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Assessment of silt from sand and gravel processing as a suitable sub-soil material in land restoration: A glasshouse study

Lucie Mašková [a], Robert W. Simmons [a], Sarah De Baets [a], Enrique Moran Montero [b], Aude Delmer [b], Ruben Sakrabani [a, *]

[a] School of Water, Energy and Environment, Cranfield University, Building 52a, Cranfield Bedfordshire, MK43 0AL, UK
[b] Tarmac Ltd., Panshanger Park, Hertford, Hertfordshire, SG14 2NA, UK

HIGHLIGHTS

- Silt is not fully utilised in quarries as a resource.
- Root development of mustard tap roots was restricted compared to grass.
- Quarry silt blended with growing medium is a suitable subsoil medium for grass and rye.

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ABSTRACT

Annually, sand and gravel processing generates approximately 20 million tonnes of non-commercial by-product as fine silt particles (<63 μm) which constitutes approximately 20% of quarry production in the UK. This study is significant as it investigated the use of quarry silt as a sub-soil medium to partially substitute soil-forming materials whilst facilitating successful post-restoration crop establishment. In a glasshouse pot experiment, top-soil and sub-soil layering was simulated, generating an artificial sub-soil medium by mixing two quarry non-commercial by-products, i.e. silt and overburden. These were blended in three ratios (100:0, 70:30, 50:50). Pots were packed to two bulk densities (1.3 and 1.5 g cm-3) and sown with three cover crops used in the early restoration process namely winter rye (Secale cereale), white mustard (Sinapis alba) and a grassland seed mixture (Lolium perenne, Phleum pratense, Poa pratensis, Festuca rubra). Three weeks into growth, the first signs of nitrogen (N) deficiency were observed in mustard plants, with phosphorus (P) and potassium (K) deficiencies observed at 35 days. Rye exhibited minor N deficiency symptoms four weeks into growth, whilst the grassland mixture showed no deficiency symptoms. The 70:30 silt:overburden sub-soil blend resulted in significantly higher Root Mass Densities of grassland seed mixture and rye in the sub-soil layer as compared with the other blends. The innovation in this work is the detailed physical, chemical and biological characterisation of silt:overburden blends and effects on root development of plants commonly used in early restoration to bio-engineer soil structural improvements.

1. Introduction

Quarry silt, which is generated during sand and gravel processing, is an un-avoidable and significant proportion of quarry outputs (Mitchell, 2007). The amount of quarry silt varies between 5 and 30% of the total volume extracted, averaging around 10–15% (Harrison et al., 2001). Mineral processing involves washing, crushing and screening of the material to separate sand and gravel aggregates from fines (<0.063 mm), which consist of silt, clay and other non-quartz particles (British Geological Survey, 2013). These fines are collected in water, giving rise to a suspension, which is then pumped into lagoons and allowed to settle out (British Geological Survey, 2013). The resultant suspension remains in semi-liquid, anaerobic state for many years, or even decades (Jarvis and Walton, 2010). This product is then usually referred to as 'quarry silt'.

Quarry silt is currently defined as a non-commercial by-product as there is currently no market, nevertheless it should be noted that

* Corresponding author.
E-mail address: r.sakrabani@cranfield.ac.uk (R. Sakrabani).

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quarry silt is an inert and non-hazardous material (Mitchell, 2007). Overburden, which is a layer of material lying above the product to be extracted, is also regarded as a non-commercial by-product. The need to minimise the amount of quarry non-commercial by-product is driven by environmental and social considerations and regulatory compliances (Mitchell, 2007). Quarry silt production can exceed storage capacity on site and require excavation in order to increase lagoon capacity, which causes both economical and logistical problems to the quarry operators (Mitchell, 2007). Reduction of quarry non-commercial by-product production usually starts at source, with an optimisation audit of the processing technology where emphasis is usually placed on good practice and modernization of the crushing plant (Mitchell, 2007). The main use of sand and gravel non-commercial by-products is as a backfill or sub-soil material in site landscaping and restoration (Harrison et al., 2001). Another possible use of quarry non-commercial by-products according to Mitchell (2007) is as vegetated tips around the quarry site to screen the workings. Reusing mineral non-commercial by-products such a quarry silt contributes to efficient use of resources, reduces environmental impacts, and improves sustainability for local communities (Mitchell et al., 2004).

1.1. Quarry restorations

At the end of the operating life of sand and gravel quarries, the resulting voids have to be levelled and graded to achieve landscape and landform objectives stated in restoration plans to allow agreed upon restoration objectives (CEMEX, 2014; DCLG, 2014). Quarry silt lagoons would normally be restored into wetland habitats, or capped with a $\geq$1 m thick layer of overburden and planted with willow rods (Tarmac Ltd., 2008). However, quarries often face a shortage of top-soil and sub-soil forming materials. Moreover, it is a priority to use materials available on-site to minimise the high transport costs associated with importing materials (Tarmac Ltd., 2008). A possible solution would be the use of non-commercial by-product such as quarry silt and overburden as a partial replacement for sub-soil in restorations. The suitability of quarry for use in artificial soils was evaluated by (Mitchell et al., 2004) who investigated several types of quarry fine blends as a growing medium for grass species. However biomass was restricted primarily due to nutrient deficiencies.

The aim of this project was to determine the suitability of non-commercial by-product such as quarry silt from mining lagoons in combination with overburden as a replacement for sub-soil to facilitate cover crop establishment on restoration sites and whole profile bio-remediation of soil structure. Outcomes will inform recommendations for the successful use of non-commercial by-products such as quarry silt and overburden in future restoration projects by mineral operators.

2. Materials and methods

2.1. Study area

Materials for this study were obtained from two different quarries operated by Tarmac Ltd, where there was an excess production of quarry silt and overburden. Blashford Quarry was the source of the quarry silt sub-soil material and top-soil, and Mountsorrel Quarry provided overburden. Mountsorrel Quarry is a granite quarry located between the villages of Mountsorrel and Quorn in Leicestershire. A total of 80 kg of overburden from this site was collected from 10 randomly selected points. Blashford Quarry is located in Hampshire, south of Salisbury with an annual quarry silt production of >20,000 m^3. A 10 point 210 kg composite quarry silt sample (0–0.3 m depth) was collected from two silt lagoons using excavators. Top-soil was sourced from a compacted vegetated bund lining Blashford Quarry using trowels. An 8-point 120 kg top-soil (0–0.3 m depth) sample was collected.

2.2. Experimental design

In typical quarry restorations conducted by Tarmac Ltd, a 0.6 m layer of sub-soil would be capped with a 0.3 m layer of top-soil stripped from the surface prior to sand and gravel extraction. This substrate layering ratio was also simulated in the pot experiment. As a sub-soil medium, 3 quarry silt:overburden blend ratios were selected, 100:0, 70:30 and 50:50, aiming for a high quarry silt content.

Quarry restoration can result in spatial variation in sub-soil and top-soil bulk densities (BD). Bulk density values normally vary from 1.1 to 1.8 g cm^{-3}, whilst in extreme conditions surface soil layers may have BD as low as 0.5 g cm^{-3} and heavily compacted soils may exceed 2.0 g cm^{-3} (Cresswell and Hamilton, 2002). A value of 1.3 g cm^{-3} was chosen for top-soil BD and the sub-soil materials were packed at a BD of either 1.3 or 1.5 g cm^{-3} in order to represent a low and a high degree of sub-soil compaction.

Cover crops possess traits that can effectively remediate compacted soils (Kirkegaard et al., 2008). Research has also demonstrated that the generation of biopores through a ‘bio-drilling’ effect of cover crops in compacted soils can result in increased yield of follow-on crops (Chen and Weil, 2010; Cresswell and Kirkegaard, 1995; Kirkegaard et al., 2008). Plant roots engineer soil structure directly by penetrating and displacing soil, depositing adhesive compounds which encourage aggregation, and indirectly via a range of other root deposits which provide energy and nutrient sources for soil biota (White and Kirkegaard, 2010).

Three restoration cover crops were evaluated in this study. These included white mustard (*Sinapis alba)* a tap rooted species; winter rye (*Secale cereale)* as a cereal representative; and a grassland seed mixture *(Lolium perenne, Phleum pratense, Poa pratensis, Festuca rubra)* as a reference crop already used in Tarmac Ltd restorations. No fertilizers were applied to simulate natural restoration processes. Each treatment was replicated in triplicate.

2.3. Winter rye

Seeding rates for Winter Rye depend on local climate conditions and seeding method being either drill or broadcast. Values as low as 62–67 kg ha^{-1} (Government of Alberta, 2016) and up to 56–224 kg ha^{-1} (Casey, 2012) can be used. Based on this, a seeding rate of 90 kg ha^{-1} was used, as an approximate average value for this experiment.

Winter Rye can germinate in temperatures as low as 1 °C allowing seeding as late as September, the end of October, or even December (AGRAVIS, 2017; Rosenfeld and Rayns, 2011). It is the most frost tolerant of all cereals (Oelke et al., 1990). It prefers well-drained light loams and sandy soils, but can also be established on heavy clays (Björkman and Shail, 2014; Oelke et al., 1990). It has a dense, fibrous branching root system that grows especially vigorously in the upper 0.3 m of soil.

2.4. Mustard

Mustard can be sown from March to September (Rosenfeld and Rayns, 2011). It prefers fertile, loamy, well drained soils and does not tolerate waterlogging and dry sandy soils (Oplinger et al., 1991). Seeding rates for mustard vary from 10 kg ha^{-1} (Bodner et al., 2010) up to 20 kg ha^{-1} (Rosenfeld and Rayns, 2011). A commercially adopted seeding rate of 20 kg ha^{-1} was used in this study. Mustard seedlings emerge rapidly but continue to grow slowly thereafter. It has a tap rooting architecture and is frost sensitive.

2.5. Grassland seed mixture

A standard seed mixture for quarry restoration adopted by Tarmac Ltd when restoring back to an agricultural end-use is a grassland seed mixture. It is commonly used in the first 2–3 years within a mandatory 5-year aftercare period. Seeding is usually carried out during March–April or September–October at a rate of 34 kg ha^{-1} (Walnes Seeds, 2017). Mixtures containing the same or similar grass species (Table 1) are usually designed as a damage resistant paddock mixture for grazing and hay production (Walnes Seeds, 2017).

2.6. Glasshouse experiment set-up

For both pot experiment and laboratory analyses, growing mediums (top-soil, quarry silt and overburden) were air dried and sieved to <2 mm. It should be noted, that in order to minimise heterogeneity between experimental replicates, the coarse aggregate fraction >2 mm, was removed during sample preparation. Post air-drying, quarry silt and overburden were ground to <2 mm using a mechanical sieved soil grinder.

Sub-soil medium was mixed to the desired ratios of 100:0, 70:30 and 50:50 of quarry silt:overburden. To represent the restoration layering ratio, the sub-soil layer was packed to a depth of 12 cm from the bottom of the pot, leaving the next 5 cm for the top-soil layer.

Sub-soil was packed at two bulk densities (BD), representing low and high compaction. The highest BD achievable was 1.5 g cm^{-3}, with the lower value set at 1.3 g cm^{-3}. All pots were then capped with a 5 cm layer of top-soil (previously acquired from Blashford Quarry) at a BD of 1.3 g cm^{-3} to reach a total pot volume of 2313 cm^3.

Pots were placed in the Cranfield University Glasshouse in a completely randomised layout and wetted to field capacity from the base via capillary rise. Cover crop seeds (winter rye, white mustard and grassland seed mixture) were broadcasted on the 16th of June 2017 (adopted from Tarmac Ltd seeding methods). However due to unexpectedly hot weather (~30 °C, seeds had to be incorporated to a depth of <0.5 mm. Uniform pot watering was undertaken approximately every two days, depending on weather conditions to assure crop survival. The experiment was terminated approximately 6 weeks after set-up. Pot layout was changed twice in order to randomize possible variation in growing conditions within the glasshouse. During the pot trial, mustard plants were affected by several insect species including aphids (*Lipaphis erysimi*), mustard leaf miner (*Chromatomyia horticola*) and large white butterfly (*Pieris brassicae*). The rye and grass mixture treatments had no pest infestation issues.

2.7. Laboratory analyses

At termination, the soil was carefully extruded intact from the pots a cut in half using a palette knife to visually asses root penetration through the top-soil and sub-soil layers. One quarter of each pot was the used to assess root development. Roots were extracted following the root washing method of De Baets et al. (2007). To determine the root mass density (RMD), roots had to be oven-dried at 65 °C for 24 h. Dry root mass (M_D (kg)) was then divided by the volume of the soil sample (V (m^3)) (De Baets et al., 2007) to obtain RMD.

$$RMD = \frac{M_D}{V}\left(kg\ m^{-3}\right) \tag{1}$$

Prior to packing in pots a 6-point composite sub-sample of top-soil was collected and analysed at the Cranfield University's Environmental Analytics Facility, following Standard Operating Procedures based on British Standard Methods. At termination, fresh sub-soil blends and top-soil samples were collected and analysed for nitrate and ammonium as plant available nitrogen (N) in a commercial external laboratory. Blended treatments T1-T3 and top-soil was air dried, sieved to <2 mm and analysed for electrical conductivity (EC), soil organic matter (SOM), pH and particle size distribution (PSD).

EC was determined on 1:5 soil:water extract, based on the British Standard BS 7755: Section 3.4:1995. SOM content was analysed using the loss on ignition method following British Standard BS EN 13039:2000. Soil pH was determined on a 1:5 suspension of soil in water, based on the British Standard BS ISO 10390:2005. PSD was measured using the *sieving and sedimentation method* based on the British Standard BS 7755 Section 5.4:1998. Soil mineral-N was measured using KCl extract based on MAFF Reference Book RB427 (1986).

2.8. Statistical analyses

Results were analysed using the STATISTICA 12.0 software. Soil properties were analysed using factorial analysis of variance (ANOVA) to determine the effects of multiple categorical variables, namely bulk density (BD), quarry silt:overburden ratio (sub-soil blend T1, T2 and T3) and cover crop (CC) treatment. One-way and two-way ANOVA were used to analyse single categorical independent values for either BD or sub-soil blend, where significance for the CC was not proved. Significant values were analysed following *post-hoc* Fisher LSD analysis to show differences between mean values. Normality was checked and significance was set at $p \le 0.05$. Spearman correlation was carried out on key parameters as shown in Table 4.

3. Results

3.1. Soil characteristics

In accordance with BS 3882:2015 (BSI, 2015), the texture of the top-soil derived from Blashford Quarry used in the pot experiment is classified as a silt loam. With a clay content of 17.9%, soil pH of 5.7–6.7 and OM of 2.97% the top-soil is defined as a low fertility top-soil (BSI, 2015) (Table 2; Table 4).

In accordance with BS 2601:2013 (BSI, 2013), the texture of the T1 (100:0) sub-soil blend corresponds to a clay, while both the T2 (70:30) and T3 (50:50) sub-soil blends are defined a s a silty clay. T1 and T3 blends are, with pH values of 5.4–8.5 slightly below requirements (5.5–8.5) for multipurpose sub-soil (Table 4). The T2 sub-soil blend with a pH of 7.9–8.0 falls within the calcareous sub-soil category.

Table 1
Tarmac's standard grassland seed mixture.

Common name	*Variety*	*Scientific name*	*%*
Perennial ryegrass	Temprano	*(Lolium perenne L.)*	32
Perennial ryegrass	Elital	*(Lolium perenne L.)*	29
Timothy	Alma	*(Phleum pratense L.)*	7
Smooth stalk meadow grass	Panduro	*(Poa pratensis L.)*	29
Creeping red fescue	Report strong	*(Festuca rubra L.)*	3

Table 2
Mean (n = 4) particle size distribution (PSD) of blended sub-soil treatments.

	Sand - 0.6 mm - 0.063 mm (%)	Silt - 0.063 mm - 0.002 mm (%)	Clay <0.002 mm (%)
Top-soil	6.66 (±0.90)	75.4 (±0.66)	17.9 (±0.49)
T1	5.39 (±0.62)	33.7 (±0.73)	61.0 (±0.92)
T2	6.26 (±0.95)	46.5 (±0.93)	47.3 (±0.98)
T3	5.08 (±1.01)	55.1 (±1.26)	39.8 (±0.75)

T1 = Sub-soil blend with 100% silt; T2 = 70% silt and 30% overburden; T3 = 50% silt and 50% overburden. Values in parentheses indicated ±1 SE.

Table 3
Categorical significant responses for all three variables and their combinations. RMD (kg m^{-3}) is for root mass desity, OM (%) is organic matter, EC (μS cm^{-1}) is electrical conductivity, pH is soil acidity, TS stands for topsoil and SS for subsoil.

	RMD (kg m^{-3})		OM (%)		EC (μS cm^{-1})		Soil pH		TS:SS
	TS	SS	TS	SS	TS	SS	TS	SS	
Sub-soil blend		**		***	***	**		***	
BD		***					*		
CC	***	***	**				***		***
BD*CC	*	**							*
Sub-soil blend*BD*CC									***

Mean values significant at *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

Table 4
Spearman correlation coefficients between key variables. RMD (kg m^{-3}) is for root mass density, OM (%) is organic matter, EC (μS cm^{-1}) is electrical conductivity, pH is soil acidity, TS stands for topsoil and SS for subsoil.

	RMD (kg m^{-3})		OM (%)		EC (μS cm^{-1})		Soil pH		TS:SS
	TS	SS	TS	SS	TS	SS	TS	SS	
RMD TS									
RMD SS	0.82								
OM TS	−0.02	0.02							
OM SS	0.00	−0.07	0.76						
EC TS	−0.17	−0.18	−0.22	−0.33					
EC SS	0.16	0.29	−0.56	−0.78	−0.04				
pH **TS**	0.29	0.31	0.37	0.19	−0.40	−0.55			
pH **SS**	−0.20	−0.13	−0.19	−0.52	0.17	0.25	−0.06		
TS:SS	−0.54	−0.89	−0.17	0.01	−0.01	−0.25	−0.34	0.13	
BD	−0.04	−0.10	0.03	−0.02	0.27	0.32	0.36	−0.03	0.10

Marked correlations are significant at p < 0.05.

3.2. Soil-root interaction

To quantify the root distribution between substrate layers, values for RMD were used to create a top-soil:sub-soil (TS:SS) ratio. Low TS:SS values represent a balanced root distribution between the TS and SS, high TS:SS ratio values correspond to few or no roots found within the SS layer, hence root mass being mostly restricted to the TS layer.

Significant relationships between soil and root properties are shown in Table 3. The categorical variable with the largest number of significant relationships was the SS blend. Root mass densities were most affected by type of cover crop (CC) (Table 5). The RMD of SS was also significantly affected by BD. Further, the TS:SS RMD ratio was significantly affected by CC type.

Correlation coefficients shown in the Table 4 indicate, that there is a high correlation between RMD TS/RMD SS and the TS:SS ratio. Also OM TS/SS correlates with EC SS, OM TS correlates with OM SS and pH SS correlates with OM SS.

Sub-soil blend (quarry silt:overburden ratio) had a significant effect on all of the metrics measured. RMD of SS was significantly higher in SS blend T2 (0.1 kg m^{-3}) as compared with T1 (0.06 kg m^{-3}) and T3 (0.06 kg m^{-3}), which had comparable values (Table 4).

Cover crop significantly ($p \leq 0.001$) influenced RMD in both the TS and SS layers (Table 3). A balanced root distribution (TS:SS) was noted for rye treatments, followed by the grassland mix. Conversely, a significantly lower TS:SS was observed for the mustard cover crop treatments (Table 5). This corresponds with the visual assessment of pots where in most cases, mustard roots did not penetrate into the SS layer (Fig. 4). Bulk density significantly influenced the RMD of the SS (Table 5).

The combination of CC and BD variables significantly influenced RMD of both TS and SS, which is reflected in the TS:SS (Table 6). Mustard had in general significantly lower RMDs as compared with rye and grassland cover crop treatments (Table 6). High BD (1.5 g cm^{-3}) of the SS was associated with increased RMD of TS in pots with mustard and rye as compared to the low BD treatments (1.3 g cm^{-3}). High BD (1.5 g cm^{-3}) of the SS in grassland mixture treatments was conversely followed by decrease in RMD of TS.

The most significant dependence was found for the TS:SS ratio (Table 6). Highest ratios, which indicate uneven root distribution, were observed on mustard treatments. The lowest values for TS:SS ratio were obtained on rye.

3.2.1. Available N

Cover crops significantly influenced the amount of nitrate in both TS and SS, and available N in TS. Different SS blends only had

Fig. 1. Visual assessment of mustard root development (T3 (50:50), BD 1.5).

Table 5
Mean (n = 18) significant root mass densities (RMD, kg m^{-3}) and soil physico-chemical characteristics between blended treatments. OM (%) is organic matter, EC (μS cm^{-1}) is electrical conductivity, pH is soil acidity, TS stands for topsoil and SS for subsoil.

	RMD – SS (kg m^{-3})	OM - SS (%)	pH - SS	EC – TS (μS cm^{-1})	EC – SS (μS cm^{-1})
T1	0.06^{a} (±0.014.5)	4.37^{b} (±0.31)	5.7^{b} (±0.16)	8.86^{a} (±0.84)	19.1^{a} (±0.96)
T2	0.1^{b} (±21.1)	3.80^{ab} (±0.31)	8.0^{a} (±0.01)	10.3^{ab} (±1.27)	27.8^{a} (±1.65)
T3	0.06^{a} (±18.4)	3.15^{a} (±0.35)	7.9^{a} (±0.16)	13.8^{b} (±1.70)	21.3^{b} (±2.16)

Within the same column values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD analysis. Values in parentheses indicated ±1 SE.

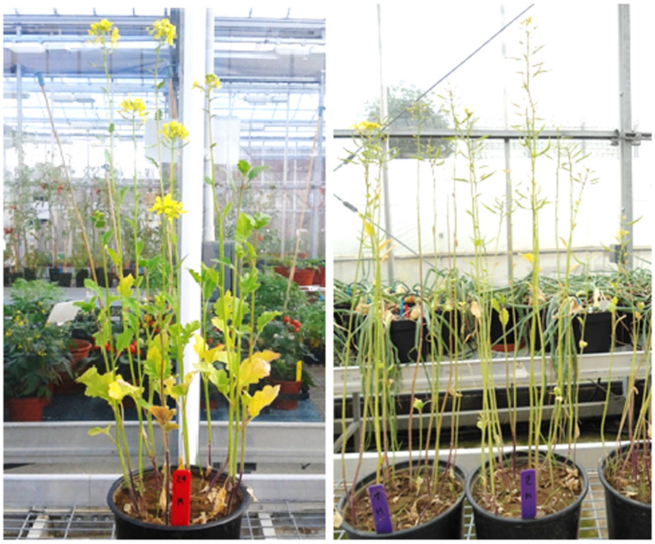

Fig. 2. Effects of nutrient deficiency on mustard plants 36 days (left) and 47 days (right) after sowing.

Fig. 3. Mustard plant showing N deficiency signs – stunned growth and chlorosis on older leaves (27 days after sowing) (left) and possible P deficiency signs – purple petioles (35 days after sowing) (right) (Berry, 2006; Kumar and Sharma, 2013).

an effect on the ammonium content (Table 7). In general, mustard treatments were associated with significantly higher amounts of available N in top-soil as compared to rye and grass mixture treatments. Sub-soil blend T1 had the highest amounts of ammonium as compared with T2 and T3 irrespective of CC treatment(Table 7).

3.3. Plant response

In general, roots avoided the sub-soil layer by growing in the space between the soil and the pot. Mustard roots were almost always unable to penetrate into the sub-soil (Fig. 1).

3.4. Nutrient deficiency

Signs of N-deficiency were assessed by visual analysis against images in Berry (2006), visible on mustard plants three weeks after sowing (Fig. 3). Four weeks into the experiment all mustard plants exhibited significant visible signs of N as well as potential phosphorus (P) and potassium (K) deficiencies (Berry, 2006; Kumar and Sharma, 2013), (Fig. 4). At four weeks, rye also started displaying N nutrient deficiency symptoms through yellowing leaf tips, the

Fig. 4. Mustard leaf showing possible K-deficiency symptoms (35 days after sowing) (Kumar and Sharma, 2013).

grassland mixture showed only minor signs of nutrient deficiency. At the time of termination of the pot trial, mustard plants were fully exhausted (Fig. 2).

4. Discussion

4.1. Cover crop treatment response

Cover crops are used as a temporary measure to facilitate the stabilisation and recover of soils and hydrology post restoration (BWSR, 2012). In a restoration context, a soil profile is re-created using materials, which might have been kept under anaerobic conditions for years, such as quarry silts. Essential first steps for effective rehabilitation of restored soil profiles are improving the soil structure and enhancing hydrological and gaseous connectivity between soil horizons. Planting a mixture of species can be advantageous to ensure soil cover and increase organic matter throughout the profile due to different root systems architectures (BWSR, 2012; Cresswell and Kirkegaard, 1995). Cover crops influence soil properties through the decomposition of crop residues (Radicetti et al., 2016). If used correctly, they can enhance soil properties by capturing, fixing and recycling nutrients, increase SOM, improve soil structure, enhance soil microbiology, mitigate N-leaching and protect soil from erosion (Bodner et al., 2010).

Cover crops encourage soil aggregation indirectly via root deposits which provide energy and nutrient sources for soil biota (White and Kirkegaard, 2010). These biota improve the architecture of the soil by mechanisms including adhesion, kinetic restructuring and filamentous binding (Miransari, 2014). Herrera et al. (2017) also

Table 6
Effect of cover crop treatment and subsoil blend bulk density (BD) on topsoil (TS) and subsoil (SS) root mass densities (RMDs) and topsoil:subsoil ratio (TS:SS ratio).

COVER CROP	BD (g cm^{-3})	RMD – TS (kg m^{-3})	RMD – SS (kg m^{-3})	TS:SS
Grassland	**BD 1.3**	0.76^{bc} (±121)	0.08^{c} (±10.7)	10.5^{a} (±1.76)
Grassland	**BD 1.5**	0.56^{b} (±70.3)	0.04^{b} (±5.55)	18.5^{ab} (±5.43)
Mustard	**BD 1.3**	0.17^{a} (±22.7)	0.01^{a} (±1.05)	45.9^{c} (±9.00)
Mustard	**BD 1.5**	0.21^{a} (±30.8)	0.01^{ab} (±5.51)	29.8^{b} (±5.55)
Rye	**BD 1.3**	0.86^{c} (±82.9)	0.19^{e} (±24.6)	5.24^{a} (±1.57)
Rye	**BD 1.5**	1.13^{d} (±169)	0.14^{d} (±14.3)	8.94^{a} (±1.90)

Within the same column values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD analysis. Values in parentheses indicated ±1 SE.

Table 7
Soil N values, significantly dependent ($p \leq 0.05$) on CC and sub-soil blends.

CC	Nitrate N (+) (mg kg^{-1})		Available N (+) 30 cm profile[a] (kg N ha^{-1})	Sub-soil blend	Ammonium (+) (mg kg^{-1})
	TS	SS	TS		SS
Grassland	0.58^{a} (±0.50)	0.19^{a} (±0.00)	5.22^{a} (±1.82)	**T1**	0.90^{b} (±0.05)
Rye	1.56^{a} (±0.35)	0.07^{a} (±0.10)	8.12^{a} (±1.44)	**T2**	0.50^{a} (±0.15)
Mustard	5.85^{b} (±0.11)	0.62^{b} (±0.08)	24.5^{b} (±0.44)	**T3**	0.51^{a} (±0.07)

[a] The amount of soil N as kg ha^{-1} has been estimated assuming the standard Tarmac TS depth of 0.3 m for soil N profiling; Within the same column values followed by the same letter(s) are not significantly different ($p \leq 0.05$) following Factorial ANOVA and *post-hoc* Fisher LSD analysis. Values in parentheses indicated ±1 SE.

observed that the choice of CC influences the C and N input into the soil via root decomposition dynamics and variable root biomass production. Brennan and Acosta-Martinez (2017), observed that frequent cover cropping can have more significant beneficial impacts on soil microbiology than using compost.

Adaptation for local environmental conditions and suitability for the specific agro-ecological target are however essential (Bodner et al., 2010). Materechera et al. (1991) have observed, that roots of larger diameters such as taproots of dicotyledonous plants penetrated soil more than those with smaller diameters. Perkons et al. (2014) also found, that tap-root plant species create larger biopores thus allow subsequent crop roots to penetrate to deeper soil layers. Yu et al. (2016) claim, that especially for annual plants, root thickness is very important for improving soil structure. Nonetheless, Cresswell and Kirkegaard (1995) suggest that tap rooted annual crops are unlikely to improve porosity of deeper, compacted soil horizons.

At the higher BD (1.5 g cm^{-3}) of SS blends, RMD of rye in the TS increased, with a corresponding decrease in RMD in the SS. This could be explained by the inability of rye to penetrate into the compacted SS, hence the root mass remained limited to the TS layer. Root growth rate is minimally affected by BDs below 1.4 g cm^{-3}, however, values above together with the absence of pre-existing biopores considerably decreases root elongation rate (Gaiser et al., 2013). Contrary to this, the TS:SS ratio of rye was significantly lower (low TS:SS ratio represents even root distribution throughout the pot) as compared with mustard, which can be explained by a proportion of the rye roots growing in the space between the pot and the soil, distorting the RMD ratio.

Soil compaction does not only increase BD, resulting in greater mass per volume, it also changes soil properties, such as water retention, hydraulic conductivity, nutrient transport and uptake, N mineralization, soil gases movement etc. (Guaman et al., 2016; Lipiec et al., 2003; Miransari et al., 2009; Wolkowski and Lowery, 2008). Most importantly, soil compaction may alter root penetration between restored soil layers, or even limit root growth to the TS only, thereby considerably reducing water and nutrient availability to plants, resulting in plant growth reduction (Lipiec et al., 2003; Miransari et al., 2009; Pabin et al., 2003; Wolkowski and Lowery, 2008).

Lipiec et al. (2012) observed that soil compaction (Soil penetration resistance exceeding 2 MPa at field capacity) directly affects root length and root anatomy of 7-day old cereals. Materechera et al. (1991) grew seedlings of twenty-two plant species for 10 days and observed that soil compaction reduced root elongation by 90% while increasing root diameters. Strongly compacted soils are usually only penetrated by roots through cracks and/or pre-existing biopores (Głab, 2008). This may in large part explain the RMD results observed for rye treatments in this study. Nevertheless, it is important to note that in this pot study, rye roots avoided penetrating the SS mainly by growing through the macro-pore space at the soil-pot interface. Evidence suggest that yields of some grasses might be unaffected by compaction (Głab, 2013, 2008). Vallance and Sonogan (1995) stated that fibrous roots of rye grow especially well in the first 30 cm of soil, however, Chen and Weil (2010) claim that rye roots are strongly affected by soil compaction. Scholefield and Hall (1985) claim that the ability of grasses to penetrate highly compacted soils by becoming constricted can be considered as a compensation of radial pressure. Growing rye may however be considered in mixtures with other grass species, or legumes. According to Clark (2007), a rye-legume mixture is able to adjust to different N levels, meaning that in soils rich on N, rye tends to grow better while in soils poor on N, the legume grows better. Another advantage of a rye-legume mixture is that rye holds N while improving soil structure and legumes fix N, making some of it available for rye (Kammermeyer, 2016). Rye can also be useful in restoration projects taking place in the autumn, as late seeding is required, owing to its ability to germinate at low temperatures and produce sufficient soil cover for the winter (AGRAVIS, 2017; CEMEX, 2014).

4.2. Growing media characteristics

According to results of the PSD, quarry silt contains a large proportion of clay sized particles. Clays tend to be chemically and physically active, which means that their ability to hold water and nutrients is increased (Hazelton and Murphy, 2007). High clay content however increases susceptibility to compaction (Frost, 1988).

Critical BDs, which are likely to severely affect plant growth and root penetration, are different for different soil textures. For clay loam and clay soils, the critical values are >1.6 and > 1.4 g cm^{-3} (Hazelton and Murphy, 2007). This may in large part explain the observation that for blends T1, T2 and T3, the higher SS BD significantly reduced RMD of rye.

Quarry silt from Blashford Quarry contained not only fine particles, but also a coarse fraction of cobbles and boulders (>63 mm), which is not uncommon for a quarry silt (Harrison et al., 2001). Under field conditions, this may positively influence root penetration by creating macro pores and voids within the substrate.

EC values for the T1-T3 treatments varied between 9 and 28 $\mu S\,cm^{-1}$, which is classified as non-saline and is typical for normal surface soils (Hazelton and Murphy, 2007). To accelerate the process of silt-water separation within silt lagoons, some quarries choose to use anionic flocculants such as iron (Fe) and aluminium (Al) salts to accelerate water and silt separation. This could influence EC values of quarry silt as well as be one of possible causes of highly restricted mustard root development. Testing silt for flocculants or other potentially phytotoxic elements is therefore recommended.

Soil pH may be used as an indicator for suitability for specific grass or crop species (Hazelton and Murphy, 2007). Baize (1993) suggests that optimum pH should be between 6.5 and 7.5. As sub-soil blends T2 and T3 resulted in a pH typical for alkaline soils (7.9 and 8.0, respectively), this should be approached with caution. Soil pH above 7 reduces bioavailability of trace metals such as Cu, Zn and Ni, (Han, 2007). Nevertheless, according to Hazelton and Murphy (2007), pH values of the T1-T3 SS blends and TS used in this study should not affect availability of N, P, K, S, Ca, or Mg as they were always >5.0 and < 8.5, with the exception of availability of Fe being reduced in pH < 7.5, which applies for both T2 and T3.

4.3. Nutrient deficiency associated with experimental treatments

N, P and K, also known as primary nutrients, are essential macronutrients promoting growth, energy storage and higher plants cell wall strength (Kumar and Sharma, 2013). In restored soils blended with quarry non-commercial by-product, a lack of nutrients should be expected (Mitchell et al., 2004). N-deficiency was visible on mustard plants as early as 3 weeks into growth. The lack of N was noticeable through retarded growth and leaf symptoms. These symptoms were first observed in older leaves owing to translocation of N through the plant to younger tissues, leaving lower leaves yellow chlorotic and in later stages necrotic (Kumar and Sharma, 2013). This nutrient deficiency was aggravated by buds being visible at week four. Typically in mustards, buds are usually visible after 5 weeks and flowers appear 7–10 days later (Oplinger et al., 1991). Early flowering of mustard results in short lived preservation of accumulated N, as stated by Herrera and Liedgens (2009). According to Rosenfeld and Rayns (2011), mustard will start to flower once its canopy reaches 0.5–0.7 m of height and continues to grow even after that, exceeding 1 m. In this study, the average height of mustard plants in bloom was only 0.38 m as a result of stunted growth induced by lack of essential nutrients. According to (Kumar and Sharma, 2013), lack of N is likely to occur in waterlogged conditions, and soils with pH < 6.0 or pH > 8.0. Most plants absorb N as ammonium (NH_4^+) or nitrate (NO_3^-), which is also soluble in water and therefore easily leachable (Hosier and Bradley, 1999). Laboratory results showed that pots treated with mustard had significantly higher NO_3^- concentrations in both TS and SS as compared with other CC treatments. This suggests that mustard is not effective in scavenging nutrients due to its root structure lacking fine roots. Phosphorus P deficiencies on mustard plants were also visible across all blended treatments as purple petioles, dwarfed plants (P promotes root development) and marginal and interveinal chlorosis (Berry, 2006; Kumar and Sharma, 2013).

The additional of supplementary nutrient sources should be considered if quarry silt as non-commercial by-products are to be used as sub-soil media. Results from the research project ‘Minerals from Waste’ suggest that quarry non-commercial by-products can be successfully used; especially if mixed with a green waste compost in order to prevent any possible nutrient depletion and improve the initial soil structure (Mitchell et al., 2004).

5. Conclusions

Across all cover crop types, the best preforming sub-soil blend was the T2 (70:30) treatment in terms of significantly higher RMD in the sub-soil. Mustard with tap roots performed poorly in comparison to the rye and grassland mix treatments which are associate with dense fine roots. Therefore, mustard cannot be recommended as a suitable cover crop for restoration projects where quarry silt is used in a blended sub-soil medium. Both the grassland mixture and winter rye had significantly better performance, as compared to mustard with a different root type. It can be suggested that improving top-soil/sub-soil connectivity could be achieved if rye and grasses were grown together in a mix, or in conjunction with legume species to facilitate successful biological and hydrological connectivity in restored soils. The results indicate that quarry silt can be used for this purpose, nevertheless, due to its high clay content, blending quarry silt with overburden, or PAS 100 organic compost is highly advisable.

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