Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.807056

52 (2014) 2688–2694
March

Taylor & Francis
Taylor & Francis Group

Ecological remediation of waste resources by comprehensive afforestation utilization in mudflat ecosystem

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Received 12 July 2012; Accepted 29 April 2013

ABSTRACT

The ecological rehabilitation engineering out of the coastal mudflat ecosystem was accomplished principally by virescence. However, the lack of proper soil resources for reformation of the coastal mudflat was the primary difficulty. Artificial soil mounds composed of three solid wastes (dredged sediments, caustic sludge, and coal ash) were constructed and afforested. The waste properties and the effects of the unnatural soil on tree growth, desalination, pH value, biomass, microbial community, and toxic metals were investigated in the next couple of years. After four growing seasons, salt content was reduced to the threshold for salt-sensitive plants and the pH value remained stable (below 8.30). The total biomass of the tree–shrub–herb community, which was composed of *Fraxinus pennsylvanica Marsh*, *Populus tomentosa Carr*, *Robinia pseudoacacia Linn*, *Loniccra macckii. Maxim*, *Tamarix chinensis Lour, and Medicago sativa L*, was above 31.92 t hm^{-2}. The survival, tree height, diameter, and biomass of these plants varied significantly across plant species. The number of colony-forming units (CFU) per gram of dry artificial soil was significantly higher than foreign soil and coastal solonchak at 0–40 cm deep. The concentrations of Hg, Cr, Cd, As and Pb in leachates and the artificial soil were below nationally accepted norms. The results show that the comprehensive afforestation utilization in Tianjin coastal ecosystem could solve the problems of solid waste pollution and the damage to nearby ecosystem as well as reducing the cost of rehabilitations.

Keywords: Ecological remediation; Costal ecosystem; Afforestation

1. Introduction

The intensive use and misuse of soil, water, and air resources due to population expansion and the increasing level of degradation accompanying an increasing standard of living have augmented the hazard of declining soil productivity in China. High population, manufactory density, and intensive use of land in tianjin economic technology development area (TEDA), China cause a shortage of land for the discarding of three solid wastes: dredged sediments,

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Presented at the Second International Conference on Water Resources Management and Engineering (ICWRME 2012) Zhengzhou, China, 14–16 August 2012

caustic sludge, and coal ash. Dredged sediments were a by-product of Tianjin Soda Plant, which was founded in 1917, and has deposited about 15,000,000 tons on a land base of 3.5 km^2, and continued to produce sludge at a rate of 650,000 $m^3 y^{-1}$. The plant has managed to store the dredged sediments in the existing area by raising the height of the storage dam, which is now about 10 m above the ground level [1,2]. So, there are plans to build a long pipe system to deposit the sludge into the sea. However, the construction of the necessary dikes and pipe systems is very expensive and has serious negative effects on marine ecosystems. Coal ash, a waste product of coal-burning power stations, has already occupied over 66 ha of land [3]. As a result of the pollution, the amount of heavy metals as well as the presence of salt and the high pH limit the range of the use to which the caustic sludge and dredged sediments can be put [4,5].

In TEDA, there are huge amount of solid wastes, such as dredged sediments, caustic sludge, and coal ash [6]. These three solid wastes are inappropriate for application in agriculture and horticulture. Nevertheless, these materials can be used for afforestation because forests have many functions which do not interact with the human food chain. To bring in good soil from neighborhood farmland was both costly and ecologically damaging. Each of them is not suitable for any plant to grow if exists alone. However, when the three wastes were mixed at certain proportion, the mixture is more suitable for plant growth than solonchak. So, the mixture could be utilized as soil resource. In the past, there have been many research papers about agricultural and industrial utilization of coal ash and caustic sludge, such as soil ameliorants, fertilizers, and architectural materials [7,8], but for technical and financial reasons, they have not been utilized effectively. In this paper, the present work shows that the combination of dredged sediments, coal ash, and caustic sludge with proper treatment can replace farm soil to serve as a new source of soil for landscaping purposes [9]. The objective of this paper is to follow the track of the environmental and biological effect of waste resources by comprehensive afforestation utilization in coastal systems and to evaluate the risk of ecological remediation after many years' plantations.

2. Materials and methods

2.1. Site description

The site is located in the eastern part of Tianjin (38˚ 44´ N, 117˚46´ E), the west coast of Bohai Gulf (China), a coastal plain at the mouths of the Haihe River and it has been covered with brine water for the production of sea salt. This coastal area is characterized by a typical clay sediment substrate, 1.0–2.5 m above mean sea level, sloping roughly 0.1%. The groundwater level is only 0.5–1.0 m, and the degree of mineralization of the groundwater is 9–46 $g L^{-1}$. The average annual rainfall is approximately 570 mm, evaporation is 1,750–1940 $mm y^{-1}$, annual accumulated solar radiation is 2891.4 h, and the frost-free period is 234 days [10].

2.2. Species

The plantation was established during April 1999. The test field was divided into 10 rows. Fraxinus pennsylvanica Marsh (red ash) was planted from the first row to the fifth row; from the sixth to the eighth rows grew Populus tomentosa Carr (Chinese white poplar); Robinia pseudoacacia Linn. (yellow locust) cropped in the 9th and 10th rows. The distance between rows was 4m and the distances between plants was 3m. Loniccra macckii Maxim (Amur Honeysuckle) was planted at the midpoint of two Populus tomentosa Carr rows. The six-meter-wide test field along Donghai Road planted Tamarix chinensis Lour (Chinese tamarisk), with nine bare root seedlings per square meter. Bare root seedlings of Chinese white poplar (500), yellow locust (330), red ash (830), Amur honeysuckle (500), and Chinese tamarisk (27,000) were planted by hand. Medicago sativa L (Linn.) (clover) was seeded between rows (Fig. 1(a)).

2.3. Engineering design of the drainage system

Fig. 1 shows a systematic model of the shallow-dense underground drainage salt and groundwater, designed according to such characteristics of the three solid wastes as salt content, hydrological condition, groundwater mineralized degree and level. The aim was to increase this artificial soil desalinization ratio, steadily control salt content in 1-m-deep soil about 0.2–0.3% , eliminate salt damage in the topsoil, control underground water level, and finally create the basic conditions for plant growth and development. The underground drainage system was composed of main drain pipes, catchment pipes, and catchment well. The ripple PVC drainpipes and catchment pipes were vertically interconnected, and leaching water drained into the municipal pipe network. The main parameters are listed as follows: Slope: the slope of the catchment pipe is 1/1,000, the drainpipes are 3/1,000; Diameter: the diameter of ripple PVC drainpipes is 60 mm and that of catchment pipe is 110 mm. Ripple PVC pipes were embedded in artificial soil at a depth of 2.1 m. The space between drainpipes is 8 m; the length of pipe is from 80 to 100 m.

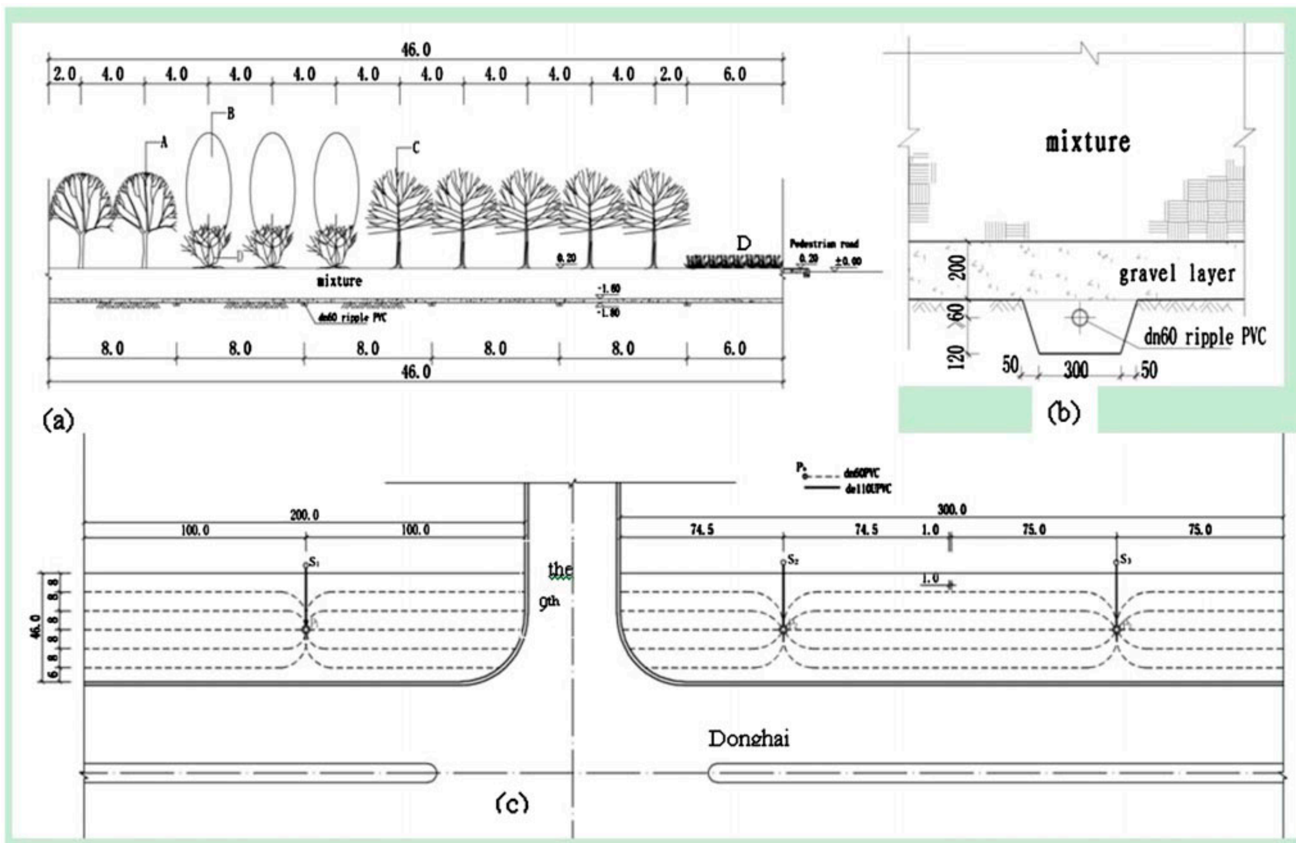

Fig. 1. (a) Cross-section of the artificial soil mound. Planting space between species; (b) section of drainpipe, gravel layer, and soil; (c) sketch map of ripple PVC drainage system; P, catchment well; S, municipal sewage system; A, Robinia pseudoacacia Linn.; B, Populus tomentosa Carr; C, Fraxinus pennsylvanica Marsh (red ash); D, Tamarix chinensis Lour.

2.4. Sampling and analysis

The particle size distribution of the dredged sediment was determined by using the hydrometer method, pH H_2O in a 1:1 soil-to-water ratio, the electrical conductivity of one volume unit of soil in five units of water, the ions concentration of CO_3^{2-}, HCO_3, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+, Na^+, cation exchange capacity, and organic matter content according to [11]. Mineral composition was measured by pressure membrane method. The total heavy metal (Cd, Cr, Cu, Pb, Zn, Fe, and Hg) content was determined on an atomic absorption photospectrometer. A and B were measured by spectrophotometric method with potassium borohyride and silver nitrate and methylthionine chloride spectrophotometry, respectively [12].

Leachates samples were taken from the catchment well on 15 May 1999 by desalinization process, and the concentration of Hg, Cr, Cd, As, Pb, Ni, Cu, Zn, Mn, and Ag was measured. Biomass estimates were determined by dry weight of the plant in March 2002. Soil microbial communities were analyzed for the artificial soil, and Taifeng Park (foreign soil) and bare coastal soil-alkali land in TEDA were control experiments. Soil was sampled at two different depths (0–20 and 20–40 cm) on 17 April, 25 July , and 28 October 2002 in each plot, on approximately the same spots. The soil samples were placed in sterilized brown paper bags, each of which held about one kilogram. Bacterium, actinomycete, and fungus were isolated by soil dilution plating technique with 10-fold dilution in 24 h; bacterium and actinomycete were incubated at 28℃ for 3–5 days. Fungus was incubated at 25℃ and grew into colonies that could be readily counted as described by Analytical Methods of Soil Agri-chemistry [12]. Meanwhile, analyses of total salt, pH, N, P, and K organic matter were run as described by Ye et al. [13]. The soil was sampled before plants were planted at two different depths (0–40 cm and 40–60 cm) on 11 October 2000. Plant metals (As, Hg, Pb, Cd) and soil metals (As, Pb, Cd, Cr, Hg) contents were analyzed as described by Li et al. [14]. Statistical procedures were carried out with the software package SPSS 14.0 for Windows.

3. Results and discussion

3.1. Tree mortality and growth

All plants from the experimental design were checked for survival status in October 1999. Survival ($p < 0.01$) of trees and shrubs, tree height ($p < 0.01$) of three trees was markedly different. Red ash was influenced by salt dust, with the salt content up to 9% in the dominant wind direction of SW-NE axis, parallel with the dominant wind direction. Pumpkin ash mortality just up to 7% was observed. This might be a native salt-tolerant tree. The mortality of poplars was just 74% because of bacterial disease in their stems in high pH conditions. The diameter at 1.2 m growth for all trees was measured (Table 1). The chart shows that the growth ratio of Chinese white poplars exceeded that of the yellow locust and red ash. Average height of poplars was 9.59 ± 0.83 m, which was significantly higher ($p < 0.01$) than the average growth of 5.4 ± 0.47 m for Pumpkin ash and 6.74 ± 0.40 m for yellow locust.

3.2. Biomass

Table 2 shows that the amount of total biomass differed significantly between species, as did the amount of all biomass components except that of leaves. The biomass production of yellow locust and Chinese white poplar was the highest, essentially because of their greater biomass of the stems and branches. In the aboveground biomass percentage, the biomass of yellow locust was the highest (71%), compared with red ash (65%), Chinese white poplar (61%), Chinese tamarisk (61%) and Amur honeysuckle (62%). In the total biomass, poplars and Chinese tamarisk had the greatest percentage of roots (39%), most of which were concentrated in the top 60 cm of the artificial soil. In this community, the distribution of biomass of tree, shrub, herb was 75.42, 28.88, and 0.7%, respectively. The table shows that the biomass of this tree–shrub–herb community (31.92 t hm^{-2}) was higher than that of the primary halophyte community (0.275 t hm^{-2}) and that of the Saxoul (*Haloxylon ammodendron* [*C.A. Mey*] Bunge) forest (6.424 t hm^{-2}) in the Jilantai area of Inner Mongolia and that of fineflowered alkaligrass (*Puccinellia tenuiflora* [Turcz.] Scribn. & Merr.) (0.984 t hm^{-2}) in degenerated grassland of Chang Lin, Jilin Province, which is a warm temperate zone. But it was lower than that of the coastal artificial shelter forest in the North of Jiangsu Province, which is a subtropic zone.

3.3. Analysis of cultured microorganisms

The textural composition of the dredged sediment shows a predominance of clay loam (52%), followed by silty-clay loam (45%) and sandy loam (3%). Minerals analyzed by X-rays indicated that the mineral dredged sediment was composed of illite (45%), montmorillonite (16.9%), chlorite (23.2%), and kaolinite (14.9%). Hydrophilic mineral, illite and montmorillonite, was above 60%. The concentrations of sodium and calcium were absolutely dominated. But the total salt content of coal ash was lower. Caustic sludge had abundant soluble Ca^{2+}, and its total salt content was more than 13%. Fig. 2 shows the trend of salt content in the artificial soil profile. The rate of desalination increased markedly when low bulk weight, high porosity coal ash, and caustic sludge were mixed into brackish sediment sludge in suitable proportion. The artificial soil was irrigated with secondary-treated municipal effluent in March 1998. Soil salinity was significantly reduced over the four-year period in all horizons, because under the high rate of irrigation with effluent of medium salinity there would have been continual leaching of salt to the drainage system.

3.4. Soil

The CFU per gram of dry artificial soil was significantly higher ($p < 0.01$) than foreign soil and coastal

Table 1
The dynamic data chart of red ash, yellow locust, and Chinese white poplar in six growth seasons

Species time	Red ash				Black acacia				Chinese white poplar			
	Average	SE	SD	N	Average	SE	SD	N	Average	SE	SD	N
Nov. 1999	4.70 ± 0.18	0.09	0.66	56	6.14 ± 0.18	0.09	0.68	56	5.13 ± 0.16	0.08	0.61	56
Nov. 2000	5.78 ± 0.39	0.19	0.93	24	7.44 ± 0.35	0.17	0.82	24	7.16 ± 0.25	0.12	0.59	24
Mar. 2001	5.89 ± 0.38	0.18	0.9	24	7.85 ± 0.26	0.12	0.61	24	7.43 ± 0.22	0.11	0.52	24
Apr. 2002	7.04 ± 0.38	0.18	0.9	24	8.64 ± 0.30	0.14	0.71	24	9.39 ± 0.36	0.18	0.86	24
Apr. 2004	12.48 ± 0.43	0.80	0.64	16	–	–	–	–	–	–	–	–

Table 2
Distribution of total biomass (aboveground tree weight, roots to soil depth of 80 cm) for six plants planted in the artificial soil, aged four years, and halophyte growing for only one season)

Species	Part	Biomass of different part (kg ha^{-1})	Aboveground biomass	Biomass (kg ha^{-1})
Populus tomentosa Cars	Root	3301.55	5124.74	8426.29
	Branches	2386.98		
	Stem	2350.77		
	Cortex	386.99		
Fraxinus pennsylvanica Marsh.	Root	3082.54	5730.02	8812.56
	Branches	2316.21		
	Stem	3033.09		
	Cortex	380.72		
Robinia pseudoacacia L.	Root	1990.45	4846.66	6837.11
	Branches	1774.72		
	Stem	1983.82		
	Cortex	1088.12		
Tamarix chinensis Lour.	Branches	2058.94		3370.02
	Root	1311.08		
Lonicera macckii Maxim. (Amur honeysuckle)	Root	1619.5		4251.63
	Branches	2632.13		
Medicago sativa L. (Alfalfa)	Root	224.84		224.84
halophyte				275

solonchak at 0–40 cm depth. The CFU of 0–20 cm layer were markedly higher than those of 20–40 cm layer for all samples. on all sampling dates. The total number of CFU was low in April and relatively high in October at 0–20 cm depth. But the CFU of coastal alkali-saline soil changed a little at different seasons. Among bacteria, actinomyces and fungi, bacteria were absolutely dominating communities. Fungi in all soil samples were the least (Table 3). The number of microorganisms in the three soil samples can be explained by the clay content, compacted structure, salt content, and pH value, etc. The portion of bacteria was absolutely dominating communities (Table 3) in accord with the distribution of common soil. The number of bacteria and actinomyces had a significantly negative correlation with the total content of salt ($p < 0.05$), while the number of bacteria had a sharply positive correlation with the content of soil organic matter ($p < 0.01$). But the actinomyces and fungi had no correlation with soil mineral nutrition and organic matter.

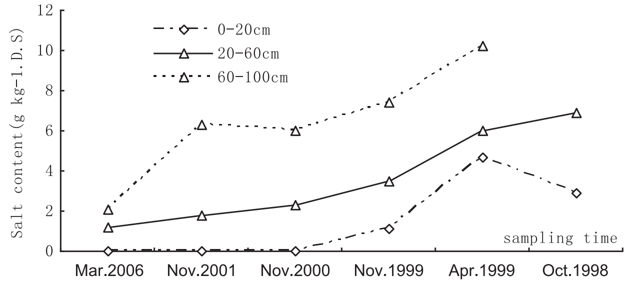

Fig. 2. Dynamic varieties of soil salt at 1 m depth.

3.5. Heavy metals

The analysis of sampled leachates (Table 4) from the catchment well during the desalination process indicated that the concentrations of Hg, Cr, Cd, As, Pb, Ni, and Mn exceeded values established as norms for environmental quality standards for surface water and groundwater, but they were below nationally accepted norms [15]. The high pH and organic matter quantity of the artificial soil in this experimental design limited the solubility of metals and mitigated potential problems.

Table 5 shows the content of As, Hg, Pb, Cd, and Cr in the artificial soil from two different depths. At 0–40 and 40–60 cm layer, the concentrations of all heavy metals were below the nationally accepted norms. However, the level of As accorded with most

Table 3
The numbers of each category of soil microorganism (×104 cfu g^{-1} dry soil)

Treatment	Sampling depth (cm)	Bacteria			Actinomycetaceae			Fungi		
		April 17	July 25	October 28	April 17	July 25	October 28	April 17	July 25	October 28
Test field	0–20	377.6	339.6	593.017	22.66	131.1	39.396	0.906	0.32	1.41
	20–40	93.1	100.5	170.521	33.29	81.4	39.095	0.692	0.33	0.029
Coastal solonchak	0–20	n.d.	0.800	5.070	0.830	0.080	n.d.	0.004	0.020	n.d.
	20–40	n.d.	0.600	3.581	n.d.	0.050	n.d.	n.d.	0.002	n.d.
Planting foreign soil	0–20	42.600	231.900	288.478	5.420	3.060	26.302	0.116	0.110	2.885
	20–40	30.400	63.300	43.747	5.500	0.800	14.032	0.136	0.020	0.024

Table 4
The heavy metal content of leachates (mg. L^{-1})

Heavy metal	Hg	Cr	Cd	As	Pb	Mn	Ag
Range of content	0.012–0.045	0.789–1.137	0.023–0.082	0.263–0.403	0.564–0.785	1.598–1.866	0.098–0.135
Average value	0.028	0.961	0.062	0.361	0.698	1.7305	0.11575
[a]IWDS(1996)	0.05	1.5	0.1	0.5	1.0	2.0	0.5

[a]IWDS = Integrated Wastewater Discharge Standard.

Table 5
Average concentration of toxic metals in the artificial soil for construction of afforestation (all data in mg kg^{-1} D W)

Sample	Depth (cm)	Heavy metal species (mg kg^{-1})				
		As	Hg	Pb	Cd	Cr
Artificial soil	0–40	10.6–12.8	0.030–0.031	3.66–4.52	0.036–0.043	56.9–72.1
	40–60	11.1–13.7	0.030–0.034	3. 58–4.78	0.039	74.6–78.9
AVFa		40	1.5	500	1.0	300

[a]AVF = Allowable values suitable for forest.

soil types and had no harmful effects on the plants planted.

4. Conclusions

(1) Studies have shown that this comprehensive soil afforestation utilization based on solid wastes is more conducive to the growth and survival of the plant. The plant can grow well in such sets of comprehensive soil after six months. More than 95% of the plant can survive in its matrix composed of dredged sediments, caustic sludge, and coal ash. The recommended mixing proportion of dredged sediments, coal ash, and caustic sludge is 4:3:3. The adoption of the technology must be combined with the corresponding row of salt and lowering the water level engineering, while prerequisite for the success of these projects is to have high capital investment as a guarantee in the economic conditions, which does not permit successful implementation of this project.

(2) It is very difficult to do ecological restoration projects in the coastal ecosystem due to its high salinity level. In this paper, comprehensive afforestation utilization in the coastal system was applied successfully and the results are ideal through many years of efforts. It has provided a new soil viable alternative solution and formed a green ecological restoration model in a coastal ecosystem. It will not only solve the largest of solid waste pollution on the coastal ecosystem, but also can reduce the damage to ecological

environment of the surrounding area with minimal cost. In further research, attention will be paid to the mobility of heavy metals in the artificial soil under forest and development of the forest and the artificial soil management systems will be investigated so that technical parameters will be optimized. Meanwhile, the root development of the trees and the roots competition between the trees and water–salt movement dynamics should be investigated as well.

Acknowledgments

This research was supported by National Basic Research Program of China (973 Program, No. 2012CB417005), National Science & Technology Pillar Program during the 12th Five-year Plan Period (2012BAC06B01), National Natural Science Foundation of China (41271034) and the Special S & T project on Treatment and Control of Water Pollution (2012ZX07101-007-01). The authors would like to express sincere thanks to the reviewers and the editor for their helpful suggestions and comments.

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