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# The purposeful use of pedological concepts in guiding the remediation of mine tailings in China

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## ABSTRACT

Remediation of degraded lands and soils or of mine wastes is often guided by a limited perspective in terms of natural sciences and time horizon, and biased in favour of an engineering approach. The main natural sciences relevant to remediation are soil science (pedology), geochemistry, geology and geomorphology, biology and ecology. Soil science tends to be used only at a very basic level in remediation, but it has much more to offer, especially through soil formation theory.

Two pilot projects for remediating copper mine tailings undertaken by the China-Australia Research Institute for Mine Waste Management, provided an opportunity to demonstrate a more holistic and systematic approach to such tasks. The projects were located at Yuanqu, in the Zhong Tiao Shan hills, Shanxi Province, and at Tong Ling in the Yangtse River floodplain, Anhui Province. The experimental design focussed on the following problems:

1) unsatisfactory particle size distributions and waterholding capacity;
2) lack of soil structure and particle cohesion;
3) lack of plant available phosphorus and nitrogen;
4) absence of organic matter;
5) excess heavy metals, specifically copper and cobalt;
6) a large component of dolomite and lime;
7) the “chemical time bomb” effect - the risk of heavy metal liberation associated with possible changes in soil pH over long time periods;
8) formation of new compounds from native tailings minerals capable of occluding and adsorbing liberated heavy metals;
9) crop and forage selection based on ecological criteria and local agricultural practices;
10) uptake and translocation of heavy metals in the food chain and potential health impacts on humans.

The results showed that mine tailings could be converted to productive agricultural land, producing safe food. It was demonstrated that the path to remediation can be clearly mapped so that the work can be carried out with increased efficiency and

effectiveness and confidence in its ultimate success, and that the long-term prospects can be predicted (CARIM, 1993-1997).

## 1. INTRODUCTION

In China approximately 20,000 ha of land is degraded each year by mining activities such as the dumping of waste rock and tailings. As land for agricultural, urban and recreational uses is scarce, and natural waters are often detrimentally affected, it is important to maximise the area to be rehabilitated. In addition, the tailings deposits often caused severe dust problems in adjoining areas. The Chinese and Australian Governments have co-operated to mitigate the environmental degradation by setting up the China-Australia Research Institute for Mine Waste Management (CARIM) in 1993. CARIM became an Institute within the Beijing General Research Institute for Mining and Metallurgy (BGRIMM) and BGRIMM is a department of the China Non-ferrous Metals Industry Corporation. This joint Australia-China initiative was successfully concluded in 1997.

The task of CARIM was, and is, to develop suitable strategies and methodologies for rehabilitating mine wastes and land degraded by mining activities following a multi-disciplinary approach. Its scope included geomechanics (tailings dam stability, dam permeability and building foundation stability), geohydrology, mine development and planning for mine waste rehabilitation, soil science, geochemistry, agronomy, human health and community affairs.

This paper illustrates how pedological concepts can be used to guide the rehabilitation process to set and reach its goals with optimal efficiency. We define pedology as the study of soil formation, or pedogenesis. Dokuchayev (1846-1903) is generally recognised as the originator of the idea of soil as a body which has resulted from, and is constantly changing under, the influence of local climate, parent material, plant and animal organisms, relief or topography, and time. The climate factor was emphasised excessively and diverted attention away from landscape and soil processes. Since his time an enormous amount of research has been done to increase our knowledge on these aspects of soil formation. We now know that soil-forming factors can act independently and can interact in complicated ways. Therefore the only way to understand soils, to modify them and to predict future trends is to consider the wide range of chemical, biological and physical processes that operate in the soil and in entire landscapes.

Paton et al (1995) consider pedogenesis as the result of the following separate processes:

(a) epimorphism – the manner in which minerals formed deep within the Earth react and adjust to near-surface conditions, involving
  - weathering of primary minerals
  - leaching of different breakdown products having different mobilities
  - new mineral formation through the interaction of weathering and leaching
  - inheritance, which relates to the amount of material not affected by or residual from epimorphism

(b) bioturbation, which is the local displacement of soil by living organisms

(c) rainwash, the combined effects of soil detachment, movement, soil sorting and re-deposition by moving water
(d) aeolian processes, the combined effects of soil detachment, transport, sorting and re-deposition by wind
(e) soil creep, the effects of gravity-induced down slope movement of soil.

In the planning of rehabilitation of mine tailings we are mainly concerned with epimorphism in all its aspects, but bioturbation, rainwash and aeolian processes also play a role in the model.

## 2. APPROACH TO REHABILITATION IN THE TWO PILOT PROJECT AREAS

### 2.1 Objectives

Both pilot projects concerned tailings from copper mines. It was known that the tailings consist of pulverised ore rock still containing copper and cobalt, were largely devoid of vegetation and incapable of growing desirable plants, and when dry were a source of dust. The objectives of rehabilitation at Zhong Tiao Shan (ZTS) therefore were:

1) to create a material suitable for productive cropping;
2) to produce foods that were safe to eat in terms of heavy metal contents;
3) to prevent the leaching of heavy metals to the nearby small river where it could contaminate the water and fish; and
4) to minimise the dust and health problem in an adjacent village.

At the Wu Gong Li tailings pond on the outskirts of Tong Ling (TL) the objectives were:

5) to revegetate the tailings with grass and trees, as a prelude to ultimate urbanisation; and
6) to minimise a future dust and health problem to the city and surroundings.

All objectives involve the successful growing of plants and a consideration of the mobility and toxicity of heavy metals over a long time frame.

A productive soil possesses more or less equal proportions of sand, silt and clay particles, as well as adequate organic matter in the surface layer, a suitable pH (say between 5.5 and 8.0), and adequate levels of plant-available major nutrients N, P and K, as well as minor nutrients and essential trace elements. Such a soil is not extremely sandy or clayey, and has an adequate water holding capacity in relation to local rainfall and evaporation. It does not have excessive levels of soluble trace elements that can cause toxicity or other physiological damage to plants, or those who consume the plants. It has a strong microbiological life and supports other soil-inhabiting fauna.

## 2.2 Setting out a path

### *2.2.1 Particle size distribution and mineralogy - potential for making a new soil*

The first step in creating a new soil is to consider the potential for beneficial or adverse effects of the four components of epimorphism: weathering, leaching, new mineral formation and effect of inherited properties. One must therefore characterise the tailings in terms of particle size distribution, mineralogy, pH and major nutrient concentrations. Without this information the starting point for creating soil from tailings is unknown, and the potential soil forming processes cannot be predicted.

The Mao Jia Wan and Wu Gong Li tailings consisted of very fine sand to fine sand sized particles (0.2 – 0.02 mm). As they were discharged in the tailings ponds or dams as a watery slurry, they formed deposits similar to an alluvial fan. At the upper end of the fan they were coarser than at the lower, far end of these dams. At the low end the tailings tended to be of silty texture (0.02 to 0.002 mm) and are referred to as slimes. The clay fraction was less than 1.5%. These predominantly sandy textures indicate a low water holding capacity (perhaps between 8-15 vol.%) and a low cation exchange capacity (up to <5 meq/100g).

The Wu Gong Li tailings near Tong Ling (TL) contained 3.5-8.0% carbonate and the Mao Jia Wan tailings near Yuanqu had about 30% carbonate. Consequently, there was no problem with acid drainage in these areas. Quartz, dolomite and feldspar were co-dominant minerals, with muscovite subdominant and calcite a minor constituent in the Mao Jia Wan tailings. There were also traces of pyrites and talc. A local industry had sprung up along the tailings discharge channel where magnetite was being removed from the tailings. Although not identified by X-ray diffraction there were also other dark minerals in the tailings, which presumably contained iron.

Chlorite, muscovite and vermiculite, with trace amounts of calcite, dolomite, feldspar and quartz, though very small, dominated the very small clay fraction of the Mao Jia Wan tailings.

Clearly, the formation of a significant clay fraction by weathering of the feldspars and micas in the tailings would take many thousands of years. Therefore, a clay fraction should be imported in developing a productive agricultural soil.

In the region around Yuanqu enormous slump deposits of loess were observed on lower mountain slopes. The loess is believed to pre-date the last glaciation, because it has been mixed with large boulders and stones (glacial erratics) of local bedrock. Loess samples taken at 3 or 4 m depth in a quarry contained about 0.2-4.0% calcium carbonate and had gypsum crystals. From this it could be deduced that since the end of the last glacial period the local climate had not been wet enough to cause much leaching of soluble salts. Currently, annual rainfall is 630 mm with humid hot summers and dry cold winters.

The loess has a silty clay loam texture with about 34% clay, a CEC of 42 meq/100g and a reddish brown colour. It had been used in earlier years to cover disused tailings ponds with 1.5 to 2 m thick layer and in many other places it was also being quarried for brick making. It was a good material for mixing with tailings to increase clay content.

In the TL area the local soil type appeared to be a Terra Rossa formed on limestone. It contained a significant clay fraction and it is probable that at least the upper part of the soil profile has been leached and has an acid reaction. However, it proved to be impossible to obtain sufficient quantities of the Terra Rossa soil for mixing with the tailings.

With such high carbonate contents (3.5 to 30%) in the tailings, it is clear that the pH of a new soil will be controlled for millennia to come at values between 7.5 and 8.0. This high pH will also control the solubility and mobility of many heavy metals, particularly copper, and of phosphate. Thus it could be predicted that copper would not be taken up in excess by any crop grown on the rehabilitated tailings.

At the Mao Jia Wan tailings dam we set up trial plots with three levels of loess (T2, T3 and T4) added to the tailings and a control (T1), which was tailings only. The highest level of loess (T4) was a cover of 0.4 m of loess over the tailings, and the two intermediate ones were T2 with 0.15 m of loess and T3 with 0.3 m of loess. T2 and T3 were mixed with the underlying tailings using an ox-drawn plough first and a small ride-on tractor and shovels by hand. The mixing with inadequate equipment was difficult and only partly achieved. The aimed mixing ratios of tailings to loess and the achieved ratios, calculated from average calcium carbonate contents of the tailings (30%) and the loess (1.2%), are tabulated below.

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| Objective | Tailings 100% | Loess:Tailings 1:1 | Loess:Tailings 3:1 | Loess 100% |
| Achieved | Tailings 100% | Loess:Tailings 2:1 | Loess:Tailings 2.8:1 | Loess 100% |

It will be understood that it was not possible to create a uniform mix of these materials with the equipment available. However, over the years, continued cultivation will lead to a more uniform soil texture. It was assumed that the roots of the crops in the T4 treatment are largely exploiting the upper 0.4 m of loess soil and that the tailings below can be ignored.

### *2.2.2 Inherited trace elements and heavy metals - potential for toxicity or deficiency*

Total and EDTA-extractable heavy metals were determined in all tailings samples, but only total concentrations will be discussed in this paper. At both pilot locations the tailings contained between 200-600 mg/kg Cu, 50-150 mg/kg Co, 5-35 mg/kg As as well as minor concentrations of Mn, Pb, Se and Zn, and very low levels of Cd.

Uptake of heavy metals by plants is governed by solubility in the soil water and hence by speciation. Since the root zone of the tailings and the amended tailings may be characterised as a generally oxidising and alkaline environment, the predicted species are (Hutchinson, I.P. and Ellison, R.D., 1992):

for cobalt: solid phase (s) and suspended solid (ss) - $Co(OH)_2(ss)$, $Co_3O_4(s)$, and $(Co_2O_3(s)$
ionic forms - $Co^{+2}$, $Co_2(OH)^{+3}$

for copper: solid phase - $Cu_2O(s)$, $Cu(OH)_2(s)$, $CuCO_3(s)$
ionic forms - $Cu^{+2}$, $Cu(OH)^+$, $Cu_2(OH)_2^{+2}$

Since the tailings and the amended tailings as well as the loess have free calcium carbonate it is likely that both metals commonly occur as carbonates in the solid phase.

Baker (1990) describes the existence of copper in soils as being in six ‘pools’: soluble ions, soluble inorganic and organic complexes, exchangeable Cu, stable organic complexes, adsorbed Cu on hydrous oxides of Mn, Fe and Al, adsorbed Cu on the clay-humus colloidal complex, and crystal lattice-bound Cu. The copper in the tailings is likely to exist primarily as the crystalline copper carbonate (malachite), and in the presence of an abundance of dolomite and calcite it will be stable.

Copper in the soil solution is largely complexed to dissolved organic matter. Römkens (1994) found that there was an interaction between dissolved organic carbon (DOC) and $Ca^{+2}$ ions in the soil moisture resulting in a precipitation of DOC when $Ca^{+2}$ concentrations increased. The DOC concentration decreased linearly with increasing calcium from 120 mg/L (zero calcium) to about 20 mg/L (90 mg/L calcium). With the increase of calcium in the soil solution there was a proportional decrease in dissolved copper.

Applying this finding to the tailings rehabilitation we predicted that it was most unlikely for crops to take up excessive copper from their root zones, particularly because organic matter contents will rise over time.

Because of its siderophile nature Co in the tailings may be present in iron- and manganese-bearing minerals substituting for Fe and Mn. This Co is not readily available to plants. The solid phase forms of cobalt are all very insoluble (Smith, 1990) and Co is expected to be immobile in alkaline environments. Other soil minerals, especially Fe and Mn oxides, may sorb Co released by weathering. Adsorption of Co to $MnO_2$ is well documented by Gilkes and McKenzie (1988), and increases with pH (McKenzie, 1967). Thus, excessive uptake of cobalt by the crops grown on the amended tailings is not expected.

We have observed that, as the tailings weather, iron oxy-hydroxide coatings are forming on the particles as evidenced by colour changes from light grey to yellow browns and rusty colours. These iron compounds should capture and immobilise Cu and Co ions from the water phase.

In summary, considering the heavy metals in the light of epimorphic processes distinguished by Paton et al (1995), we can conclude that the rehabilitation of the tailings does not need any further inputs from us in both pilot projects. As time goes on the tailings can only become safer through natural processes.

### *2.2.3 Accumulation of organic matter and nutrient capital - potential for creating fertility*

The accumulation of organic matter in soils is a relatively fast process, but the earliest soil organic matter components are relatively easily degraded. Stable forms of humus develop more slowly. The equilibrium organic matter level in natural soils is a complex function of the fertility and climate of a given location. High fertility, good rainfall and moderate to low temperatures tend to lead to high organic matter levels.

Crocker (1960) dated the rate of organic matter accumulation on a series of mudflows in the Mt Shasta area of California. These mudflows ranged in ages from 27 years to 12,000 years. It appeared that there was a rapid increase in organic matter in the first 60 years after vegetation re-established itself on the mudflow, but then the rate of accumulation decreased to approach steady state conditions. He determined that likewise nitrogen accumulation in the soil was quite rapid, and calculated that nitrogen build-up was of the order of 55 kg/ha.year. In cropped soils, the root mass of the crops is the main contributor to soil organic matter.

In rehabilitation work it is not readily possible to affect the rate of decay and mineralisation of organic matter, but it is possible to stimulate the formation of biomass by ensuring high soil fertility and adequate water for the crop or the pasture. It is also possible to sacrifice a crop harvest in some years by planting a green manure crop and adding the aboveground biomass to the soil. The annual application of fertilisers and incorporating crop residues in the amended tailings should give measurable increases in organic matter in 10 years or so.

The tailings and the loess in ZTS and the tailings in TL had no detectable plant-available phosphate (Olsen et al., 1954) - detection limit was 0.1 mg/kg - and very low Total Kjeldahl Nitrogen (10-68 mg/kg), except where some sparse weed growth occurred (127 mg/kg). Soil $\mathrm{pH}_{(1:5\ \mathrm{water})}$ ranged from 7.5 to 7.7. Plant-available potassium at ZTS was around 360 mg/kg.

The trials plots were given fertiliser at double the local district rate: 180 kg/ha of N, 239 kg/ha of P, 36 kg/ha of K, 177 kg/ha of S and follow up nitrogen (245 kg/ha) later in the season. The fertilisers were selected from those available at the Government stores. The use of a double fertiliser application rate was intended to raise the nutrient capital of the amended tailings and stimulate biomass production. Building up the nutrient capital of the soil should take less time than increasing organic matter content.

Some plots at the Mao Jia Wan tailings dam were planted to one of three green manure crops: (a) Sudax, a sorghum-Sudan Grass hybrid, (b) mung beans (Chinese lentils, *Vigna radiata*), and (c) perennial rye grass plus white clover (*Lolium perenne* & *Trifolium repens*). The green manures were ploughed under at the end of the cropping season. These plots were planted initially to winter wheat and after that to various summer crops followed by winter wheat.

There were no worms or other burrowing animals in the tailings or the amended tailings. Harvesting the peanuts and removing the maize stalks at the end of the summer season and cultivation of the soil for the new growing seasons were the only forms of bioturbation of the soil.

#### *2.2.4 Soil detachment, movement, sorting and re-deposition - potential for stabilising the tailings*

The bare surfaces of the tailings suffered severely from wind erosion when they were dry. At ZTS the dust problem downwind was also severe, such that dust must have penetrated all the houses and buildings down wind for a considerable but unknown distance. Visibility was sometimes limited to 20-30 m during these dust events. Because of the very high permeability of the fine sandy tailings there did not appear to be much water erosion.

To protect the experimental plots at the Mao Jia Wan dam a 15 m wide wind break was planted using Sudax and sorghum and a double fertiliser application rate, as in the experimental plots. This worked well as could be seen by the building up of a sand ridge inside the windbreak.

At the Wu Gong Li tailings pond, the surface of the tailings was mainly moist, with stagnant water at the bottom end, and dust did not cause problems there. Because of the high water table at this site, excess rainfall could cause much erosion. To facilitate surface drainage shallow parallel trenches were dug along the length of the dam.

As the tailings had been discharged for many years from the same location in the pond, the particle size decreased systematically from the high lying discharge points to the low lying bottom area. The tailings resembled an alluvial fan. The bottom end was generally too rich in ‘slimes’ and too soft to be included in the rehabilitation.

## 3. EXPERIMENTAL CROPS, PASTURES AND TREES

### 3.1 Selection of crops and species

As stated, at the Mao Jia Wan experimental site peanuts, sorghum, maize and soybeans were grown as summer crops and winter wheat as the winter-spring crop. In addition, three areas were planted to different green manures. These were Sudax, mung beans and perennial rye grass with white clover. The only difference between plots was the proportion of loess soil added to the tailings. In the second winter and summer of cropping, these same crops were extended on the green manure plots.

At the Wu Gong Li experimental site the tailings treatment consisted of fertiliser application, but the trials focused on the establishment and growth of eleven grass and clover species and a number of tree and shrub species. The herbaceous species included couch grass (*Cynodon dactylon*), tall fescue (*Festuca arundinaria*), perennial rye grass (*Lolium perenne*), brome grass (*Bromus inermis*), cocksfoot (*Dactylis glomerata*), zoysia (*Zoysia japonica*), white clover (*Trifolium repens*), lucerne (*Medicago sativa*), crown vetch (*Coronilla varia*), yellow lotus clover (*Lotus corniculata*) and serradella (*Ornithopus perpusifolia*). The tree species included poplar (*Populus spp.*), honey locust or Chinese scholar (*Robinia pseudoacacia*), willow (*Salix spp.*), camphor tree (*Camphora japonica*), holly (*Ilex spp.*), and *Amorpha fruticosa.*

## 3.2 Mao Jia Wan - Crop growth results, yields and quality of produce

Sufficient water existed in the soil at summer crop planting time (May) at the Mao Jia Wan site to start the swelling of the seeds. A good rainfall occurred a few days after sowing to produce good seedling emergence. The summer however was the driest for 30 years. A weather station had not yet been installed so no exact rainfall data were available in that year. Soy bean and maize yields in the surrounding district were very low. At the experimental site the soy beans failed to set seed after flowering very well, and the maize grew to full height but the cobs remained small. The sorghum and peanuts performed well. Sinclair and Serraj (1995) provide a possible explanation for the different behaviour of these two leguminous crops. They suggested that soy beans belong to a group of legumes which transport N as ureides from the roots into the above-ground plant and is unable to do so under drought conditions, while peanuts belong to a second group which transports N as amides and is less sensitive to soil drying. First season yields in kg/ha of sun dried weights are summarised below.

| **Crop** | **Long Term District Ave.*)** | **T1 treatment** | **T2 treatment** | **T3 treatment** | **T4 treatment** |
|---|---|---|---|---|---|
| Peanuts (in shell) | 2250-3000 | 2353 | 3184 | 2716 | 1636 |
| Sorghum (grains) | 7500 | 4588 | 8082 | 6702 | 4537 |
| Maize (kernels) | 5100 | 2409 | 4269 | 3986 | 3244 |
| Soybean (beans) | 2400 | 88 | 153 | 129 | 236 |

*) Information obtained from Yuanqu County Department of Agriculture

Peanuts on tailings with only fertiliser added (T1) yielded as well the district average and sorghum performed as well as the district average with only 15 cm loess soil added. The reduced yield in the T4 treatment soil is most likely due less available water because of the 34.5% clay, compared to the T1, T2 and T3 soils, which had more sand. Soil water monitoring with a neutron meter did not start until the 1996 growing season.

Winter wheat on the T4 treatment gave the best results, especially on the T4-Sudax plots. The 1995 yield was about 15% below average district yield, but the 1995 year was also abnormally dry and district yields were less than half long-term average yields.

Table 1 below summarises the results from two full years of cropping. Table 2 gives heavy metal concentrations in the harvested produce, the seed used for the experiments, the soil and amended tailings, and recent data on tolerable daily intake (TDI) values. The TDI values are expressed on the maximum quantity of heavy metals that may be ingested by a person without risking unfavourable health effects. Note that uptake in the produce of Cu and Co appears to be unrelated to the levels of these metals in the T1 to T4 soil/tailings media. This is expected on the basis of established geochemical principles.

Table 2 also shows that Cu concentrations in the produce are very similar to those in the bought seeds, which, presumably were grown on 'normal' soils in the district. The leguminous crops appear to have a tendency to take up much more Cu than the graminaceous crops. For Co the picture differs in that the produce contains 4-8 times as much of this metal than did the original seed. Again, the leguminous crops accumulate more Co than the grains.

The quoted tolerable daily intakes (TDI) by humans in Table 2 are official Government standards in The Netherlands, (Vermeire et al., 1991; van den Berg, 1995). Table 2 suggests that for a person of 50 kg body weight a daily consumption of about 0.05 kg of maize, or about 0.23 kg of sorghum, or 0.11 kg of peanuts would approximate the TDI for Co, but only a much smaller proportion of the TDI for Cu. Controlled Co toxicity experiments with humans have not been carried out, but it is known that with very high intakes, intestinal absorption of cobalt is reduced and that up to 80% is excreted in faeces (Vermeire et al., 1991). Heavy drinkers of cobalt-fortified beer, who drank up to 10 litres per day had Co intakes equalling a few milligrams per day, and suffered outbreaks of cardiomyopathy with up to 50% mortality (IARC, 1991). Vermeire et al. (1991) arrived at human TDI criteria for several heavy metals by taking the sub-acute toxicity concentrations for experimental rats and dividing this by 1000. Their procedure may be overly conservative. However, even with this degree of conservatism, it would be concluded that the produce grown on the remediated tailings at the Mao Jia Wan site is generally acceptable for human consumption, especially since it is unlikely that a farming family rely entirely on their own crops for their diet.

### 3.3 Mao Jia Wan - Soil development

The trials have not been conducted long enough to detect increases in soil organic matter concentrations with certainty. However, the colour of the tailings, which was originally various shades of grey, has become darker under cultivation. This may be due to increasing organic matter and formation of dark-coloured oxide iron and manganese coatings on the sand particles. In the T1 plots, the organic matter concentration of a single sample of old tailings with sparse weed growth was 1.4% when cropping began in Spring 1994. It appeared to have risen to 2.1% by October 1995. However, only limited samples have been taken and the trend is not well established.

The loess soil on the T4 plot had between 0.6 and 0.8% organic matter in Spring 1994. No further samples were taken.

Available soil phosphate levels in the tailings were always less than the detection limit (0.1 mg/kg), and about 0.2 mg/kg in the loess. In October 1995 these had risen to 5.5-7.6 mg/kg in T1 plots, 9.4 mg/kg in T2 plots, 10.6 mg/kg in T3 plots and 22-26 mg/kg in all T4 plots. It is possible that the high concentration of carbonates in the

T1, T2 and T3 plots, inherited from the tailings, is reducing the availability of P compared to the loess.

Table 1 Crop yields in relation to Yuanqu County yields, 1994-1996

| | T1 | T2 | T3 | T4 | | ***Soil treatments*** | | | | | | Normal average Yuanqu district | 1994-95 ave. district yields |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | T1-GM Sudax | T1-GM mung | T1-GM rye/clov. | T4-GM Sudax | T4-GM mung | T4-GM rye/clov. | | |
| ***Summer crops 1994*** | | | | | | | | | | | | | |
| **peanuts** in shell | 2353 | 2184 | 2716 | 1636 | | *All plots covered by a green manure crop* | | | | | | 2250-3000 | n.a. |
| **sorghum** grain | 4588 | **8082** | 6702 | 4537 | | | | | | | | 7500 | n.a. |
| **maize** kernels | 2409 | 4269 | 3986 | 3244 | | | | | | | | 5100 | n.a. |
| **soybeans** | 88 | 153 | 129 | 236 | | | | | | | | 2250-2400 | n.a. |
| *Notes:* | *Bold numbers where yield exceeded the normal year average*<br>*The 1994 summer season was the driest on record for 30 years* | | | | | | | | | | | | |
| | T1 | T2 | T3 | T4 | | ***Soil treatments*** | | | | | | Normal average Yuanqu district | 1994-95 ave. district yields |
| | | | | | | T1-GM Sudax | T1-GM mung | T1-GM rye/clov. | T4-GM Sudax | T4-GM mung | T4-GM rye/clov. | | |
| ***Winter wheat crop 1994-95*** | | | | | | | | | | | | | |
| **wheat** | 675 | 1275 | 1215 | 1455 | | 1170 | 870 | 675 | 1845 | 1485 | 1290 | 3750-4500 | 1500-1875 |
| *Notes:* | *GM = green manure; either Sudax, mung beans or perennial rye and white clover*<br>*No rain fell at all after the beginning of May '95 till the wheat was harvested on 8 June '95, severely depressing that season's yield* | | | | | | | | | | | | |
| | T1 | T2 | T3 | T4 | | ***Soil treatments*** | | | | | | Normal average Yuanqu district | 1994-95 ave. district yields |
| | | | | | | T1-GM Sudax | T1-GM mung | T1-GM rye/clov. | T4-GM Sudax | T4-GM mung | T4-GM rye/clov. | | |
| ***Summer crops 1995*** | | | | | | | | | | | | | |
| **peanuts** *) in shell | 1698 | 0 | 0 | 0 | | np | np | np | np | np | np | *Most farmers did not plant summer crops due to lack of rain* | |
| **sorghum** grain | np | np | np | np | | np | np | np | np | np | np | | |
| **maize***) kernels | 0 | 0 | 0 | 0 | | 990 | 866 | 0 | 0 | 0 | 0 | | |
| **soybeans** | np | np | np | np | | np | np | np | np | np | np | | |
| *Notes* | *The 1995 summer was again a very dry summer, all seeds germinated one month too late, and yields were poor.*<br>*Crops in several plots were pulled out to ready the land for winter wheat sown in October 1995.*<br>*Plot T1(pr/c) missed out on fertiliser and was a total failure.*<br>*) = *Peanuts were sown into a standing winter wheat crop; 90 day maize variety in view of short season after wheat*<br>*np = not planted in this season*<br>*n.a. = data not obtained from Yuanqu Department of Agriculture* | | | | | | | | | | | | |
| | T1 | T2 | T3 | T4 | | ***Soil treatments*** | | | | | | Normal average Yuanqu district | 1994-95 ave. district yields |
| | | | | | | T1-GM Sudax | T1-GM mung | T1-GM rye/clov. | T4-GM Sudax | T4-GM mung | T4-GM rye/clov. | | |
| ***Winter wheat crop 1995-96*** | | | | | | | | | | | | | |
| wheat | np | 1437 | 1665 | 1257 | | np | np | 390 | 1964 | 1021 | 1369 | | 2250 |

Table 2` Soil-Food chain relationship between heavy metal concentrations in seeds and produce at the Mao Jia Wan Site

| Material type & location | Sample No. | Depth (cm) | Total As (mg/kg) | Total Cd (mg/kg) | Total Co (mg/kg) | Total Cr (mg/kg) | Total Cu (mg/kg) | Total Hg (mg/kg) | Total Ni (mg/kg) | Total Pb (mg/kg) | Total Zn (mg/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soil materials** | | | | | | | | | | | |
| Soil - T1 treatment spring sample | 12329/94 | 0 - 10 | 19 | <0.6 | n.d. | 29 | 330 | <0.2 | 33 | <30 | 20 |
| *ditto autumn sampling '94* | *21093/94* | | | | *91* | | *320* | | | | *19* |
| *ditto autumn sampling '95* | *14624/95* | | | | *80* | | *270* | | | | *40* |
| Soil - T2 treatment spring sample | 12330/94 | 0 - 10 | 14 | <0.6 | n.d. | 36 | 290 | <0.2 | 39 | <30 | 37 |
| *ditto autumn sampling '94* | *21094/94* | | | | *80* | | *240* | | | | *41* |
| *ditto autumn sampling '95* | *14625/95* | | | | *130* | | *320* | | | | *30* |
| Soil - T3 treatment spring sample | 12331/94 | 0 - 10 | 18 | <0.6 | n.d. | 35 | 230 | <0.2 | 35 | <30 | 39 |
| *ditto autumn sampling '94* | *21095/94* | | | | *64* | | *190* | | | | *41* |
| *ditto autumn sampling '95* | *14626/95* | | | | *130* | | *350* | | | | *20* |
| Soil - T4 treatment spring sample | 12332/94 | 0 - 10 | 15 | <0.6 | n.d. | 40 | 32 | <0.2 | 30 | <30 | 55 |
| *ditto autumn sampling '94* | *21096/94* | | | | *14* | | *29* | | | | *54* |
| *ditto autumn sampling '95* | *14627/95* | | | | *20* | | *60* | | | | *40* |
| **Seeds** | | | | | | | | | | | |
| Seeds - maize | 12325/94 | n.a. | <0.2 | 0.01 | <0.03 | <0.6 | 2.1 | n.d. | n.d. | <0.2 | 15 |
| Seeds - sorghum | 12326/94 | n.a. | <0.2 | 0.01 | 0.14 | 0.6 | 5.3 | n.d. | n.d. | <0.2 | 20 |
| Seeds - peanut | 12327/94 | n.a. | 0.2 | 0.02 | 0.12 | <0.6 | 14 | n.d. | n.d. | <0.2 | 41 |
| Seeds - soybean | 12328/94 | n.a. | <0.2 | 0.01 | 0.41 | 0.7 | 17 | n.d. | n.d. | <0.2 | 47 |
| **Produce** | | | | | | | | | | | |
| Produce - maize - T1 | 21077/94 | | 0.2 | <0.02 | 0.13 | 1 | 4 | | 2 | <0.3 | 19 |
| Produce - maize - T2 | 21078/94 | | <0.2 | <0.02 | 0.12 | 1 | 4 | | 2 | <0.3 | 19 |
| Produce - maize - T3 | 21079/94 | | 0.2 | <0.02 | 0.12 | 1 | 4 | | 2 | 0.3 | 19 |
| Produce - maize - T4 | 21080/94 | | 0.2 | <0.02 | 0.18 | 1 | 3 | | <2 | <0.3 | 14 |
| Produce - sorghum - T1 | 21081/94 | | 0.7 | <0.02 | 0.25 | 1 | 5 | | 0.7 | 0.3 | 16 |
| Produce - sorghum - T2 | 21082/94 | | 0.2 | <0.02 | 0.32 | 1 | 5 | | 0.2 | 0.3 | 18 |
| Produce - sorghum - T3 | 21083/94 | | 0.2 | <0.02 | 0.21 | 1 | 5 | | 0.2 | <0.3 | 18 |
| Produce - sorghum - T4 | 21084/94 | | <0.2 | <0.02 | 0.44 | 1 | 5 | | <0.2 | 0.3 | 16 |
| Produce - peanuts - T1 | 21085/94 | | 0.2 | 0.02 | 0.74 | 1 | 16 | | 5 | <0.3 | 31 |
| Produce - peanuts - T2 | 21086/94 | | <0.2 | 0.02 | 0.61 | 1 | 15 | | 4 | <0.3 | 33 |
| Produce - peanuts - T3 | 21087/94 | | <0.2 | 0.02 | 0.73 | 2 | 15 | | 5 | <0.3 | 33 |
| Produce - peanuts - T4 | 21088/94 | | 0.5 | 0.03 | 0.41 | 1 | 14 | | 4 | <0.3 | 28 |
| Produce - soybeans - T1 | 21089/94 | | <0.2 | <0.02 | 3.3 | 1 | 19 | | 14 | <0.3 | 43 |
| Produce - soybeans - T2 | 21090/94 | | <0.2 | <0.02 | 2.8 | 1 | 20 | | 12 | <0.3 | 42 |
| Produce - soybeans - T3 | 21091/94 | | 0.3 | <0.02 | 2.6 | 2 | 21 | | 12 | <0.3 | 38 |
| Produce - soybeans - T4 | 21092/94 | | <0.2 | <0.02 | 2.7 | 2 | 19 | | 11 | <0.3 | 35 |
| **Seeds** - winter wheat '95 | 14623/95 | | 0.1 | 0.02 | 0.08 | 1 | 8 | <0.02 | 1 | <0.3 | 30 |
| **Produce** - winter wheat '95 | not sampled | | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| T1 plot | 14621/95 | | 0.1 | 0.01 | 0.95 | 1 | 10 | <0.02 | 1 | <0.3 | 25 |
| T1 rye grass clover plot | 14622/95 | | 0.1 | 0.01 | 1.00 | 1 | 11 | <0.02 | 1 | <0.3 | 28 |
| T1 sudax lupin plot | 14616/95 | | 0.1 | 0.01 | 0.71 | 1 | 9 | <0.02 | 1 | <0.3 | 27 |
| T1 Chinese lentil plot | 14617/95 | | 0.2 | 0.01 | 0.89 | 1 | 9 | <0.02 | 1 | <0.3 | 28 |
| T2 plot | 14620/95 | | <0.1 | 0.02 | 0.57 | 1 | 10 | <0.02 | 1 | <0.3 | 32 |
| T3 plot | 14619/95 | | 0.1 | 0.02 | 0.73 | 1 | 9 | <0.02 | 1 | <0.3 | 31 |
| T4 plot | 14618/95 | | 0.1 | 0.07 | 1.10 | 1 | 10 | <0.02 | 2 | <0.3 | 28 |
| T4 rye grass clover plot | 14615/95 | | <0.1 | 0.05 | 0.61 | 1 | 9 | <0.02 | 2 | <0.3 | 29 |
| T4 sudax lupin plot | 14613/95 | | 0.1 | 0.05 | 0.68 | 1 | 9 | <0.02 | 2 | <0.3 | 22 |
| T4 Chinese lentil plot | 14614/95 | | <0.1 | 0.05 | 0.76 | 1 | 9 | <0.02 | 2 | <0.3 | 25 |
| **Produce bought in the market** | | | | | | | | | | | |
| Houma peanuts | 11388/95 | | 0.1 | 0.03 | <0.04 | 1 | 13 | <0.02 | <2 | <0.3 | n.d. |
| Houma soybeans | 11389/95 | | <0.1 | 0.02 | 0.17 | 1 | 17 | <0.02 | 2 | <0.3 | n.d. |
| Houma red beans | 11390/95 | | <0.1 | <0.01 | 0.04 | 1 | 10 | <0.02 | <2 | <0.3 | n.d. |
| Houma Chinese lentil | 11391/95 | | <0.1 | <0.01 | 0.04 | 1 | 11 | <0.02 | <2 | <0.3 | n.d. |
| Mao Jia Wan peanuts | 11392/95 | | <0.1 | 0.02 | <0.04 | 1 | 12 | <0.02 | <2 | <.0.3 | n.d. |
| **Standard for general foods (mg/kg)** | | | 1.0 | 0.05 | ? | ? | 10 | 0.03 | ? | 1.5 | 150 |
| *( From: Standard A12, Australia)* | | | | | | | | | | | |
| **Tolerable daily intake (υg/kg.day)** | | | 2.1 | 1 | 1.4 | 5.3*) | 140 | 0.61 | 50 | 3.6 | 1000 |
| **TDI for a person of 50 kg body weight (υg)** | | | 105 | 50 | 70 | 265*) | 700 | 30.5 | 2500 | 180 | 50,000 |

*(From: van den Berg, 1995)*

*) Cr$^{3+}$; 0.000,7 for Cr$^{6+}$

Available potassium was always high (90 and 360 mg/kg), probably due to the weathering of feldspars, chlorite and muscovite.

### 3.4 Wu Gong Li - Establishment of grasses, pasture legumes and trees

The original trial plots at the Wu Gong Li tailings pond were 5 x 5 m, but when certain grasses and certain tree species showed good establishment a larger scale revegetation program commenced. The species that showed the best promise were couch grass (*Cynodon dactylon*) and tall fescue (*Festuca arundinaria*). Perennial rye grass (*Lolium perenne*, var. "Derby") was moderately successful.

All the legumes from white clover (*Trifolium repens*), alfalfa or lucerne (*Medicago sativa*), crown vetch (*Coronilla varia*) to a shrub, indigofera (*Indigofera amblyantha*) failed to establish. Most likely this was due to the absence of appropriate rhizobia.

Large-scale revegetation was carried out in 1996 (2 hectares) and 1997 (10 hectares) using all the successful grass species, which included winter-active and summer-active species, and white clover and lucerne. White clover seeds were treated with rhizobium culture in 1997 as the legumes had again not established themselves in the previous year. In an area of about 2 ha only 4 lucerne plants and 3 clumps of white clover had become established. Establishment of the clover was reported to be much better in the summer of 1997 after the seeds had for the first time been treated with the rhizobium.

Poplars (Populus spp.), Chinese scholar or honey locust (Robinia pseudoacacia) and willows (Salix spp.) were the most successful tree species. Excessive wetness of the lower part of the tailings pond caused more tree losses than occurred in the drier upper part.

The almost total lack of available nitrogen and phosphate was responsible for the absence of vegetation on the tailings. All the areas which had received fertiliser developed a cover of weeds spontaneously. Also we noted that areas near the trial plots which had received fertiliser and were located downslope from the couch grass plots were being colonised by couch grass.

In October 1996 we discovered that the 2-hectare revegetated area was visited by hares at night and colonised by insects and some frogs. A lark had made its home in the rehabilitated tailings pond.

## 4. CONCLUSION

Soil science and related earth science concepts have proved themselves of great informative value in rehabilitating mine tailings and will be essential to the effectiveness of any rehabilitation scheme for degraded lands. These concepts can give direction to the rehabilitation work because they are concerned with the questions What? Why? and How? These questions deal with natural physical, chemical and biological processes. Engineering skills, on the other hand, are necessary for the planning and logistical aspects of a rehabilitation project, because they deal with the questions When?, Where? and How Much?, but these skills alone are not sufficient. A combination of the two disciplines is required.

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