10:70 and 20:20:60, respectively, were used. Poplar trees were planted in pits filled with soils with additives (mixture of ash and sludge) as well as in the original sandy soil. In the 19th months after the trees were planted, the soils with additives were sampled and analyzed. The results show that the barren sandy soil was greatly improved after mixing with coal ash and sludge. The improved soils have remarkably higher nutrient concentrations, better texture, smaller bulk density, higher porosity and mass moisture content, and higher content of fine-grained minerals. During the first 22 months after planting, the annual increase in height of the trees grown in the soil with additives (4.78 m per year) was 55% higher than that of the control group (3.07 m per year), and the annual increase in diameter at the breast height (1.3 m) was 33 % higher (43.03 vs. 32.36 mm). Trees planted in soils with additives appeared healthier and shed leaves later than those in the control group. As the volume of the additives (30–40% in both formulas) is less than that of the sandy soil in and around the tree pits, it appears that the use of coal ash and sludge for tree planting and soil amelioration is environmentally safe even though the additives have relatively high heavy metal concentrations.

Keywords Sandy soil · Coal ash · Sewage sludge · Soil amelioration · Tree growth · Shandong · China

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Introduction

Desertification is a serious problem in China. To date, it has affected approximately 1,689,000 km^2, or 17.6% of the land area of China. Most of the desertificated areas are located in northern China, between 35°N and 50°N, and form a belt that is approximately 4,500 kms long from east to west, and 600 kms wide. In other words, currently approximately 27% of the cultivatable land in China has been desertificated. Furthermore, the desertification is still expanding at the rate of 2,460 km^2 per year (Li 2002).

Desertification may cause serious economic damages. According to surveys conducted by the Chinese Academy of Science (Wang 2001), about 55.9 million tons of the organic matter, nitrogen, phosphorus, and potassium, (equivalent of 270 million tons of chemical fertilizers), are lost every year due to desertification. The loss of the nutrients may have reduced grains production by more than 3 billion kg each year. That translates to an annual loss of 54 billion Chinese Yuan (CNY), or 6.7 billion US dollars, each year. In addition, out of 1.6 billion tons of silt discharged into Yellow River each year, of which 1.2 billion tons originate from desertificated areas (Zhou and Liu 2005). More specifically, approximately 120 million m^3 of silt is discharged into Yellow River each year in its downstream reaches alone. That causes rise of river bed and groundwater levels, as well as salination of the surrounding areas, and may have reduced grains production by approximately 4 billion kg per year (Zhou et al. 2005).

Such severe desertification may need several 100 years to rehabilitate naturally (Fyfe 1989; Fonseca et al. 1998). Artificial rehabilitation, however, could dramatically shorten the timefame. Recently, mixtures of coal ash and sludge have been used for soil amelioration (Arnold and Malcolm 2000) and experiments have shown that the quality of barren red, black, sodium-rich, and sandy soils can be improved by adding fly ash and sludge (Lai et al. 1999; Veeresh et al. 2003). The application of coal ash and sludge in appropriate ratios has led to well balanced nutrient content in the resultant soils (Guest et al. 2001; Su and Wong 2003; Shen et al. 2004), improved textures and some physical properties (Li et al. 2005; Zhou et al. 2005), and enhance growth of plant root systems (Su and Wong 2002), As a result, biological mass is increased remarkably (Wong and Su 1997a, b; Mittra et al. 2003). In some cases, the mixtures of coal ash and sludge can even be directly used as artificial soils (Wong 1995; Kelley et al. 2002).

However, heavy metal pollution could be a potential problem when the mixtures of coal ash and sludge are used for soil improvement because of their inherent composition (Abbott et al. 2001; Christie et al. 2001; Arnold and Malconlm 2004). The high alkalinity of coal ash may also potentially affect the activities of edaphons (Pichtel and Hayes 1990). On the other hand, these potential problems can be greatly alleviated through proper pretreatment and mixing with other benign components (Vempati et al. 1995; Poon and Boost 1996; Fang and Wong 2000; Fang et al. 2001; Guest et al. 2001; Chaudhuri et al. 2003a, b).

In China, approximately 140 million tons of coal ashes are generated annually, and only 41.7% of them is utilized in some applications (Han and Jiang 2001). Currently, the accumulated piles of coal ash amount to more than 1.2 billion tons (Han and Jiang 2001). As for sludge, the production rate is approximately 5.6 million tons per year, and is expected to increase by 15% a year (Zhou et al. 2005). These two types of abundant 'wastes' could become great resources if they could be used for soil improvements.

Due to the complexities and variations in the studies mentioned above, the use of mixtures of coal ash and sludge for soil improvement has more often become a matter of systems engineering. The success or failure of application depends greatly on chemical and physical properties of soil, coal ash, and sludge. This article reports the results of experiments that were conducted on sandy soils in certain desertificated area in downstream Yellow River to demonstrate the potential for soil improvements by adding mixtures of coal ash and sludge.

Materials and methods

The field area and sources of coal ashes and sludge

The field area is in Shanghe County, Shandong Province, China, approximately 70 km north of Yellow River and approximately 100 km from the capital city of the province, Jinan City (Fig. 1). The geographic coordinates are 116°58″E and 37°32″N. The altitude of the field area is 13.02 m. Average sunshine hours are 7.5 h per day, and the probability of sunshine rate is 62%. The annual mean temperature is 12.6°C and annual mean precipitation is 591.1 mm, with the main precipitation period between July and September. The area was chosen for the field experiment because it is desertificated slightly, and also because it is close to Jinan City with a large power plant, where abundant sewage sludge and coal ash can be obtained easily.

The experimental plot is in the silted plain of downstream Yellow River. The soils in the plot are fine sandy type and comprised of beach sediments of ancient Yellow River. The thickness of the sandy soils is more than 2 m. The plot was barren, and trees did not grow well in the sandy soil around the area before this experiment was carried out.

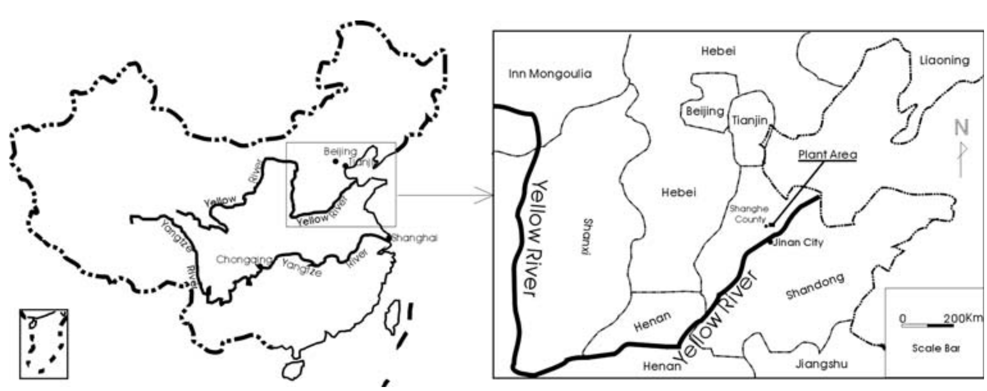

Fig. 1 The sketch map of the field experimental area

The coal ash used in the experiments came from the Daming Lake Power Plant in Jinan City. About 20–30% was bottom ash and the rest fly ash. The grain size of the bottom ash is mostly 1–5 cm in diameter.

The sewage sludge came from the Second Sewage Treatment Plant of Jinan City. Ninety percent of the sewage was residential, and the rest industrial. The sludge contains 75–80% moisture after the dehydration process.

Sample preparation

Representative samples of sandy soil were collected from the upper layer (0–50 cm) of the experimental plot in May 2002. The soil samples were air-dried, and passed through a 2-mm sieve prior to all subsequent analyses. Coal ashes were collected from the ash pool of Daming Lake Power Plant, and the representative sample was obtained by mixing ashes from five different locations in the pool. Sewage sludge was collected from the pit of the Second Sewage Treatment Plant, and the representative sample was obtained by mixing sludge from three different spots in the pit. Coal ashes and sludge also were air-dried, and passed through a 2-mm sieve prior to all analyses.

Analytical methods

The chemical analyses of the soil, coal ash, and sludge were carried out by Plant Nutrition and Resources Institute, Farming and Forestry Academy of Beijing, using the conventional methods (Nanjing Agriculture University 1998).

Particle sizes was measured by the Test Center, China University of Geosciences, Beijing, using a Mastersizer2000 Laser Size Meter. Water was used as the dispersant, and its refractive index was 1.33. The concentration of granules in the dispersant was 0.02 vol%, and the obscuration was 14.20%.

Bulk density, porosity, and mass moisture were measured by the Metallurgy Construction and Energy Saving Technology Institute of Henan, using the conventional methods (Hua and Wang 1993).

Mineral compositions were determined by the Test Center, China University of Geosciences, Beijing, using a D/MAX-RC X-ray diffractometer. The scan range was between 2.5° and 135°, resolving power was $2\theta = 0.02$, and the Cu $K\alpha$ radiation was acquired at 40 kV and 60 mA.

Chemical, physical, and mineralogical characteristics of sandy soil, coal ash, and sludge

The results of the chemical, physical, and mineralogical analyses of sandy soil, coal ash, and sludge are listed in Tables 1, 2, 3, 4 and 5.

Table 1 Chemical properties of sandy soil, coal ash and sludge

	Sandy soil	Coal ash	Sewage sludge
Total N (wt%)	0.034	\	2.840
Total P (wt%)	0.046	0.115	1.490
Total K (wt%)	1.850	1.050	0.440
Organic matter (w%)	0.246	\	34.200
Available N (mg/kg)	\	\	4,858
Available P (mg/kg)	\	166.00	248.00
Available K (mg/kg)	49.00	66.00	940.00
Available Fe (mg/kg)	2.43	58.30	264.00
Available Mn (mg/kg)	1.27	5.70	28.50
Available Cu (mg/kg)	0.45	4.97	2.31
Available Zn (mg/kg)	0.56	1.95	39.50
Available B (mg/kg)	0.17	14.60	0.27
Available Mo (mg/kg)	0.33	5.90	4.30
Available Ca (mg/kg)	1,038	3,200	10,000
Available Mg (mg/kg)	4,272	744	4,320
Available S (mg/kg)	13.90	483.00	3447.00
Total salt (wt%)	0.036	0.395	2.210
Dissoluble Na (mg/kg)	7.11	14.20	391.00
Dissoluble Cl (mg/kg)	20.60	65.50	635.00
pH	8.8	11.0	7.1
C/N	4.24	/	6.97

Analyzed by Plant Nutrition and Resources Institute, Farming and Forestry Academy of Beijing 2005

/ no detected. *C/N* carbon:nitrogen ratio

The results show that the sandy soil from the experimental plot is seriously deficient in nutrients. The contents of organic matter and available N, P, and K are greatly lower than what are required for plant growth. Other nutrients, such as, S, Fe, Mn, Cu, B etc., are also seriously

Table 2 Heavy metal concentration in sandy soil, coal ash, and sludge (mg/kg)

	Soil	Coal ash	Sludge	Standard[a]	Standard[b]
Total Cr	56.20	71.00	183.00	500	1,000
Total Pb	36.50	125.00	125.00	500	1,000
Total Cu	36.10	24.00	207.00	500	500
Total Zn	78.90	44.30	656.00	/	1,000
Total Hg	ND	0.07	3.70	/	15
Total As	8.78	8.11	10.80	75	75
Total Ni	38.00	ND	27.10	300	200
Total Cd	0.83	0.24	2.70	10	20

Analyzed by Plant Nutrition and Resources Institute, Farming and Forestry Academy of Beijing 2003

ND no detected; / no state standard value available

[a] State standard GB8173-87 for usage of coal ash on agriculture

[b] State standard GB4284-84 for usage of sewage sludge on agriculture

Table 3 Size distribution of sandy soil, coal ash, and sludge (vol%)

	Sandy soil	Coal ash	Sludge
<0.002 mm	3.37	11.81	5.23
<0.01 mm	8.84	51.80	29.37
0.01–0.05 mm	7.40	36.34	53.69
0.05–1 mm	78.39	0.32	16.94
>1 mm	5.20	11.54	0.00

Analyzed by Testing Center, China University of Geoscience 2003

insufficient. The pH value is a little high, and C/N ratio is too low. The size distribution of the sandy soil indicates that it lacks fine sized particles such as aggregates or colloidal particles, especially clay minerals. Thus the soil can be categorized as heavy sandy soil (Hua and Wang 1993). The soil has low mass moisture content, and has a serious water and fertilizer leakage problem. It is apparent that the sandy soil in the experimental plot is not suitable for normal plant growth.

In the coal ash and the sludge, most nutrients are higher in concentration than the sandy soil with the exception that there is no organic matter or nitrogen in coal ash. Some of the nutrients are dozens of times more concentrated than those in the sandy soil. The high contents of organic matter, effective N, P, K, B, Mo, and S are very important for the improvement of sandy soil. Moreover, the size distribution indicates that the coal ash and the sludge are comparable with loam soil and powdery soil (Hua and Wang 1993), respectively. The porosity of the coal ash is almost twice as much as the sandy soil, possibly because coal ash particles are easy to form aggregates (Li et al. 2005). Furthermore, the mass moisture of the coal ash and the sludge are approximately twice as much as that of the sandy soil.

While the heavy metal element contents of the sludge are generally higher than those of the sandy soil with the exception of Ni, the concentrations of the heavy metals in the coal ash are not much higher than those in the sandy soil with the exception of Pb. In addition, all of the heavy metal concentrations are lower than the acceptable levels set in the Chinese Standard of Coal Ash for Using in Agriculture (State Environmental Protection Bureau and State Technology Supervision Bureau, GB8173-87, 1998) and the Chinese Standard of Sludge for Using in Agriculture (Department of Urban and Rural Environmental Protection, People's Republic of China, GB4284-84, 1985). Therefore, coal ash and the sludge are permissible for use in soil amelioration.

Field experiments

The field experiment was carried out in a plot of 1 ha. Two formulas were selected for field testing based on previous potting experiments (Shen et al. 2001; Shen 2002). Two formulas were applied as follows: formula one: 20 wt% coal ash + 10 wt% sludge + 70 wt% sandy soil, and formula two: 20 wt% coal ash + 20 wt% sludge + 60 wt% sandy soil, respectively. The coal ash and the sludge were mixed in a 300 kg round barrel mixer for approximately 15 min, forming the mixtures that are called additives. The additives were piled for 1 week on the field before mixing with the sand soil during planting.

The shape of the tree pits used is a cylinder with a diameter of 50 cm and a depth of 50 cm, and the bottom reaches of the additives were set at 25 and 50 cm to investigate the effects of the additive at different depth. The quantities of additives used in the pits with reach depth of 50 cm were approximately 36.4 and 38.9 kg for formulas one and two, respectively, while the quantities of additives used in the pits with reach depth of 25 cm were approximately half the above, as expected. The total additives used for the experiment were 12.2 tons.

The seedlings were poplar (Latin name: *Populus deltoids*). All seedlings were selected with approximately same stem height (1.5–1.7 m) and diameter (17–19 mm) at the breast height (1.3 m from the ground). They were planted 2 m apart in the same row, and the distance between the rows was 3 m. A total of 978 trees were

Table 5 Physical properties of sandy soil, coal ash, and sludge

	Sandy soil	Coal ash	Sludge
Bulk density (g/ml)	1.48	0.50	0.96
Porosity (vol%)	42.98	78.30	50.77
Mass moisture content (wt%)	27.00	55.50	54.00

Analyzed by Metallurgy Construction and Energy Saving Technology Institute of Henan 2003

Table 4 Mineral composition of sandy soil, coal ash, and sludge (vol%)

	Quartz	Feldspar	Calcite	Dolomite	Kaolinite	Chlorite	Illite	Glassy	Mullite	FC
Sandy soil	>50	≅15	<10	ND	ND	<10	<10	ND	ND	ND
Coal ash	<5	ND	ND	ND	ND	ND	ND	>80	≅10	<5
Sludge	>90	Trace	Trace	Trace	Trace	Trace	ND	ND	ND	ND

Analyzed by Testing Center, China University of Geoscience 2003

FC Free carbon, ≅ approximate, *ND* not detected planted for the experiment. All the planting was carried out on November 27, 2003.

The control plot was next to the experiment plot, and the soil conditions were the same as those on the experiment plot before the additives were added. The trees were the same species, and were planted on the same day as those in the experiment plot.

The experimental and control plots were irrigated with groundwater from a nearby well 2 days after planting. Three more times of irrigation (May 21, 2004, April 6, 2005, and June 3, 2005) were later carried out. During the experiment period, the rainfall in the area was normal and averaged 610 mm per year.

The growth progress was monitored by measuring the stem height and diameter at breast height (1.3 m) of the trees from April 3, 2004 to October 15, 2005. The soil improvements were also evaluated by measuring the contents of nutrient elements, heavy metal element contents, pH, particle size distribution, porosity, and mass moisture contents of soil samples collected from the experimental plot in August 31, 2005. The samples were prepared and measured in the same way as described above.

Results and discussion

Soil improvements

The soils with additives, sampled in the 19th month after tree planting, were measured for organic matter (OM), nutrient elements, pH, carbon:nitrogen ratio (C/N), heavy metals, size distribution, minerals, porosity and mass moisture contents. The results and a comparison with the original sandy soil are listed in Tables 6, 7, 8, 9, and 10.

The nutrients in the soils with additives are remarkably enhanced. As can be seen in Table 6, OM, available N, P, Fe, Zn, Ca, B, and S in improved soils were increased markedly, and available K, Cu, Mn, and Mo were increased slightly. However, available Mg decreased. C/N ratio was increased to 13.94–19.24 from 4.24, and pH decreased to 7.5–7.6 from 8.8.

Soils with additives underwent amelioration in terms of particle size distribution. Table 7 shows that the original tight sandy soil was converted into better-structured loam soil after mixing with coal ash and sludge. This is attributed to more fine particles in the coal ash and fine mineral particles in the sludge (Table 3). Furthermore, porous pellets in coal ash and OM in sludge can enhance complex aggregation and have strong water absorbability (Li et al. 2005; Zhou et al. 2005).

The contents of beneficial minerals were increased in the soils with additives. As can be seen in Table 8, compared with the original sandy soil, the soils with additives have reduced quartz content, and increased contents of such fine-grained minerals as calcite and clay minerals (chlorite, illite). These changes in mineral contents are very helpful for the soils to hold moisture and nutrients.

The main physical properties of the soils with additives were ameliorated. Table 9 shows that, compared with the original sandy soil, the soils with additives have a remarkable decrease in bulk density, a dramatically increase in porosity, and a slight increase in mass moisture

Table 6 Comparison of soil chemistry before and 19 months after mixing with additives

	Original sandy soil	No.1 formula	No.2 formula
Total N (wt%)	0.034	0.0717	0.0717
Total P (wt%)	0.046	0.0425	0.0309
Total K (wt%)	1.850	1.25	1.80
Organic matter (w%)	0.246	2.38	1.83
Available N (mg/kg)	/	78.70	58.70
Available P (mg/kg)	/	58.70	50.30
Available K (mg/kg)	4 9.00	69.80	67.20
Available Fe (mg/kg)	2.43	13.60	10.10
Available Mn (mg/kg)	1.27	1.73	1.52
Available Cu (mg/kg)	0.45	1.37	1.34
Available Zn (mg/kg)	0.56	5.90	5.55
Available B (mg/kg)	0.17	0.60	0.50
Available Mo (mg/kg)	0.33	0.38	0.33
Available Ca (mg/kg)	1038	2920	2600
Available Mg (mg/kg)	4,272	1,896	1,344
Available S (mg/kg)	13.90	203	137
Total salt (wt%)	0.036	0.059	0.013
Dissoluble Na (mg/kg)	7.11	21.30	10.60
Dissoluble Cl (mg/kg)	20.60	17.00	23.50
PH	8.8	7.69	7.55
C/N	4.24	19.24	13.94

Analyzed by Plant Nutrition and Resources Institute, Farming and Forestry Academy of Beijing 2005

/ no detected *C/N* carbon:nitrogen ratio

Table 7 Comparison of size distribution before and 19 months after mixing with additives (vol%)

	Original sandy soil	No.1 formula	No.2 formula
<0.002 mm	3.55	2.93	4.33
<0.01 mm	9.32	13.48	18.28
0.01–0.05 mm	7.81	33.90	44.62
0.05–1 mm	82.69	52.60	37.10
>1 mm	0.00	0.00	0.00
Soil type	Tight sandy soil	Loam soil	Loam soil

Analyzed by Testing Center, China University of Geosciences 2005

Table 8 Comparison of mineralogy before and 19 months after mixing with additives (vol %)

	Quartz	Feldspar	Calcite	Dolomite	Chlorite	Illite	Gypsum
Original sandy soil	>50	≅15	<10	/	< 10	<10	/
No.1 formula	≅50	≅15	≅10	≅5	≅10	≅10	≅5
No.2 formula	≅35	≅25	≅10	/	≅10	≅10	/

/ Not detected, ≅ approximate

Analyzed by Testing Center, China University of Geosciences 2005

Table 9 Comparison of physical properties before and 19 months after mixing with additives (vol %)

	Original sandy soil	No.1 formula	No.2 formula
Bulk density (g/dm)	1.48	0.95	0.90
Porosity (vol%)	42.98	55.10	60.13
Mass moisture content (wt%)	27.00	29.29	29.69

Analyzed by Metallurgy Construction and Energy Saving Technology Institute of Henan 2005

Table 10 Comparison of macro and capillary porosity before and 19 months after improvement (vol %)

	Total porosity	Macro porosity	Capillary porosity
Original Sandy Soil	42.98	27.94	15.04
The soil after improvement	57.62	25.93	31.69

Analyzed by Metallurgy Construction and Energy Saving Technology Institute of Henan 2005

content. It is interesting to note that the total porosity increased significantly in the soils with additives, and the increase in total porosity contributed to the increased capillary porosity (Table 10). In fact, the macro porosity of the soils with additives actually decreased compared with the original soil. This dramatic increase in capillary porosity is very helpful to store more water and nutrients for plants to take up (Wu and Wang 1995).

The above results show that the soils treated with additives have much improved properties and textures to store more nutrients and water. In addition, the ameliorated porosity structure in the soil should be more favorable for plants to take up nutrients so that their root system can grow better (Mitsuno 2002). The porosity may also provide a favorable space for the growth of edaphon (Guest et al. 2001; Fang et al. 2001).

Increases in biomass production

The growth of the trees is quantified with two parameters: stem heights and diameters at the breast height (1.3 m). The stem heights of the trees measured on various dates are listed in Table 11. Here No.1–50 denotes trees planted in formula one soil, and the soil reaches a depth of 50 cm in the pit; No.2–50 denotes formula two and the soil reaches 50 cm in the pit, and so on. Table 11 and Fig. 2 show that all trees planted in the soils with additives were higher than those in the control group. Average height of the trees in soils with additives was 8.87 m, but the height of trees in control soil was only 6.50 m on August 31, 2005, approximately 20 months after planting. From the planting date November 27, 2003 to August 31, 2005, the height of the trees increased an average of 4.78 and 3.07 m annually

Table 11 Comparison of tree height (m)

Measurement date (dd/mm/yy)	Control (82)	No.1–50 (66)	No.2–50 (78)	No.1–25 (70)	No.2–25 (122)
03/04/04					
Range	1.61–2.27	1.56–2.05	1.55–2.14	1.63–1.99	1.58–2.02
Aver.	2.14	1.88	1.91	1.80	1.85
23/06/04					
Range	2.77–3.02	2.21–3.33	2.15–3.11	2.65–3.19	2.64–3.178
Aver.	2.84	2.94	2.61	2.71	2.86
31/08/04					
Range	4.22–4.41	4.95–5.50	4.37–5.23	4.66–5.29	4.74–5.55
Aver.	4.34	5.23	4.27	4.87	5.11
31/08/05					
Range	5.34–6.62	7.88–10.36	7.92–10.28	7.55–11.04	7.78–10.45
Aver.	6.50	9.11	8.36	8.20	8.84

Aver. Average

[a] All tree seedlings were 1.5–1.7 m height at the planting time (November 27, 2003)

[b] The numbers in parentheses are the number of trees in each group

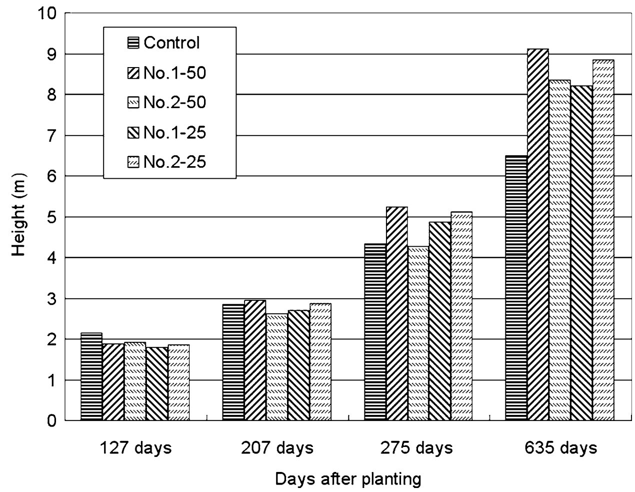

Fig. 2 Comparison of average heights of trees during experiment period

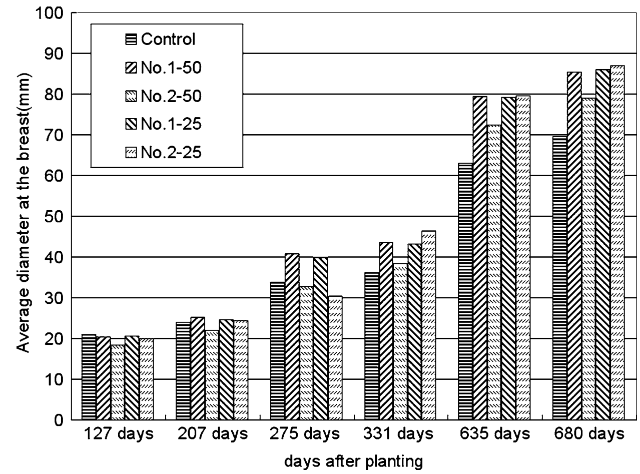

Fig. 3 Comparison of average diameters at the breast height (~1.3 m above ground) of trees during experiment period

for those planted in soils with additives and the original soil, respectively. It represented a 55% higher increase rate in height. Table 11 also shows that trees under No.1–50 grew the tallest. They reached an average height of 9.11 m on August 31, 2005, or an annual height increase of 5.10 m from planting to that date.

The diameters at the breast height (1.3 m) of the trees were measured during a period of 22 months after the trees were planted and the results are listed in Table 12. Again, trees planted in the soils with additives had larger diameter at the breast height than those in the control soil (Fig. 3). The average diameter of trees in the former group was 84.38 mm, but was only 69.58 mm in the latter group as measured on October 15, 2005, and the average annual increases were 43.03 and 32.36 mm, respectively for the period from plantation to the last measurement date. It may be worth noting that there were more measurements of diameter at breast height than those of height. The reason is simply because it is more difficult to measure the height when trees grow more than 4 m high.

It is also worth noting that, during the summer months, trees planted in the soils with additives had dark green leaves, whereas the trees in the control group had light kelly leaves. The leaves on the trees planted on the soils with additives also fell much later than those on the trees of the control group.

Table 12 Comparison of diameters of trees at the chest height (~1.3 m above ground) (mm)

Measurement date (dd/mm/yy)	Control (82)	No.1–50 (66)	No.2–50 (78)	No.1–25 (70)	No.2–25 (122)
03/04/04					
Range	20.97–21.09	19.98–20.43	18.25–20.56	19.00–21.04	19.16–20.83
Aver.	21.05	20.32	18.49	20.55	19.97
23/06/04					
Range	23.99–24.08	25.21–25.33	21.87–22.12	24.15–24.73	24.46–24.60
Aver.	24.06	25.27	22.04	24.62	24.50
31/08/04					
Range	33.76–34.01	39.96–41.11	32.82–94	39.65–40.08	30.22–31.18
Aver.	33.82	40.71	32.90	39.72	30.46
27/10/04					
Range	35.02–36.30	43.04–43.86	38.15–39.11	42.67–43.26	45.88–47.33
Aver.	36.25	43.58	38.36	43.18	46.39
31/08/05					
Range	61.54–63.61	78.97–80.38	72.02–73.24	78.53–80.66	79.21–81.08
Aver.	62.96	79.36	72.43	79.23	79.60
15/10/05					
Range	69.01–71.12	85.04–87.26	78.22–80.57	84.95–87.51	86.35–88.08
Aver.	69.58	85.50	79.00	86.00	87.00

Aver. Average

[a] The diameters of all tree seedlings were 17–19 mm at breast height at the planting time (November 27, 2003)

[b] The numbers in parentheses are the number of trees for each group

From the above results and discussions, it is apparent that the soils with additives are ameliorated and are much more suitable for plant growth. However, due to the inherent high contents of heavy metals in coal ash and sludge, there is a risk that the soils with additives could have been polluted. To see if pollution is a problem, soils with additives were analyzed for their heavy metal contents 20–22 months after the trees were planted, and the results are shown in Table 13. The results show that Cr, Pb, Cu, Zn, As, and Ni concentrations are lower, and Hg concentration is slightly higher in the ameliorated soil than the original sandy soil. More importantly, the concentrations of all the above elements are lower than the limits set in the Standard for Soil Environmental Quality of China (State Environmental Protection Bureau, State Engineering Supervision Bureau, GB15618-1995, 1995). Cd is an exception, because its concentration in ameliorated soils (1.25 mg/kg for Formula One, and 1.40 mg/kg for Formula Two) are higher than the limit set in the Standard (1.0 mg/kg). While the concentrations of total Cd in ameliorated soils are somewhat higher than the limit in the Standard, its activity may be reduced by organic matter, to which the element can adsorb strongly (Hua et al. 1994). It is interesting to note that the concentrations of most heavy metals in ameliorated soils were reduced compared with the original sandy soil. The detailed mechanisms can be elucidated by more studies. Even if the heavy metals were all lost due to leaching, it may not be a major environmental concern because the volume of the additives is quite small compared with the volume of all the sandy soil in and around the tree pits. Therefore, it appears that using coal ash and sludge for tree planting and related soil amelioration is environmentally safe.

Table 13 Comparison of heavy metal element contents of soils (mg/kg)

	Original sandy soil	No.1 formula	No.2 formula	Standard[a]
Total Cr	56.20	47.80	51.00	300
Total Pb	36.50	19.10	18.20	400
Total Cu	36.10	7.03	5.35	400
Total Zn	78.90	50.20	34.60	500
Total Hg	ND	0.110	0.035	1.5
Total As	8.78	7.28	ND	40
Total Ni	38.00	13.70	9.29	200
Total Cd	0.83	1.40	1.25	1.0

Analyzed by Plant Nutrition and Resources Institute, Farming and Forestry Academy of Beijing 2005

ND Not detected

[a] GB15618-1995

Conclusions

1. The barren sandy soil in the experimental area can be greatly improved by mixing with certain amounts of coal ash and sludge. The improvements include remarkably higher nutrient concentrations, better texture, lower bulk density, higher porosity and mass moisture content, and more fine-grained minerals.
2. Biomass production is increased in improved soils. The poplar trees planted in soils with additives grew taller and thicker than those in the control group. During the first 20 months after planting, the annual increase in height for trees planted in soils with additive (4.78 m) is 55% higher than those in the control group (3.07 m), and during the first 22 months after planting, the annual increase in diameter at the breast height (1.3 m) is 33% higher (43.03 vs. 32.36 mm). Trees planted in soils with additives appeared healthier and shed leaves much later than those in the control group.
3. It appears that using coal ash and sludge for tree planting and related soil amelioration is environmentally safe because the volume of the additives is quite small compared with the volume of all the sandy soil in and around the tree pits even though the additives have relatively high heavy metal concentrations.

Based on the results from this experiment, a plan for large-scale soil improvements of sandy soil near the experiment plot area are under preparation. The authors are also exploring the possibility of applying the technique for the reclamation of closed mines in the future.

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