·Comment from Reviewer 1

The article is very interesting and discuss a very important and updated issue on the management of abandoned quarries and its environmental rehabilitation. This paper presents the results of an applied research, showing important findings that may help researchers to identify optimal techniques to restore areas with high environmental liabilities. The methodologies used in this research are adequate and are well explained. The theoretical framework is based on world class references and complemented with several updated references. However, I think it could be improved (runoff and erosion observed). The text is clear and, properly drafted. However, I found some minor errors which can be corrected. It would be interesting to have a map with the localization of the study area, as well as with the physical conditions of the area where the monitoring was implemented. A topic that seems to be less clear (or that authors could take into consideration) is the potential erosion of soil (of the compound tested in the experimentation) by runoff (and impacts on vegetation growth) and the evolution of soil structure and composition along the period of observation. In a more comprehensive analysis, I consider the contents of this paper to be of good quality. It is very clear in terms of the methodology employed, which seems to be appropriate, and reveals a clear and logical structure. I consider the contents of this paper to be of good quality and could be published after some minor corrections and theoretical framework improvements.

·Response to Reviewer 1

a map with the localization of the study area	A map of study area is added in Fig.1.
physical conditions of the area where the monitoring was implemented	More information on the physical conditions of the area is added. P 7 LINE 111-113, LINE 127-129.
A topic that seems to be less clear (or that authors could take into consideration) is the potential erosion of soil (of the compound tested in the experimentation) by runoff (and impacts on vegetation growth) and the evolution of soil structure and composition along the period of observation.	We will also further the discussion on erosion of the fine particles. The potential erosion of soil is very important. When the proportions of LSW is low, it is very likely to move down with the infiltration through the large pores between the gravels, leaving a layer of pure gravels which is difficult for plant growth. So LGM with a low proportion of LSW will be disadvantageous for plant grown at the beginning of revegetation, and it may be more disadvantageous over time. However, we did not quantitatively measure the erosion of the fine particles. We could have measured the percentage of fine particles in the runoffs.

	Unfortunately, we didn't. We can neither sample LGM at different depths to measure the amounts of fine particles and find out how they move over time without disturbing the structure. The gravels are interlocked, so samples cannot be taken with a common cutting ring by human force, rather a large sample box must be made and pushed into the material mechanically, seriously disturbing the initial structure. However, the physical properties of LSW is similar to natural soils. And the vertical movement of fine particles in LGM with low RL is similar to the underground erosion in karst areas, which has been well-studied. We will refer to these papers for further Discussion. Please refer to P 15 LINE 305-312

·Comment from Reviewer 2

The paper is presenting important finding to management of abandoned quarry soil and mined soil rehabilitation. The methodology used was comprehensive – soil engineering and plant physiology – and the results were discussed in a balanced way. The work was sufficiently proven. The results and conclusions were robust and show a substantial contribution to scientific world. The tables and figures supported the novel findings. I may suggest some corrections on: (a) P 2-3 Line 41-42 Keywords: municipal solid waste; and landfill may be merged in one phrase; and the entry revegetation may be added; (b) P 7 Line 118-119 MPN of colliforms were tested. Is there any result of that test? The data would confirm the safety of the research site; (c) P 8 Line 139, crusgalli should be written crus-galli; (d) P 13 Line 254-255, I would suggest the add of the name of plant: ruderals or the target species?; (e) P 20-21 Line 416 and Line 420, Author name Jomaa may proceed Jordán; (f) P 21 Line 434-435; 437-438; and 440-441 the different indentation of the references; (g) P 22-23 Line 469-471, this reference (Zhang et al., 2016) is not citated in the paper; (h) P 24 Line 476, the Slit may be changed to Silt; and the adding of its unit, i.e. mm; (i) I have a question regarding the word “intermediate” (P 2 line 34, P 12 line 225, and P 18 line 351). Intermediate tells the position between two things. It’s clear, though, that the LSW:gravel ratio shows the compaction. The word “moderate compaction” was clear to the reader; (j) The adding of map of study; (k) The adding of description of physical soil appearance over time to add the discussion qualitatively; (l) The adding of the author of plant scientific names, e.g. Robinia pseudoacacia L.; (m) The adding of the books, which the authors reference the scientific names. I suggest this paper could be published after some minor corrections.

·Response to Reviewer 2

P 2-3 Line 41-42 Keywords: municipal solid waste; and landfill may be merged in one phrase; and the entry revegetation may be added.	Keyword "landfill" is deleted and "revegetation" is added. P3 LINE 41
P 7 Line 118-119 MPN of colliforms were tested. Is there any result of that test? The data would confirm the safety of the research site.	The results of MPN of coliforms are added. P7 LINE 124-125
P 8 Line 139, crusgalli should be written crus-galli.	crusgalli is changed into crus-galli. P8 LINE 145
P 13 Line 254-255, I would suggest the add of the name of plant: ruderals or the target species?	The name of the plant (ruderal) is added. P13 LINE 260
(e) P 20-21 Line 416 and Line 420, Author name Jomaa may proceed Jordán; (f) P 21 Line 434-435; 437-438; and	(e) (f) (g) we reorder the reference and adjust the indentation; papers not cited are deleted in the reference list.

440-441 the different indentation of the references; (g) P 22-23 Line 469-471, this reference (Zhang et al., 2016) is not citated in the paper.	
(h) P 24 Line 476, the Slit may be changed to Silt; and the adding of its unit, i.e. mm.	"slit" is changed to silt, the unit is added. P24 Tab.1
(i) I have a question regarding the word “intermediate” (P 2 line 34, P 12 line 225, and P 18 line 351). Intermediate tells the position between two things. It’s clear, though, that the LSW:gravel ratio shows the compaction. The word “moderate compaction” was clear to the reader.	We revise the sentence and make it clearer. P2 LINE 33 P18 LINE 364
(j) The adding of map of study.	A map of study area is added. Fig.1
(k) The adding of description of physical soil appearance over time to add the discussion qualitatively.	We did not measure the physical properties of LGM or compacted LGM over time, because materials with such fractions of gravels are hard to sample without disturbing the structure. However, we measured the properties of LSW after three years of settlement in another study. We will further discuss the possible dynamics of physical structure based on the properties of fine particles (LSW) and porosity in the revised paper.
(l) The adding of the author of plant scientific names, e.g. Robinia pseudoacacia L.	The authors of plant scientific names are added. P2 LINE 37-38 P8 LINE 143-146 P10 LINE 175-178 P11 LINE 206-207
(m) The adding of the books, which the authors reference the scientific names.	Sorry, but I don’t quite understand.

·**Comment from Reviewer 2'**

a. (h) P 24 Line 476, the Slit may be changed to Silt; and the adding of its unit, i.e. Mm. I suggest you may add "mm" after the range of silt size (0.002-0.05 mm, %)
b. (k) The adding of description of physical soil appearance over time to add the discussion qualitatively. I do understand your explanation. May I suggest you to write the qualitatively descriptive observation of the appearance of the soil over time. It will give the readers "the evolution" or the changing of the soil.

・**Response to Reviewer 2'**
We will revise the manuscript according to the comment.

(h) P 24 Line 476, the Slit may be changed to Silt; and the adding of its unit, i.e. Mm. I suggest you may add "mm" after the range of silt size (0.002-0.05 mm, %)	The mistake has been corrected. P24 Tab.1
(k) The adding of description of physical soil appearance over time to add the discussion qualitatively. I do understand your explanation. May I suggest you to write the qualitatively descriptive observation of the appearance of the soil over time. It will give the readers "the evolution" or the changing of the soil.	Please refer to P16 LINE 307-312

• **Comment and response to A. Cerdà**

Dear author I found your paper excellent. A great contribution I just found that in your introduction there is a limited information about the relationship pf soils-erosion-vegetation I think your paper will be benefit from reading the following papers which I or my team are authors García-Fayos, P., B. García-Ventoso, and A. Cerdà. 2000. Limitations to Plant Establishment on Eroded Slopes in Southeastern Spain. Journal of Vegetation Science 11 (1): 77-86. Garcia-Fayos, P., T. M. Recatala, A. Cerdà, and A. Calvo. 1995. Seed Population Dynamics on Badland Slopes in Southeastern Spain. Journal of Vegetation Science 6 (5): 691-696. Cerdà. 1998. The Influence of Aspect and Vegetation on Seasonal Changes in Erosion Under Rainfall Simulation on a Clay Soil in Spain. Canadian Journal of Soil Science 78 (2): 321-330. Cerdà. 1998. The Influence of Geomorphological Position and Vegetation Cover on the Erosional and Hydrological Processes on a Mediterranean Hillslope. Hydrological Processes 12 (4): 661-671. Cerdà, A. and S. H. Doerr. 2005. Influence of Vegetation Recovery on Soil Hydrology and Erodibility Following Fire: An 11-Year Investigation. International Journal of Wildland Fire 14 (4): 423-437. doi:10.1071/WF05044.	The studies "Limitations to plant establishment on eroded slopes in southeastern Spain", “The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hillslope”, and “The influence of aspect and vegetation on seasonal changes in erosion under rainfall simulation on a clay soil in Spain” are relevant and insightful, we will consider them when revising the Manuscript. The study of seed population is very interesting, but our experiment was conducted near farmland, and thus the study plots were invaded by many agricultural weeds. We cannot support or oppose the relationship between seed bank and successful revegetation in the abandon quarries, the site condition of which may be similar to that of badlands. The study of vegetation recovery after fire is a long-period study and valuable . But a burnt forest is very different from an abandoned quarry or coarse gravels amended with nutritive fine particles.

Note: A. Cerdà posted the same comment for twice, so we only responded once.

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

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Running title: Revegetation in abandoned quarries with LGM

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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, **and** the target species grew best **when R_L was 5:5**. (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* L.**. ***Platycladus orientalis* (L.) Franco** and ***Medicago sativa* L.** 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;

revegetation

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 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 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.). **The texture of the surrounding farmland is sandy clay, but they can be sandy loam or loamy clay depending on the land use type. The map of the study area is shown in Fig.1.** 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 **the most probable number** 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; **the most probable number of coliforms was 486±188 MPN·g^{-1}.** Basic physical and chemical properties are shown in Tab.1.

Gravels were bought from **the** local market. **The main compositions were limestone, granite and quartzite, which were the most common parent rocks around the study area.** 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 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* **(L.) Beauv.**, *Digitaria sanguinalis* **(L.) Scop.**, *Amaranthus retroflexus* **L.**, *Bidens parviflora* **Willd.**, *Pharbitis nil* **(L.) Choisy**, *Echinochloa* ***crus-galli*** **(L.) Beauv.**, *Chenopodium album* **L.** and *Metaplexis japonica* **(Thunb.) Makino** 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.

2.3.3 Retention of precipitation

Multiple regression model as follows is fitted:

$$Y=\alpha+\beta_1X_1+\beta_2X_2 \quad (1)$$

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 $mm\cdot d^{-1}$), 15 moderate rains (10~25 $mm\cdot d^{-1}$), and 5 heavy rains (>25 $mm\cdot d^{-1}$).

2.3.5 Plant growth

After clearing the colonized ruderals, seed mixture of *Robinia pseudoacacia* **L.** (leguminous tree), *Festuca elata* **Keng ex E. B. Alexeev** (perennial grass), *Orychophragmus violaceus* **(L.) O.E. Schulz** (annual or biennial herb), **and** *Viola philippica* **Cav.** (perennial herb) was sowed with a density of 15 $g \cdot m^{-2}$ (6:2:1:1 by mass) in June 2015. Former study 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 porosity and particle density of the loose LSW were constant:

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

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,

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

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* and 30 *Medicago sativa* **L.** (leguminous herb) seeds were sowed and 60 *Platycladus orientalis* **(L.) Franco** (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 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 the 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.2**, 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 **ruderal** 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 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 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. 3**).

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.4**).

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 **(Zhang et al., 2017)**. 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 **(Cerdà, 1998). When the proportions of LSW is low, more subsurface runoff was generated, which may lead to higher underground erosion of the fine grains. With a low R_L, the fine grains are also likely to move down with infiltration through the macropores between the gravels, in gentle slops or even flat lands, leaving a layer of pure gravels advantageous for plant growth. This phenomenon of soil leakage is common in the karst regions (Wang et al., 2014). As a result, R_L not only influences the current water condition of LGM, it also has a significant effect on its development.**

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. However, the target species, *R. pseudoacacia* grew best in 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 unignorable 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 uncompacted LGM in real environment i.e. abandoned quarries, should not have this good performance because the only water source was LGM 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, **and** the target species grew best when R_L was **5:5**. 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.

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

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

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.

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 Hydrophysical 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 ($g \cdot g^{-1}$)

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.

Figures:

Fig.1 Map of the study area

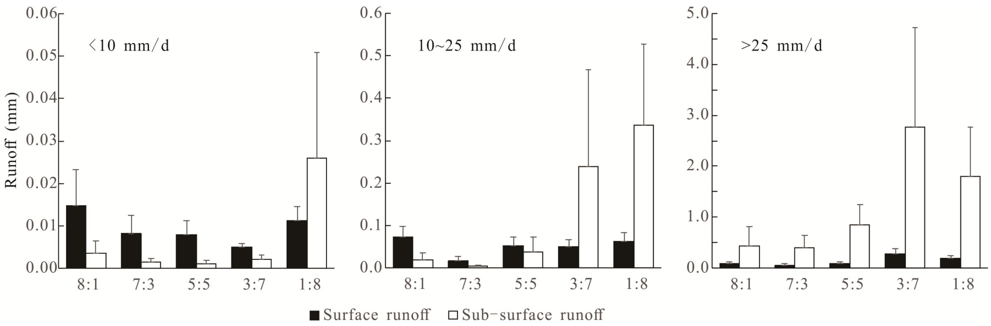

Fig.2 Average runoff generated in LGM slopes under natural precipitation

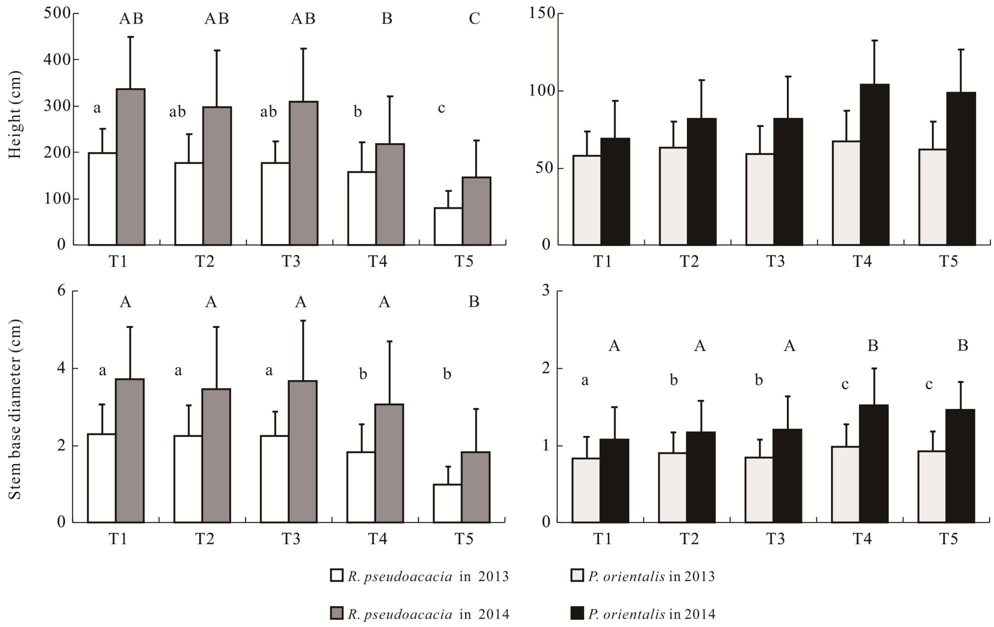

Fig.3 Wood growth

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.

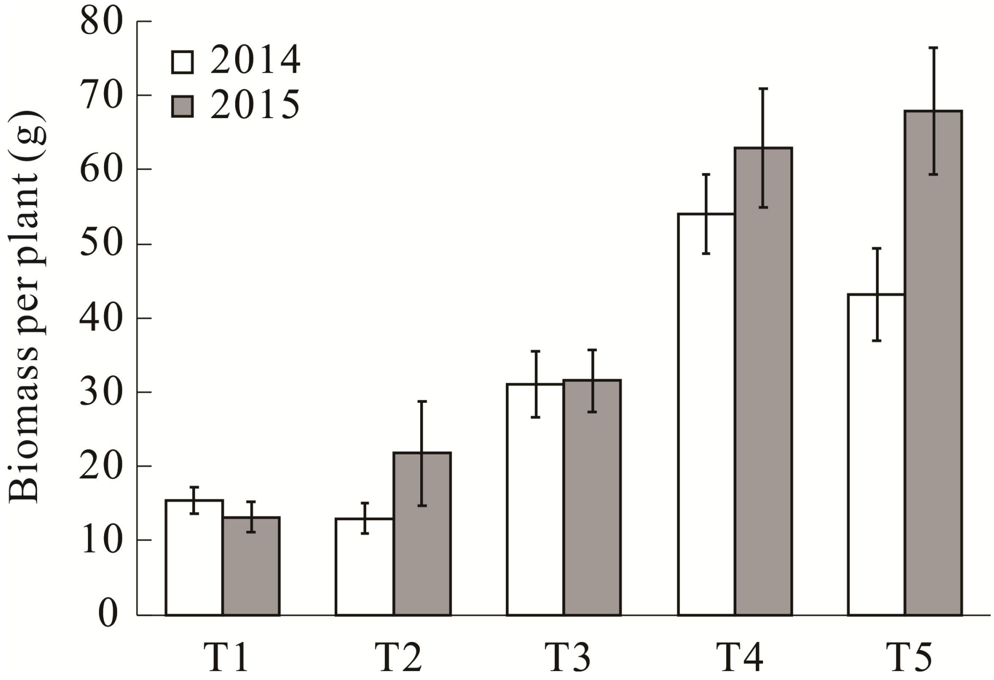

Fig.4 Herb growth