Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

Solid Earth
Discussions
Open Access

Revegetation in abandoned quarries with landfill stabilized waste and gravels: water dynamics and plant growth——a case study

Cheng-liang Zhang[a**], Jing-jing Feng[bc**], Li-ming Rong[a], Ting-ning Zhao[b]

a. Beijing Key Lab of Industrial Land Contamination and Remediation, Environmental Protection Research Institute of Light Industry, 100089, Beijing, China;

b. School of Soil and Water Conservation, Beijing Forestry University, 100083, Beijing, China;

c. School of Environmental Science and Engineering, Shanghai Jiaotong University, Shanghai 200240, China

Running title: Revegetation in abandoned quarries with LGM

Correspondence to: Tingning Zhao

Address: Beijing Forestry University, Qinghuadong Road 35, Beijing, China, 100083.

E-mail: zhtning@bjfu.edu.cn

**These authors contributed to the work equally and should be regarded as co-first authors.

ABSTRACT

Large amounts of quarry wastes are produced during quarrying. Though quarry wastes are commonly used in pavement construction and concrete production, in-situ utilization during ecological restoration of abandoned quarries has its advantage of simplicity. In this paper, rock fragments of 2~3 cm in size were mixed with landfill stabilized waste (LSW) in different proportions (LSW: gravel, R_L), which was called LGM. The water content, runoff and plant growth under natural precipitation were monitored for two years using a runoff plot experiment. LGM with a low fraction of LSW was compacted in different degrees to achieve an appropriate porosity; water dynamic and plant growth of compacted LGM were studied in a field experiment. The results showed that, (1) LGM can be used during restoration in abandoned quarries as growing material for plants. (2) R_L had a significant effect on infiltration and water holding capacity of LGM, and thus influenced retention of precipitation, water condition and plant growth. LGM with R_L ranging from 8:1 to 3:7 was suitable for plant growth, but the target species grew best when R_L was intermediate. (3) Compaction significantly enhanced water content of LGM with a low R_L of 2:8, but leaf water content of plants was lower or unchanged in the more compacted plots. Moderate compaction was beneficial to the survival and growth of *Robinia pseudoacacia*. *Platycladus orientalis* and *Medicago sativa* were not significantly affected by compaction, and they grew better under high degree of compaction which was disadvantageous for the uppermost layer of vegetation.

Keywords: abandoned quarry; rock fragment; compaction; municipal solid waste;

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

landfill

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

1 Introduction

During the process of civilization and urban construction, quarrying industry has fast developed in order to satisfy the growing demand for stones (Duan et al., 2008). Large amounts of quarry wastes are produced during quarrying. In 2006, the byproduct of mining and quarrying accounted for 55% of industrial waste in Europe (Castro-Gomes et al., 2012). Eighty percent of stones or soils extracted during quarrying are wasted (André et al., 2014). Thirty percent and forty percent of marble blocks are wasted as powder and rock fragments, respectively (Akbulut & Gürer, 2007). Quarry wastes occupy a lot of lands, have a low aesthetic value, and may lead to soil erosion, landslide or debris flow.

Reusing is an environmental friendly way to deal with quarry wastes. Coarse and fine aggregates are commonly used in quarry settlement, the production of concrete, mortars and ceramic tiles, and highway construction (Amin et al., 2011; Safiuddin et al., 2010, 2007). The coarse waste aggregates could also be used to make high value-added products such as sculpture and architecture (Castro-Gomes et al., 2012), while the ultra-fine marble wastes are used in various industrial processes such as plastic, paper, pharmaceuticals industry and agriculture (Gazi et al., 2012). However, the reuse of quarry waste on a national scale is primarily constrained by economic aspects such as transport (Castro-Gomes et al., 2012) as well as the lack of industrial symbiosis. Most quarrying and stone processing activities are performed by small medium enterprises. This fragmental quarry industry hardly shares information, services and by-product resources with other industrial practitioners in order to add

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

value, reduce costs, and improve environment, leading to inefficient waste management (Gazi et al., 2012; Rubio et al., 2010). As stated by Tiruta-Barna et al. (2007), the practitioners were lacking of unambiguous references concerning the feasibility of specific reuse projects. Considering the current situation, in-situ utilization of quarry waste during ecological restoration of abandoned quarries has its advantage of simplicity.

Water and nutrient deficiencies are the main environmental factors constraining natural recovery in abandoned quarries. These disadvantages site conditions have to be changed to facilitate plant survival and growth (Luna et al., 2016). In the last decade, many arable topsoil materials were bought and transported from other places to replace or cover the barren spoil or waste in abandoned quarries or mines in China, which was very expensive, accounting for about 50% of the total cost of restoration. The environment of the places where surface soils are taken may also be adversely affected. Soil-like materials containing high values of nutrients such as sewage sludge and waste compost are effective topsoil substitutes because of their economic and environmental advantages (Luna et al., 2016; Forján et al., 2016; Jordán et al., 2016). Landfill stabilized waste (LSW) is the aged municipal solid waste which went through a series of microbiological processes in the closed landfills. It is similar with municipal waste compost in the source, production process and the properties of end products. Previous research indicated its promising potential as growing substrate for plants (Zhang et al., 2017; Zhou et al., 2015; Feng et al., 2017). However, compared with sewage sludge and waste compost, LSW has not been fully exploited, and the

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

research on its properties and application is still limited.

When LSW is mined from the landfill, the original structure is inevitability destroyed. With a high compressibility, LSW lacks of hydrostructural stability and is very sensitive to compaction (Schäffer et al., 2008). On the contrary, quarry spoil and waste may be highly compacted by machines or vehicles and thus have low hydraulic conductivity. If LSW is directly placed on this impervious layer, slip surface may generate between the two layers with dramatic difference in hydraulic conductivity or within LSW layer because of the low shear strength of unconsolidated LSW (Okura et al., 2003). As a result, instead of directly topsoiling with LSW, we mixed it with gravels (2~3 cm in size) in different proportions, reusing rock fragments of quarry wastes as part of the growing substrate for plants, which is called LGM hereinafter. Not only the embedded gravels constitute the primary fabric and thus enhance the stability of the mixture, the surface gravels can also reduce soil evaporation and conserve surface water (Yuan et al., 2009), and prevent fine earth from wind and splash erosion (Jomaa et al., 2012).

When the fraction of LSW is low and most macropores between rock fragments are not filled with LSW, the water holding capacity and thus the water condition may be disadvantageous for plant growth. In order to achieve an appropriate porosity, LGM with a low LSW: gravel ratio (2:8) was compacted in different degrees. The effects of compaction on water condition and plant growth were also studied.

2 Materials and methods

2.1. Study area

The research was conducted in the Ecological Restoration Research Base of Environmental Protection Research Institute of Light Industry, located in Changping County, Beijing (40°9’56.73’’N, 116°9’1.04’’E, 57 m a.s.l.). Beijing has a continental monsoon climate with a rainy season from June to September. The mean annual precipitation is 600 mm, the mean annual temperature is 8~12℃, and the mean annual evaporation is 1800~2000 mm.

2.2. Materials

LSW was taken from five landfills in different districts of Beijing, transported to the study site, and mixed in 2012. Texture, chemical properties such as nutrient and heavy metal contents, concentrations of semi-volatile contaminants and MPN of coliforms were tested. The texture of LSW was in accord with sandy clay loam; generally, the nutrient contents of LSW were higher than the local agricultural soil; the concentrations of heavy metals and organic contaminants were lower than the national limits or similar to the concentrations in natural soil. Basic physical and chemical properties are shown in Tab.1.

Gravels were bought from local market. The mean values (with standard deviation) of maximum, medium and minor axis length were 31±24, 21±4 and 15±4 mm respectively. LSW and gravels were mixed with a mixing machine in different fractions. The LSW: gravel ratios by volume (R_L) were 8:1, 7:3, 5:5, 3:7 and 1:8, which were marked as L1, L2, L3, L4 and L5. LGMs were oven-dried, weighted, and filled into 660-cm^3 cubic flowerpots. They were saturated and weighted to calculate

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

porosity (saturated water content), and then allowed to drain freely under gravity for one day and weighted to calculate field capacity. The upper openings of the flowerpots were sealed with plastic film to prevent evaporation, and gauze was used to avoid leakage of the finer grains through the drain holes.

2.3 Runoff plots of LGM

2.3.1 Setting of runoff plots

Five 2.8-m-wide, 3.6-m-long runoff plots with a slope degree of 38 ° were set in 2012. 70-cm-thick LGM (L1~L5) was spread on the impervious liners and was settled for 1 year. Ruderal species such as *Setaria viridis*, *Digitaria sanguinalis*, *Amaranthus retroflexus*, *Bidens parviflora*, *Pharbitis nil*, *Echinochloa crusgalli*, *Chenopodium album* and *Metaplexis japonica* colonized during the 1-year settlement. During the rainy season the vegetation coverages from L1 to L4 were 100% while that of L5 was about 50%. Litters in two 1-m^2 quadrats for each runoff plot were collected in November 2014 to evaluate the abundance of ruderals.

2.3.2 Water content

The volumetric water content at 10~50 cm depths was measured using a capacitance probe (Diviner 2000, Sentek Pty Ltd., Australia) from August 2013 to August 2015, three times a month; these data were averaged to calculate annual and monthly mean water content. The volumetric water content was also measured every sunny day from May to August 2014; these data were used to study the relationship between soil moisture and precipitation during the rainy season.

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

2.3.3. Retention of precipitation

Multiple regression model as follows is fitted:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 \quad (1)$$

where X_1, X_2 and Y represent antecedent water content (%), precipitation (mm) and water content one day after the rainfall event (%), respectively. The partial regression coefficient for precipitation (β_2) is used as a measure of water conservation, i.e., the average increment of water content each additional precipitation is associated with, for any given antecedent water content (Cohen et al., 2003). Retention of precipitation, which is the percentage of precipitation able to infiltrate and stored in the LGM profile after one night's drainage is calculated as follows:

$$RP = \beta_2 \times D \quad (2)$$

where RP is the retention of precipitation, and D is the depth of LGM.

2.3.4 Runoff

Surface and subsurface runoff were collected separately one day after each rainfall event from June to September (the rainy season) in 2013 and 2014. During the experimental period, there were altogether 32 rainfalls, including 12 light rains (<10 mm d^{-1}), 15 moderate rains (10~25 mm d^{-1}), and 5 heavy rains (>25 mm d^{-1}).

2.3.4 Plant growth

After clearing the colonized ruderals, seed mixture of *Robinia pseudoacacia* (leguminous tree, the target species), *Festuca elata* (perennial grass), *Orychophragmus violaceus* (annual or biennial herb), *Viola philippica* (perennial herb) was sowed with a density of 15 g m^{-2} (6:2:1:1 by mass) in June 2015. Former study

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

indicated its efficiency in fast revegetation and providing a stable soil cover (Feng et al., 2015). Vegetation coverage was measured from August to November 2015 using eight 1-m^2 fixed sample plots (Xie, 2010). Two tallest *R. pseudoacacia* seedlings in each sample plots were cut in November 2015, oven dried for 12 h, and the biomass was measured.

2.4 Compacted plots of LGM

2.4.1 Setting of compacted plots

Five 5-m-long, 3-m-wide, 1-m-deep plots were dug and filled with the LGM with a low LSW: gravel ratio of 2:8 (R_L=2:8). LGM was compacted using a vibratory roller in different degrees.

2.4.2 Determination of theoretical porosity

Because the porosity of compacted LGM was difficult to attain, it was calculated theoretically, assuming that the mass and particle density of the loose LSW were constant:

$$\rho = M / V_0 (1-P_0) = M / V_c (1-P_c) \quad (3)$$

where ρ is particle density; P_0 or P_c is the porosity of LGM before or after compaction; M is the mass of LGM particle; V_0 or V_c is the volume of LGM before or after compaction. Hence,

$$P_c = 1-(1-P_0) \times V_0/V_c \quad (4)$$

P_0 was measured as described in Section 2.2; V_0 and V_c were measured before and after the compaction.

2.4.3 Water content and retention of precipitation

The volumetric water content at 10~100 cm depths was measured from three PVC tubes in each compacted plot using the capacitance probe. The measurement of water content and the calculation of RP in the compacted plots were the same with the measurement and calculation in the runoff plots.

2.4.4. Plant growth

56 *R. pseudoacacia* (leguminous tree) and 30 *Medicago sativa* (leguminous herb) seeds were sowed and 60 *Platycladus orientalis* (evergreen conifer) seedlings were transplanted in each compacted plot after compaction in 2012. No water or nutrients were applied. Germination rate was measured in October 2012 and survival rate was measured in October 2014. From 2013 to 2014, three times a month during rainy season, leaves were collected at 12 a.m., weighted, oven-dried and weighted again to calculate leaf water content; height and stem base diameter of each woody seedling were measured in October; 15 individuals of *M. sativa* were cut after flowering, oven-dried and the aboveground biomass was measured.

2.5. Data analysis

Data were log-transformed and normalized when necessary. One-way analysis of variance and least significant difference test were used to compare height and biomass of *R. pseudoacacia* seedlings growing in LGMs with different R_Ls. This test was also used to compare leaf water content, height or diameter growth (for trees) and biomass (for herbs) of seedlings growing in different compacted LGM plots. Friedman test was used to compare water content, runoff and vegetation coverage of different runoff

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

plots. Linear regression model was used to describe the relationship between antecedent water content, precipitation and water content. SPSS software was used for data analysis.

3 Results

3.1 LGM with different fractions of LSW

3.1.1 Water content and use efficiency of precipitation

As shown in Tab.2, the field capacity of LGM decreased significantly with decreasing R_L ($P<0.01$), reflecting a positive relationship between water holding capacity and R_L since most capillary pores were provided by LSW. The saturated water content was lowest when R_L was intermediate and LSW exactly filled the voids between the gravels, but the difference was not significant.

The annual mean, maximum and minimum monthly mean water contents of all LGM plots were much lower than field capacity, indicating prolonged soil water deficit. However, plants may response quickly to pulsed rainfall events and make the best of precipitation (Huxman et al., 2004). R_L had a positive effect on retention of precipitation. With a decreasing R_L, the percentage of precipitation which was able to infiltrate and was stored in the LGM profile dropped from 70.5% to 24.5%.

3.1.2 Runoff generation

Under light rains, surface or subsurface runoff did not change significantly with R_L, but the volume of total runoff in L5 was significantly higher than those in L2 and L3 ($P<0.05$). During moderate rainfalls, the surface runoff in L2 was significantly lower than those in L3, L4 and L5 ($P<0.05$), but subsurface or total runoff did not change significantly with R_L. During heavy rainfalls, surface, subsurface or total runoff did not change significantly with R_L. However, as shown in Fig.1, generally, during moderate and heavy rainfalls, subsurface and total runoff had a tendency to increase with decreasing R_L. The failure in passing the significance test may result from the high variation of runoff under natural precipitation, indicated by its high standard deviation, which may be caused by the different intensity and/or duration of each rainfall event and the antecedent water content (Liu et al., 2012).

3.1.3 Plant growth

From August to December, vegetation coverage from L1 to L5 were 28.9%~86.0%, 20.2%~96.0%, 37.2%~93.4%, 24.8%~82.3% and 6.2%~43.0%, respectively. Generally, the speed of vegetation formation, the mean coverage and the duration of land cover were similar from L1 to L4, but L5 showed distinctly lower values. Height and biomass of *R. pseudoacacia* were significantly higher in L3 ($P<0.01$); the differences were not significant between L1, L2 and L4; L5 still had the lowest performance (Tab.3).

3.1.4 Litter

The dry weights of litter from L1 to L5 were 0.283, 0.257, 0.197, 0.217 and 0.086 kg m^{-2}, respectively, which showed a decreased tendency with decreasing R_L.

3.2 Compacted LGM with low fraction of LSW

3.2.1 Water condition of compacted LGM

As shown in Tab.4, the annual mean water content of LGM (R_L=2:8) increased significantly with increasing degree of compaction ($P<0.01$). The theoretical porosity

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

was 13.3%~26.1% higher than the annual mean water content in CL1~CL4, but 2.1% lower in CL5, indicating its poor aeration, which may hinder microbial activity, nutrient mineralization, and the uptake of water and nutrient by plants.

Compaction had a positive effect on retention of precipitation. With an increasing compaction degree, the percentage of precipitation which was able to infiltrate and was stored in the LGM profile increased from 34% to 97%.

3.2.2 Plant growth in the compacted LGM

3.2.2.1 Leaf water content

Leaf water content of *R. pseudoacacia* and *M. sativa* decreased significantly with increasing degree of compaction ($P<0.05$). But the difference of *P. orientalis* was not significant between different compacted plots (Tab.5).

3.2.2.2 Survival rate

The germination rates of *R. pseudoacacia* from CL1 to CL5 were 95%, 87%, 92%, 64% and 34% respectively in 2012；the survival rates were 59%, 56%, 56%, 28% and 31% respectively in 2014.

The survival rates of *P. orientalis* from CL1 to CL5 were 100%, 97%, 97%, 95%, and 95% respectively in 2012 and were 85%, 83%, 83%, 88% and 88% respectively in 2014.

3.2.2.3 Growth rate

Compaction had a significant suppressive effect on height or diameter growth of *R. pseudoacacia* ($P<0.01$), but the height and stem base diameter of *P. orientalis* increased with an increasing degree of compaction (Fig. 2).

The effect of compaction on biomass of *M. sativa* was positive and significant ($P<0.01$). The difference between CL1 and CL2 was not significant, but the biomass was significantly higher in CL3~CL5 compared to CL1 in both 2014 and 2015 (Fig.3).

4 Discussion

4.1 Using LGM as growing substrate for plants

LSW is a soil-like material containing high values of organic matter and other nutrients such as nitrogen and potassium, and thus has a promising prospect as topsoil substitute during environmental restoration. However, unconsolidated LSW is unstable and prone to wind or water erosion especially when its structure is destroyed during landfill mining. When LSW is mixed with rock fragments, friction force and interlock capacity would increase while surface runoff and soil erosion would decrease (Descroix et al., 2001). Compared to LSW, less surface runoff was generated in LGM regardless of R_L or precipitation intensity. The effect of R_L on surface runoff was not significant, probably because the infiltration rate was always higher than the intensity of precipitation, and thus most rainfall infiltrated into LGM profile, held by capillary force or discharging as subsurface runoff. Though the water content of LGM was only 15.4%~50.9% of LSW under natural precipitation (Zhang et al., 2017), plants grew well in L1~L4. R_L significantly influenced water holding capacity of LGM, which was reflected by the positive relationship between R_L and field capacity and the negative relationship between R_L and subsurface runoff. More water was retained in the LGM profile with a higher R_L and available for plant use, thus facilitating plant growth. However, the target species, *R. pseudoacacia* grew best in

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

L3, which may result from the less severe inter-specific competition compared to L1 and L2. A higher contents of nutrients provided by LSW may be more beneficial to ruderals and other herbaceous species (Le Stradic et al., 2014), which was consistent with the higher amount of ruderal litters in L1 and L2. L5 showed the poorest water condition and plant growth because water cannot be held within macropores between gravels, and thus LGM with this R_L is not recommended unless other ameliorative measures are supplemented.

4.2 Using compacted LGM as growing substrate for plants

Compaction had a significant effect on improving water holding capacity. With an increasing compaction degree, the annual mean water content increased from 5% to 15.4%, and retention of precipitation increased from 34% to 97%. However, leaf water contents of *R. pseudoacacia* was significantly lower in the compacted plots, indicating water deficit. *R. pseudoacacia* is a fast-growing species with deep root system. The high transpiration demand was not satisfied probably for two reasons: firstly, soil water in the compacted plots may be harder to extract because of lower water potential and hydraulic conductivity; secondly, water uptake may decrease because of the constrained development of roots (Sharrow, 2007; Nadian et al., 1996).

An unneglectable deficiency of the experiment was that plant roots could grow through the 1-m-thick LGM layer and absorb water from the underlying natural soil because impervious liner was not set between LGM and the underlying soil. Plants growing in the uncompacted LGM in real environment i.e. abandoned quarries, should not have this good performance because the only water source was LGM

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

which contained only 5% water under natural precipitation. *R. pseudoacacia* growing in CL3 should have the best performance in the real environment although the germination, survival and growth were not significantly different from CL1 in our experiment, which was consistent with Jeldes et al. (2013).

Leaf water content of *P. orientalis* was not affected by compaction, and seedlings grew better in the more compacted plots, indicating that water or compaction degree was not the key factor constraining growth rate. Many researches have shown that, conifers have a more conserving water use strategy compared to board-leaved tree species (Catovsky et al., 2002; Wullschleger et al., 1998) and evergreens are more adapted to compacted soils than deciduous (Alameda & Villar, 2009). However, light intensity may have a significant effect on *P. orientalis*. As the canopy density of *R. pseudoacacia* decreased with increasing degree of compaction, more light was available to *P. orientalis* which grew underneath, improving its performance.

Leaf water content of *M. sativa* decreased while biomass increased with increasing degree of compaction. *M. sativa* was well adapted to compacted plots, which was consistent with Cresswell & Kirkegaard (1995). The higher biomass may result from less intensive interspecific competition for resources such as light, or because plant growth was accelerated under mild or temporary water stress (Shao et al. 2010).

5 Conclusion

LGM, the mixture of landfill-stabilized waste and coarse quarry waste can be used during restoration in abandoned quarries as growing material for plants. The LSW:

gravel ratio had a significant effect on the physio-chemical properties such as nutrient level, water condition, physical stability, and thus the performance of plants growing in LGM. LGM with R_L ranging from 8:1 to 3:7 was suitable for plant growth, but the target species grew best when R_L was intermediate. When R_L was lower than 3:7, compaction enhanced the retention of precipitation, but leaf water content of plants was lower or unchanged in the more compacted plots. Moderate compaction was beneficial to the survival and growth of *R. pseudoacacia*. *P. orientalis* and *M. sativa* were not significantly affected by compaction; they grew better in highly compacted area where the uppermost layer of vegetation was suppressed and thus more light was available. Compared to fast-growing broad-leaved trees, conifers and herbaceous species may be more adapted to compacted LGM, and interspecific interaction showed a significant effect on plant performance. Nutrient or pollutant leaching with the deep percolation water or surface run-off are not covered in this paper, but they are very important factors considering the long-time impacts of LGM or LSW application. Some work has been done on the chemical and hydrological properties of LSW (Zhang et al., 2017; Feng et al., 2017) but more study should be taken on the environmental effects of municipal solid waste application.

Acknowledgements

Funding: This work was supported by the R&D Special Fund for Forestry Public Welfare Industry “Key re-vegetation technology research on woodland damaged by construction” (200904030); and the Reform and Development Project of Beijing Municipal Science & Technology Commission.

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

References

Akbulut, H. and Gürer, C.: Use of aggregates produced from marble quarry waste in asphalt pavement, Building and environment, 42(5), 1921-1930, 2007.

Alameda, D. and Villar, R.: Moderate soil compaction: implications on growth and architecture in seedlings of 17 woody plant species, Soil and Tillage Research, 103(2), 325-331,2009.

Amin, S.K., Youssef, N.F., El-Mahllawy, M.S., and El-Abd, H.: Utilization of Gebel Attaqa Quarry Waste in the manufacture of Single Fast Firing Ceramic Wall Tiles, International Journal of Environmental Sciences, 2(2), 765-780, 2011.

André, A., de Brito, J., Rosa, A., and Pedro, D.: Durability performance of concrete incorporating coarse aggregates from marble industry waste, Journal of Cleaner Production, 65, 389-396, 2014.

Castro-Gomes, J.P., Silva, A.P., Cano, R.P., Suarez, J.D., and Albuquerque, A.: Potential for reuse of tungsten mining waste-rock in technical-artistic value added products, Journal of Cleaner Production, 25, 34-41, 2012.

Catovsky, S., Holbrook, N.M., and Bazzaz, F.A.: Coupling whole-tree transpiration and canopy photosynthesis in coniferous and broad-leaved tree species, Canadian Journal of Forest Research, 32(2), 295-309, 2002.

Cohen, J., Cohen, P., and West, S.G.: Applied multiple regression/correlation analysis for the behavioral sciences, Oxon, Routledge, 2003.

Cresswell, H.P., and Kirkegaard, J.A.: Subsoil amelioration by plant roots, the process and the evidence Soil Research, 33(2), 221-239, 1995.

Descroix, L., Viramontes, D., Vauclin, M., and Barrios, J.L.G., Esteves, M.: Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre (Durango, Northwest Mexico), Catena, 43(2), 115-135, 2001.

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

Duan, W.J., Ren, H., Fu, S.L., Wang, J., Yang, L., and Zhang, J.P.: Natural recovery of different areas of a deserted quarry in South China. Journal of Environmental Sciences, 20(4), 476-481, 2008.

Feng, J., Zhang, C., Zhao, T., and Zhang, Q.: Rapid revegetation by sowing seed mixtures of shrub and herbaceous species, Solid Earth 6(2), 573-581, 2015.

Feng, J., Zhang, C., Zhao, T., and Rong, L.: Potential harmful effects of landfill stabilized waste: semi-volatile organic compounds and salinity, a case study in Beijing, China, Environmental Earth Sciences, 76(11): 387, 2017.

Forján, R., Asensio, V., Rodríguez-Vila, A., and Covelo, E.F.: Contribution of waste and biochar amendment to the sorption of metals in a copper mine tailing, Catena 137, 120-125, 2016.

Gazi, A., Skevis, G., and Founti, M.A.: Energy efficiency and environmental assessment of a typical marble quarry and processing plant, Journal of Cleaner Production 32, 10-21, 2012.

Huxman, T.E., Cable, J.M., Ignace, D.D., Eilts, J.A., English, N.B., Weltzin, J., and Williams, D.G.: Response of net ecosystem gas exchange to a simulated precipitation pulse in a semi-arid grassland: the role of native versus non-native grasses and soil texture, Oecologia, 141(2), 295-305, 2004.

Jeldes, I.A., Drumm, E.C., and Schwartz, J.S.: The low compaction grading technique on steep reclaimed slopes, soil characterization and static slope stability, Geotechnical and Geological Engineering, 31, 1261-1274, 2013.

Jordán, M.M., García-Sánchez, E., Almendro-Candel, M.B., Pardo, F., Vicente, A.B., Sanfeliu, T., and Bech, J.: Technosols designed for rehabilitation of mining activities using mine spoils and biosolids. Ion mobility and correlations using percolation columns, Catena, doi:10.1016/j.catena.2016.02.027, 2016.

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

Jomaa, S., Barry, D.A., Brovelli, A., Heng, B.C.P., Sander, G.C., Parlange, J.-Y., and Rose, C.W.: Rain splash soil erosion estimation in the presence of rock fragments, Catena, 92, 38-48, 2012.

Le Stradic, S., Buisson, E., and Fernandes, G.W.: Restoration of Neotropical grasslands degraded by quarrying using hay transfer. Applied vegetation science, 17(3), 482-492, 2014.

Liu, Z.-D., Gao, Y., Duan, A.-W., and Gong, W.J.: Influence factors of rainfall runoff in the winter wheat field. Journal of soil and water conservation, 26(2), 38-44, 2012.

Luna, L., Miralles, I., Andrenelli, M.C., Gispertd, M., Pellegrinic, S., Vignozzic, N., and Solé-Benet, A.: Restoration techniques affect soil organic carbon, glomalin and aggregate stability in degraded soils of a semiarid Mediterranean region, Catena 143, 256-264, 2016.

Nadian, H., Smith, S.E., Alston, A.M., and Murray, R.S.: The effect of soil compaction on growth and P uptake by *Trifolium subterraneum*: interactions with mycorrhizal colonization, Plant and Soil, 182, 39-49, 1996.

Okura, Y., Kitahara, H., Kawanami, A., and Kurokawa, U.: Topography and volume effects on travel distance of surface failure, Engineering Geology, 67(3), 243-254, 2003.

Rubio, M.C., Moreno, F., Belmonte, A., and Menéndez, A.: Reuse of waste material from decorative quartz solid surfacing in the manufacture of hot bituminous mixes. Construction and Building Materials, 24(4), 610-618, 2010.

Safiuddin, M., Jumaat, M.Z., Salam, M.A., Islam, M.S., and Hashim, R.: Utilization of solid wastes in construction materials. International Journal of Physical Sciences, 5(13), 1952-1963, 2010.

Safiuddin, M., Raman, S.N., and Zain, M.F.M.: Utilization of quarry waste fine aggregate in concrete mixtures, Journal of Applied Sciences Research, 3(3), 202-208, 2007.

Schäffer, B., Schulin, R., and Boivin, P.: Changes in shrinkage of restored soil caused by compaction beneath heavy agricultural machinery, European journal of soil science, 59(4), 771-783, 2008.

Shao, G.-C., Liu, N., Zhang, Z.-Y., Yu, S.-E., and Chen, C.-R.: Growth, yield and water use efficiency response of greenhouse-grown hot pepper under Time-Space deficit irrigation, Scientia Horticulturae, 126(2), 172-179, 2010.

Sharrow, S.H.: Soil compaction by grazing livestock in silvopastures as evidenced by changes in soil physical properties, Agroforestry Systems, 71(3), 215-223, 2007.

Tiruta-Barna, L., Benetto, E., and Perrodin, Y.: Environmental impact and risk assessment of mineral wastes reuse strategies: Review and critical analysis of approaches and applications. Resources, Conservation and Recycling, 50(4), 351-379, 2007.

Wullschleger, S.D., Meinzer, F.C., and Vertessy, R. A.: A review of whole-plant water use studies in tree, Tree physiology, 18(8-9), 499-512, 1998.

Xie, L.: Application of Photoshop in cartographic area calculation, Computer knowledge and technology, 6(15), 4021-4022, 2010.

Yuan, C., Lei, T., Mao, L., Liu, H., and Wu, Y.: Soil surface evaporation processes under mulches of different sized gravel, Catena, 78(2), 117-121, 2009.

Zhang, C.-L., Feng, J.-J., Zhao, T.-N., and Rong, L.-M.:. Physical, chemical and engineering properties of landfill stabilized waste, Land Degradation & Development, 28(3), 1113-1121, 2017.

Zhang, Y., Zhang, M., Niu, J., Li, H., Xiao, R., Zheng, and H., Bech, J.: Rock fragments and soil hydrological processes: Significance and progress, Catena 147, 153-166, 2016.

Zhou, C., Xu, W., Gong, Z., Fang, W., and Cao, A.: Characteristics and fertilizer effects of soil-like materials from landfill mining, CLEAN - Soil Air Water, 43(6), 940-940, 2015.

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

476 Tab.1 Basic physical and chemical properties of LSW (±standard deviation)

Objects	Mean values	Objects	Mean values
Sand (0.05~2 mm, %)	64	As (mg kg^{-1})	10.1±5.5
Slit (0.002~0.05, %)	16	Cr (mg kg^{-1})	91.2±46.4
Clay (<0.002 mm, %)	20	Cu (mg kg^{-1})	77.6±51.6
Total K (g kg^{-1})	25.5±7.7	Ni (mg kg^{-1})	31.9±12.4
Available K (mg kg^{-1})	503±124	Pb (mg kg^{-1})	54.2±30.8
Total N (g kg^{-1})	1.95±0.51	Zn (mg kg^{-1})	215±136.1
Nitrate-N (mg kg^{-1})	105.9±105.1	Cd (mg kg^{-1})	0.29±0.05
Ammonium-N (mg kg^{-1})	9.21±4.78	Hg (mg kg^{-1})	0.78±0.45
Total P (g kg^{-1})	1.12±0.33	pH value	8.2
Available P (mg kg^{-1})	75.08±145.87	Organic matter (g kg^{-1})	40.12±22.27

477

478

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

Tab.2 Hydrophysical properties of LGM

LSW fraction	Moisture content (%)					RP (%)
	Saturated moisture content	Field capacity	Annual mean	Maximum monthly mean	Minimum monthly mean	
L1	48.9 ±2.0	42.9 ±2.0	8.7 ±1.6	10.9	6.8	70.5
L2	39.2 ±10.8	33.2 ±10.8	4.8 ±0.8	5.8	3.6	34.0
L3	31.6 ±0.1	25.7 ±0.1	5.2 ±1.3	7.6	3.8	49.0
L4	34.3 ±4.1	13.6 ±3.4	3.2 ±0.7	4.5	2.3	26.5
L5	41.9 ±1.2	8.7 ±1.2	2.6 ±0.8	3.9	1.9	24.5

Note: The multiple regression fitted to attain RP was significant at the 0.01 level. Antecedent water content and precipitation accounted for 73.4%~87.6% variance of water content 1 d after the rainfall event.

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

Tab.3 Height and single plant biomass *R. pseudoacacia*

Runoff plot	Height (cm)	Above ground biomass of single plant (g)
L1	22±6[b]	0.759±0.159[b]
L2	25±8[b]	0.958±0.317[b]
L3	35±6[a]	2.035±0.480[a]
L4	26±7[b]	0.917±0.095[b]
L5	11 ±4[c]	0.171±0.031[b]

Note: the same letter indicates that the difference is not significant at the 0.05 level.

Tab.4 Hydro-physical properties of LGM (R_L=2:8) with different compaction degrees

Compacted plot	Moisture content (%)				RP (%)
	Theoretical porosity	Annual mean	Maximum monthly mean	Minimum monthly mean	
CL1	31.1	5.0±0.8	6.1	4.1	34
CL2	26.8	6.4±1.2	8.0	5.0	45
CL3	22.1	7.8±1.2	9.4	6.5	44
CL4	21.1	7.7±1.2	8.9	6.4	53
CL5	13.3	15.4±2.1	17.8	13.4	97

Note: the multiple regression fitted to attain RP was significant (P<0.01). Antecedent water content and precipitation accounted for 65.7%~86.1% variance of water content 1 d after the rainfall event.

Tab.5 Average leaf water contents of plants growing in the compacted LGM (g g^{-1})

Plant species	CL1	CL2	CL3	CL4	CL5
R. pseudoacacia	2.25 ± 0.09^{A}	2.19 ± 0.06^{A}	2.20 ± 0.13^{AB}	1.99 ± 0.06^{B}	1.88 ± 0.09^{B}
P. orientalis	2.04 ± 0.17	2.16 ± 0.14	2.10 ± 0.16	2.07 ± 0.15	2.12 ± 0.17
M. sativa	3.79 ± 0.15^{A}	3.50 ± 0.18^{A}	3.29 ± 0.19^{A}	3.13 ± 0.22^{AB}	2.45 ± 0.18^{B}

Note: the same letter indicates that the difference between different compacted plots is not significant at the 0.05 level.

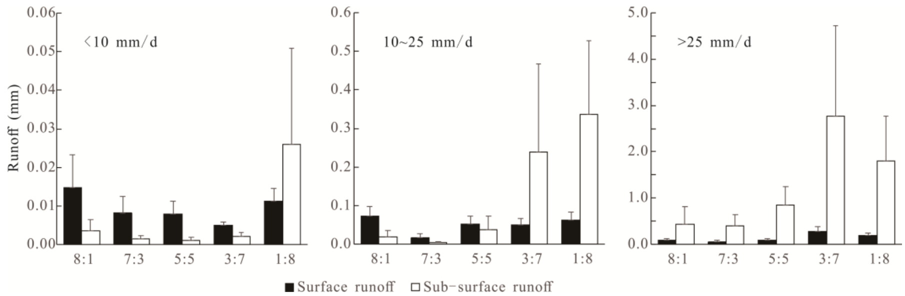

Fig.1 Average runoff generated in LGM slopes under natural precipitation

Solid Earth Discuss., https://doi.org/10.5194/se-2017-72
Manuscript under review for journal Solid Earth
Discussion started: 21 July 2017

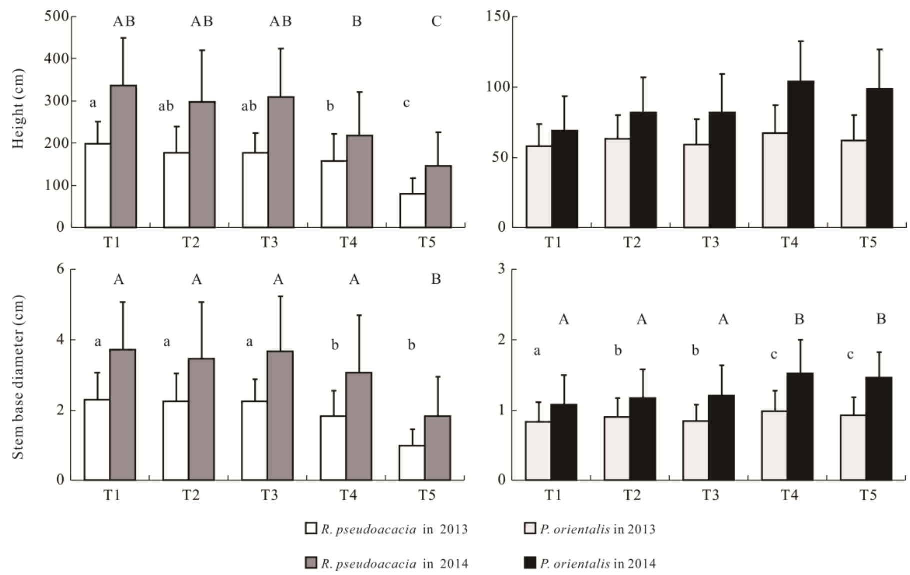

Fig.2 Wood growth

Note: the same small or capital letter indicates that in 2013 or 2014 the difference between different compacted plots is not significant at the 0.05 level.

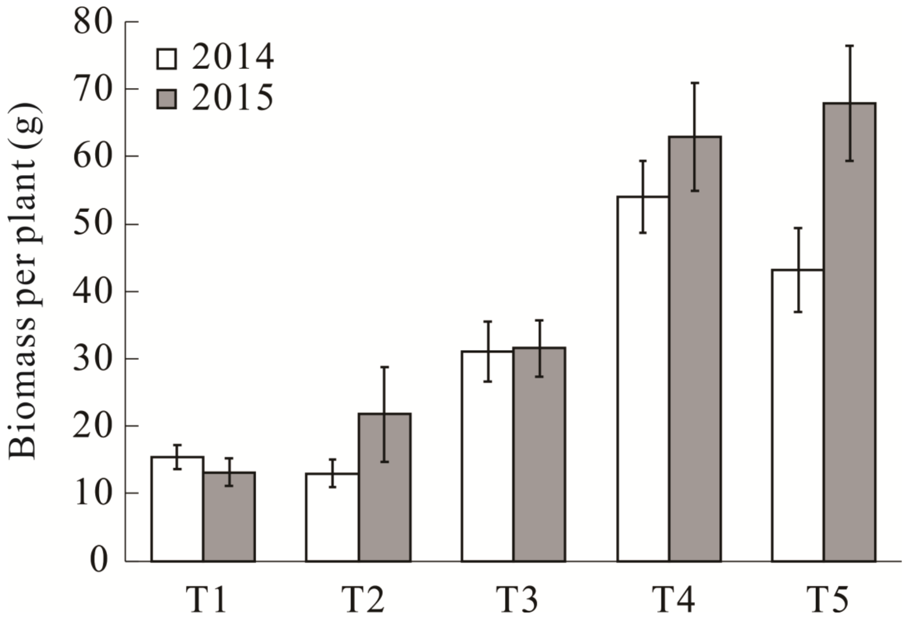

Fig.3 Herb growth