CRANFIELD UNIVERSITY

LUCIE MAŠKOVÁ

EVALUATION OF SILT FROM SAND AND GRAVEL PROCESSING AS A SUITABLE SUBSOIL MATERIAL

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
Land Reclamation and Restoration

MSc
Academic Year: 2016 - 2017

Supervisor: Dr. Rob Simmons
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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

ABSTRACT

Sand and gravel processing generates large amounts of fine particles (< 63 μm) which constitute approximately 20 % of quarry production in the UK. There is, however, no market for this by-product therefore industry treats this material as a waste. Quarries often face shortage of soil to use in restorations and have to look for other options to restore land successfully. This study investigated possible use of silt as a subsoil medium to partially substitute soil-forming materials while facilitating successful crop establishment. In a glasshouse pot experiment, topsoil and subsoil layering has been simulated, generating an artificial subsoil medium by mixing two quarry waste materials: silt and overburden. These were blended in three different ratios (100:0, 70:30, 50:50), aiming for high use of silt. Pots were packed in two bulk densities and sown with three cover crop treatments, being winter rye (*Secale cereale*), white mustard (*Sinapis alba*) and a Tarmac grassland seed mixture *(Lolium perenne, Phleum pratense, Poa pratensis, Festuca rubra).* Three weeks into experiment, mustard displayed first signs of nitrogen deficiency, with phosphorus and potassium deficiencies following later. Rye exhibited minor effects four weeks into growth, grassland mixture showed barely any. Nutrient deficiency visibly inhibited growth of aboveground biomass of Mustard. Root development of mustard with tap roots was the worst in comparison with fine roots of grasses. Both grassland mix and rye performed well. Silt, especially if blended with another growing medium, is suitable as a subsoil medium for successful grass cover crops establishment and initiation of the soil forming process. Mustard cannot be recommended as a suitable cover crop where silt is used as a subsoil medium. Future studies are recommended in order to further investigate long term subsoil and topsoil structural and hydrological connectivity induced by different cover crop mixtures.

Keywords:

Quarry waste, *Secale cereale, Sinapis alba*, Restoration, Sand and gravel extraction, Root density

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BD	Bulk Density
RMD	Root Mass Density
FSD	Frequency of Surface Drying
WC	Water Content
OM	Organic Matter
EC	Electrical Conductivity
TS	Topsoil
SS	Subsoil

NOTATIONS

This thesis has been prepared in the format used for scientific papers appearing in the journal *Ecological Engineering*. An extended literature review has been included following the requirements of Cranfield University.

Word Count: 7 930

Evaluation of silt from sand and gravel processing as a suitable subsoil material

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ABSTRACT

Sand and gravel processing generates large amounts of fine particles (< 63 μm) which constitute approximately 20 % of quarry production in the UK. There is, however, no market for this by-product therefore industry treats this material as a waste. Quarries often face shortage of soil to use in restorations and have to look for other options to restore land successfully. This study investigated possible use of silt as a subsoil medium to partially substitute soil-forming materials while facilitating successful crop establishment. In a glasshouse pot experiment, topsoil and subsoil layering has been simulated, generating an artificial subsoil medium by mixing two quarry waste materials: silt and overburden. These were blended in three different ratios (100:0, 70:30, 50:50), aiming for high use of silt. Pots were packed in two bulk densities and sown with three cover crop treatments, being winter rye (*Secale cereale*), white mustard (*Sinapis alba*) and a Tarmac grassland seed mixture *(Lolium perenne, Phleum pratense, Poa pratensis, Festuca rubra).* Three weeks into experiment, mustard displayed first signs of nitrogen deficiency, with phosphorus and potassium deficiencies following later. Rye exhibited minor effects four weeks into growth, grassland mixture showed barely any. Nutrient deficiency visibly inhibited growth of aboveground biomass of Mustard. Root development of mustard with tap roots was the worst in comparison with fine roots of grasses. Both grassland mix and rye performed well. Silt, especially if blended with another growing medium, is suitable as a subsoil medium for successful grass cover crops establishment and initiation of the soil forming process. Mustard cannot be recommended as a suitable cover crop where silt is used as a subsoil medium. Future studies are recommended in order to further investigate long term subsoil and topsoil structural and hydrological connectivity induced by different cover crop mixtures.

1 INTRODUCTION

1.1 Sand and gravel extraction and the origin of silt

Processing of sand and gravel involves washing, crushing and screening of the material to separate sand and gravel aggregates rich in silica (quartz, quartzite and flint), from fines (< 0.063 mm) which consist of silt, clay and other non-quartz particles (BGS, 2013). These fines are collected in water, giving rise to a suspension, which is then pumped into lagoons and allowed to settle out (BGS, 2013). This suspension remains in semi-liquid, anaerobic state for many years, or even decades (Jarvis and Walton, 2010). This product is usually referred to as 'silt'.

Quarry silt is un-avoidable and significant proportion of quarry outputs (Mitchell, 2007). The amount of quarry silt varies between 5-30% of the total volume extracted, averaging around 10-15% (Harrison et al., 2001). It is defined as a waste as there is no market for this by-product, nevertheless it should be noted that silt is an inert and non-hazardous material (Mitchell, 2007). Overburden is also regarded as a waste product.

The need to minimize the amount of quarry waste is driven by environmental consequences, social consequences and regulatory compliances (Mitchell, 2007). Most importantly, sometimes, there is more silt than expected and it has to be excavated in order to increase lagoon capacity, which causes both economical and logistical problems to the company (Mitchell, 2007).

Reduction of quarry waste 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 waste products is as a backfill or subsoil material in site landscaping and restoration (Harrison et al., 2001). Another possible use of quarry wastes according to Mitchell (2007) is as tips around the quarry site to screen the workings, which however have to be vegetated as soon as possible. Reusing mineral wastes contributes to efficient use of resources, reduces environmental impacts, and improves sustainability for local communities (Mitchell et al, 2004).

1.2 Quarry restoration

At the end of operating life of sand and gravel quarries, resulted voids have to be levelled and graded to achieve landscape and landform objectives stated in restoration plans, and to allow further agricultural restoration (CEMEX, 2014; DCLG, 2014). This is usually achieved by using silt and overburden available on site, capping the filled area with topsoil stripped and stored aside prior to the extraction process (Mitchell, 2007). Depths usually depend on the predicted volumes of topsoil, subsoil and overburden (CEMEX, 2014). Silt lagoons would normally be restored into wetland habitats, or capped with at least 1 m thick layer of overburden and planted with willow rods (Tarmac, 2008). However, quarries often face shortage of topsoil or other soil-forming materials. Also it is a priority is to use materials available on-site rather than import (Tarmac, 2008). A possible solution would be the use of silt and overburden as a partial replacement of those in restorations.

Suitability of quarry waste in artificial soils was evaluated in the past in a research project ‘Minerals from Waste’, in which several quarry fines blends were used as a growing medium for grass and the amount of biomass produced was evaluated (Mitchell et al., 2004). Results however showed a problem of nutrient shortage in such materials.

According to the DCLG (2014), minerals operator has a responsibility for the restoration and aftercare of mineral sites, for a period of 5 years at minimum. The first two years should be reserved for cover crops to allow sufficient rehabilitation of soil, before an arable crop is grown. It is advisable to prolong the cover crop period for as long as possible, to allow topsoil/subsoil layers to blend and rehabilitate its organic matter and nutrients (CEMEX, 2014).

1.3 Soil compaction

Soil compaction does not only increase bulk density, resulting in greater mass per volume, it also changes soil properties, such as water retention, hydraulic conductivity, root growth, nutrient transport and uptake, N mineralization, soil gases movement, soil porosity etc. (Guaman et al., 2016; Wolkowski and Lowery, 2008; Lipiec, Arvidsson and Murer, 2003; Miransari et al., 2009).

Pore volume is reduced resulting in less air and less water content in the soil, large pores are completely destroyed and water infiltration is reduced, increasing the potential of surface runoff and waterlogging (Wolkowski and Lowery, 2008). By modifying soil gas dynamics, compaction may induce nutrient deficiencies through reduced aeration, which increases the potential for denitrification, involving emission of N_2O and N_2 to the atmosphere, this occurs especially in soils where water content rises above 60% (Soane and van Ouwerkerk, 1995; Lipiec and Stepniewski, 1995). Under some conditions, the amount of N2O lost from compacted soils may be even 400-500% larger compared to uncompacted soil (Soane and van Ouwerkerk, 1995; Lipiec and Stepniewski, 1995). Other nutrients uptake, (for example potassium (K)) can also be reduced if its absorption process requires cellular respiration (Wolkowski and Lowery, 2008).

Most importantly, soil compaction may alter root development between soil layers, or even limit root growth to the topsoil layer only, thereby considerably reducing water and nutrient availability to plants, resulting in plant growth reduction (Lipiec, Arvidsson and Murer, 2003; Miransari et al., 2009; Pabin et al., 2003; Wolkowski and Lowery, 2008). Even though root growth rate is minimally affected by bulk densities below 1.4 g cm^{-3}, values above, together with no biopores present, decrease root elongation rate considerably (Gaiser et al., 2013).

Lipiec et al. (2012) in his study of 7-day old cereals demonstrated that soil compaction directly affects root length and root anatomy. Materechera et al. (1991) grew seedlings for 10 days and observed that soil strength reduced root elongation by 90% while increasing root diameters. Also Gaiser et al. (2013) reported that mean root elongation rate was reduced in soil without biopores to less than 50% compared to soil with biopores, which negatively influenced both water and N uptake and reduced the biomass production by about 26%.

1.4 Cover crops

Cover crops are a temporary measure for allowing soil and site hydrology to stabilise (BWSR, 2012).

In restoration context, new soil horizons are created using materials, which might have been kept in anaerobic conditions for years, such as silt. First steps in rehabilitating such soils are improving the soil structure, adding organic matter and enhancing connectivity of soil layers. This can effectively be achieved by using suitable single cover crops such as oats, winter wheat or other cereal species, however planting a mixture of species can be advantageous to ensure soil cover across all soil conditions and increase of organic matter input through different root systems (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 in many different ways such as; capturing, fixing and recycling nutrients, input of organic matter, improving soil structure, mitigation of nitrate leaching and protecting soil from erosion (Bodner et al., 2010). Adaptation for local environmental conditions and suitability for the specific agro-ecological target are however essential (Bodner et al., 2010).

When soil is highly compacted, mulch and root channels left by winter cover crops can positively influence growth of summer crops by conserving water through surface mulch and enhancing access to subsurface water (Chen and Weil, 2011). Also fields with cover crops compared to no-cover crop fields recorded a 3.5% decrease in soil bulk density (Haruna and Nkongolo, 2015).

Root architecture is a term used to refer to the shape and spatial configuration of root systems (Lynch, 1995). The importance of root architecture comes from the significant role it plays in water and nutrients transport to the shoots, as plant growth is strongly limited by availability of soil resources to plant roots (Lynch, 1995). Yu et al. (2016) suggests that different root systems have to be considered in order to achieve an effective cover crop system. Herrera et al. (2017) also claims that the choice of cover crop influences the C and N input into the soil by different root decomposition dynamics and variable root biomass production.

Yu et al. (2016) claims that especially for annual plants, root thickness is very important for improving soil structure. This claim was encouraged by Materechera et al. (1991) who observed, that roots with large diameters 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 crops to grow more roots in deeper soil layers. Nonetheless, Cresswell and Kirkegaard (1995) suggest that tap rooted annual crops are unlikely to improve porosity of deeper, compacted soil horizons. It should be noted that vertical root length density distribution is also a crucial element influencing water and nutrient uptake, therefore biomass production (Gaiser et al., 2013).

1.5 Aims and Objectives

The aim of this project was to determine suitability of silt from mining lagoons in facilitating crop establishment on restoration sites. This study should provide recommendations for successful use of silt in future restoration projects.

Objectives of this study were as follows:

- Evaluation of optimal silt/overburden blending ratio for use as a subsoil medium by simulating a topsoil and subsoil layering.
- Assessment of a soil profile connectivity achieved through cover crop root development.
- Evaluation of specific cover crop scenarios and their suitability for soil rehabilitation.
- Evaluation of changes in key physical and chemical properties of growing media used.

Hypothesis that were tested include: (i) use of silt as a subsoil medium is suitable for successful crop establishment, (ii) root penetration facilitates gradual blending of topsoil and subsoil layers.

2 MATERIALS AND METHODS

2.1 Study materials

Tarmac is the UK's leading building materials and construction business, operating over 100 quarries and aiming to meet the highest standards of sustainability (Tarmac, 2017). Materials for this study experiment were acquired from two different quarries operated by Tarmac Company. Blashford Quarry was the source for the silt and topsoil, and Mountsorrel Quarry provided us with overburden samples. These quarries were selected due to the excess of silt, topsoil and overburden.

2.2 Field Sampling

Mountsorrel Quarry is a granite quarry located between villages Mountsorrel and Quorn in Leicestershire. A total of 80 kg of overburden from this site has been acquired. Those were collected from 10 random points.

Blashford Quarry is located in Hampshire, south from Salisbury. It covers an area of 234 ha and its annual silt generation is about 20 000m^3. This site has produced more silt than expected and consequently has to excavate some of it to increase the capacity of silt lagoons.

Material from Blashford Quarry was acquired on a field visit on 26th of May 2017. At the time of sampling, dry weather contributed to lower water content of the silt lagoon surface, which simplified the sampling process and subsequent subsoil substrate preparation. Silt was excavated on the day of the visit in two bulks of approximately 1 m^3 from one of the silt lagoons of Blashford Quarry. The first bulk was excavated near the edge of the lagoon and the second from the inner area of the lagoon. A total of 210 kg of silt samples have been acquired. Silt lagoons in Blashford are lined with clay to ensure impermeability, therefore some of this clay from the lining was present in our samples.

Topsoil was taken from a bund lining the quarry, which was highly compacted but still moderately vegetated. Approximately 15 kg of topsoil from each of the 8 randomly chosen points within the bund was taken, making up a total of 120 kg of topsoil. Randomising ‘zigzag’ pattern was followed, as defined by Sabbe and Marx (1987), choosing a starting point on a random location on the bund, placing every next point 10-15 m from the previous one and following a predetermined course, so that most of the area was covered (Sabbe and Marx, 1987).

2.3 Experimental design

In typical quarry restorations conducted by Tarmac Company, a 0.6 m layer of subsoil would be capped with a 0.3 m layer of topsoil stripped from the surface prior to sand and gravel extraction. This substrate layering has been simulated in a pot experiment. As a subsoil medium, 3 different silt-overburden blend ratios were chosen, 100:0, 70:30 and 50:50, aiming for high silt content. Another variable was to test two soil compaction levels, high and low, values of which were precisely chosen during the experimental set-up. Finally, as a cover crop treatment, three cover crop scenarios were used and tested. These were white mustard (*Sinapis alba)* which was requested for this experiment by Tarmac; winter rye (*Secale cereale)* as a cereal representative; and a grassland seed mixture *(Lolium perenne, Phleum pratense, Poa pratensis, Festuca rubra)* as a reference cover crop already used in Tarmac restorations. No fertilizers were applied.

2.3.1 Bulk density

The *soil bulk density* (ρ_b) is expressed by soil weight per unit volume. For units, g cm^{-3} were chosen being closest to the actual amount of material used in the experimental design (Cresswell and Hamilton, 2002):

$$\rho_b = \frac{\text{Mass of soil}}{\text{Totoal volume of soil}} \quad (g\ cm^{-3}) \qquad \textbf{(2-1)}$$

Bulk density (BD) values normally vary from 1.1 to 1.8 g cm^{-3} , in extreme conditions surface soil layers may have BD as low as 0.5 g cm^{-3}, heavily compacted soils may exceed 2.0 g cm^{-3} (Cresswell and Hamilton, 2002).

Bulk density is affected by soil texture, due to the fact that fine particles tends to form larger aggregates in comparison to light soils (Wolkowski and Lowery, 2008). Interestingly, Tracy et al. (2013) revealed, that different soil texture may result in plants reacting differently to higher BDs in early stages of root growth.

2.3.2 Winter Rye

As a cereal, winter rye (*Secale cereale*) was used. Seeding rate for Rye varied greatly depending on the local climate conditions and on seeding method being either drill or broadcast. According to Björkman and Shail (2014), seeding rate also depends on the date of sowing. Values as low as 62-67 kg ha^{-1} (Government of Alberta, 2016) up to 56-224 kg ha^{-1} (Casey, 2012). For our experiment, 90 kg ha^{-1} of rye was chosen as this rate appeared to be the most common.

Winter rye is the most frost tolerant of all cereals (Oelke et al., 1990). Its great advantage of being able to germinate in temperatures as low as 1°C allows seeding as late as September, the end of October, or even December (Rosenfeld and Rayns, 2011; AGRAVIS, 2017). Generally, rye preforms best in temperate climate zones (Clark, 2007). It prefers well-drained light loams and sandy soils, but can also be established on heavy clays (Oelke et al., 1990; Björkman and Shail, 2014). Some varieties even withstand waterlogging (Clark, 2007). Winter rye is fairly draught tolerant and can also endure low fertility and acid soils better than other cereal species (Government of Alberta, 2016; Kammermeyer, 2016). Ideally though, it should be sown on well drained soils of pH 5.6 – 5.8 or slightly higher, up to pH of 6.5 (Oelke et al., 1990; Kammermeyer, 2016). Rye should be sown into firm and moist soil, about 2.5 – 3.8 cm deep, but no more than 5 cm deep (Clark, 2007; Government of Alberta, 2016). It should be drilled on a ploughed surface, however, if ploughing is impossible, it can be broadcast on moist, untilled soil and covered with 2.5 cm of soil, or lightly disked or cultipacked to increase its contact with soil moisture (Björkman and Shail, 2014; Clark, 2007; Rosenfeld and Rayns, 2011; Government of Alberta, 2016).

Winter rye is an annual, upright grass growing 61-122 cm tall, usually reaching its mature stage in 90-110 days if planted in autumn (Deer Creek Seed, 2017; Kammermeyer, 2016).

Growing Rye has many positive effects on soil. According to Clark (2007), rye is a leading soil-building crop through adding organic matter and conserving soil moisture. Its straw is very slow to decompose, providing a long-lasting conservation measure through holding the soil together (Government of Alberta, 2016). Rye does not fix soil N, but is good in absorbing unused N and slow in releasing it (Clark, 2007, Rosenfeld and Rayns, 2011). Its fast growing fibrous root system can take-up 25-100 % of residual N from the field, while preventing N leaching over the winter and protecting water quality (Rosenfeld and Rayns, 2011; Clark, 2007).

Rye's branching root system grows especially vigorously in the first 30 cm of soil, which is the main reason for its draught resistance (Vallance and Sonogan, 2010). Chen and Weil (2010) found though, that fibrous roots of rye are considerably inhibited by soil compaction compared to tap-rooted plant species, especially in high clay content soils.

Cereal rye performs especially well as a cover crop or green manure in mixture with legume (Casey, 2012). According to Clark (2007), a rye-legume mixture is able to adjust to different nitrogen (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 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). Brennan and Acosta-Martinez (2017) suggest that rye in a rye-legume mixture could decompose more easily than rye grown alone. Positive effects are also given by fact that rye, thanks to its fast growth, acts as a nursing crop for the legumes in the first weeks after seeding making it possible for the legumes to develop sufficient root systems (Kammermeyer, 2016). Finally, legumes improve rye's conservation potential and together they produce even greater amounts of biomass. The most popular legume species to be mixed with rye is hairy vetch (Clark, 2007). Another legume option for rye sown in spring would be red clover (Björkman and Shail, 2014).

2.3.3 Mustard

White mustard (*Sinapis alba*) was used for our experiment. Seeding rate of mustard varied from 10 kg ha^{-1} (Bodner et al., 2010) or 15 kg ha^{-1} (Yu et al., 2016), up to 20 kg ha^{-1} (Rosenfeld and Rayns, 2011). The most common seeding rate of 20 kg ha^{-1} has been adopted.

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). Mustard prefers neutral pH 7.0, although some alkalinity and salinity can be tolerated (Oplinger et al., 1991). Mustard seedling emerge rapidly but continue to grow slowly afterwards. It has tap roots, which can grow 1.5 m into the soil under dry conditions (Oplinger et al., 1991).

Due to its small size, mustard should be shallow sown at 2.5 cm at most or ideally, surface broadcast (Rosenfeld and Rayns, 2011; Oplinger et al., 1991). It is not as hardy in resisting frost as winter cereals, however, it is easy to break down and incorporate into soil as a green manure or use as a mulch. When chopped and incorporated into the soil, thanks to its large volumes of green matter and residual fibre, mustard can improve soil texture and moisture retention, especially when used on sandy soils (Green Manure, 2017).

Mustard does not fix nitrogen (N), but can effectively prevent its leaching (Rosenfeld and Rayns, 2011). Mustard, similar to rye, is one of the fast growing plant species producing large amounts of biomass and if used as green manure, it is very effective at supressing weeds, soil pests and diseases (Rosenfeld and Rayns, 2011).

2.3.4 Grassland seed mixture

As a third cover crop treatment, the standard seed mixture usually used by Tarmac has been chosen. It is a standard grassland seed mixture used in agricultural land restorations in the first 2-3 years within the 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 same or similar grass species (Table 1) are usually designed as a damage resistant paddock mixtures for grazing and hay production (Walnes Seeds, 2017).

Table 1 Tarmac standard grassland seed mixture plant species specifications

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

2.4 Experimental set-up

For both pot experiment and laboratory analyses, growing mediums (topsoil, silt and overburden) were air dried and sieved to <2 mm. It should be noted, that these results do not include the coarse friction of aggregates >2 mm, which has been removed during the preparation.

Silt in its original state had a very high moisture content, therefore was subject to a longer preparation process consisting of spreading the material on trays and air drying. Air-dried silt then formed hard aggregates, which required manual crushing in order to be further crushed in the mechanical grinder. Overburden had also to be grinded using a mechanical grinder.

2.5 Glasshouse experiment

Subsoil medium had to be mixed to desired ratios of 100:0, 70:30 and 50:50 of silt:overburden. To represent the layering, the subsoil layer was packed up to the first 12 cm from the bottom of the pot, leaving the next 5 cm for the topsoil layer.

Subsoil was packed in two bulk densities (BD), representing low and high compaction. The highest BD achievable was 1.5 g cm^{-3}, low value was left at 1.3 g cm^{-3}. All pots were then capped with a 5 cm layer of topsoil (silt loam/silty clay loam) which was packed at BD of 1.3 g cm^{-3} to reach the total pot volume of 2 313 cm^3. Hazelton and Murphy (2007) describe the BD of 1.4-1.6 g cm^{-3} on clay soils as very compact, BD of 1.2-1.4 g cm^{-3} on loams is described as satisfactory. To represent every treatment in 3 replications, a total of 54 pots were produced.

Pots were placed into the glasshouse and wetted using the capillary pressure. Cover crop treatments (winter rye, white mustard and grassland seed mixture) were broadcasted on the 16th of June 2017, however due to unexpectedly hot weather, they had to be slightly incorporated only a few days later. Pot layout has been changed twice in order to randomize possible variances resulting from a specific position on the bench in the glasshouse. First change after sowing was done on the 7th of July, second change on the 21st of July. This made up three growing periods of 21, 14 and 12 days.

2.6 Laboratory analyses

Samples from the pot trial were taken during the period of 2nd – 9th August 2017. Pots were cut in half using a palette knife to visually asses the root penetration into the substrate. One quarter of each pot was used for root washing. To determine the root mass density (RMD), roots had to be oven-dried at 65°C for 24 hours. Dry root mass (M_D (kg)) was then divided by the volume of the soil sample (V (m^3)) (De Baets et al., 2007).

$$\mathrm{RMD} = \frac{\mathrm{M_D}}{\mathrm{V}} \quad (\mathrm{kg\ m^{-3}}) \qquad \textbf{(2-2)}$$

Air dried soil samples were grinded, sieved on a 2 mm sieve and analysed using Cranfield University’s Environmental Analytics Facility, following Standard Operating Procedures based on British Standard Methods. Fresh soil samples were analysed at NRM Laboratories.

Base materials and samples from the glasshouse experiment were analysed for electrical conductivity (EC), water content (WC), soil organic matter (OM), pH, particle size distribution (PSD), nitrate, ammonium and available N.

EC was determined on 1:5 soil:water extract based on the British Standard BS 7755: Section 3.4:1995. Water content (WC) was measured based on the based on the British Standard BS 7755: Section 3.1:1994. Soil OM content was analysed using the loss on ignition method based on the British Standard BS EN 13039:2000. Soil pH was determined on a 1:5 suspension of soil in water bases 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 nitrogen was measured on 'dry matter' basis. The available N content (kg/ha) was estimated assuming the 30 cm depth of N profiling.

2.7 Statistical analyses

Results were analysed using the STATISTICA 12.0 software. Soil properties were analysed using the factorial analysis of variance (ANOVA) to analyse effects of multiple categorical variables, these being bulk density (BD), subsoil blend type (treatment) and cover crop (CC). One-way and two-way ANOVA were used to analyse single categorical independent values for either BD or treatment, where significance for the CC was not proved. Significant values were then tested by the post-hoc Fisher LSD test to show differences among mean values. Normality was checked and significance was set at $p \leq 0.05$.

3 RESULTS

3.1 Soil characteristics

According to the BS 3882:2015 (BSI, 2015), texture of the topsoil used in the pot experiment can be classified as a silt loam or silty clay loam. Across the three treatments, clay content was highest for pure silt treatment (T1), whereas for the T3 with 50 % of overburden, silt content was the highest (Figure 1). For clay content of 17.9 %, soil pH of 5.7-6.7 and the mean mass loss on ignition of 2.97 % slightly below requirements (3-20 %), our soil can be characterised as a low fertility topsoil (Table 2).

According to the BS 2601:2013 (BSI, 2013), texture of the T1 (100:0) subsoil blend corresponds to clay texture, while both T2 (70:30) and T3 (50:50) subsoil blends fall within the silty clay textural category. T1 and T3 treatments are with pH values of 5.4 – 8.5 slightly below requirements (5.5 – 8.5) for the multipurpose subsoil (Table 4). T2 treatment with pH of 7.9 - 8.0 (Table 4) is placed the calcareous subsoil category.

Table 2 Particle size distribution (PSD) for growing media used in the experiment

	Sand - 0.6mm - 0.063mm (%)	**Silt - 0.063mm - 0.002mm (%)**	**Clay <0.002mm (%)**
Topsoil	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)

Mean values ± SE; T1=Subsoil blend with 100% silt; T2=70% silt and 30% overburden; T3=50% silt and 50% overburden

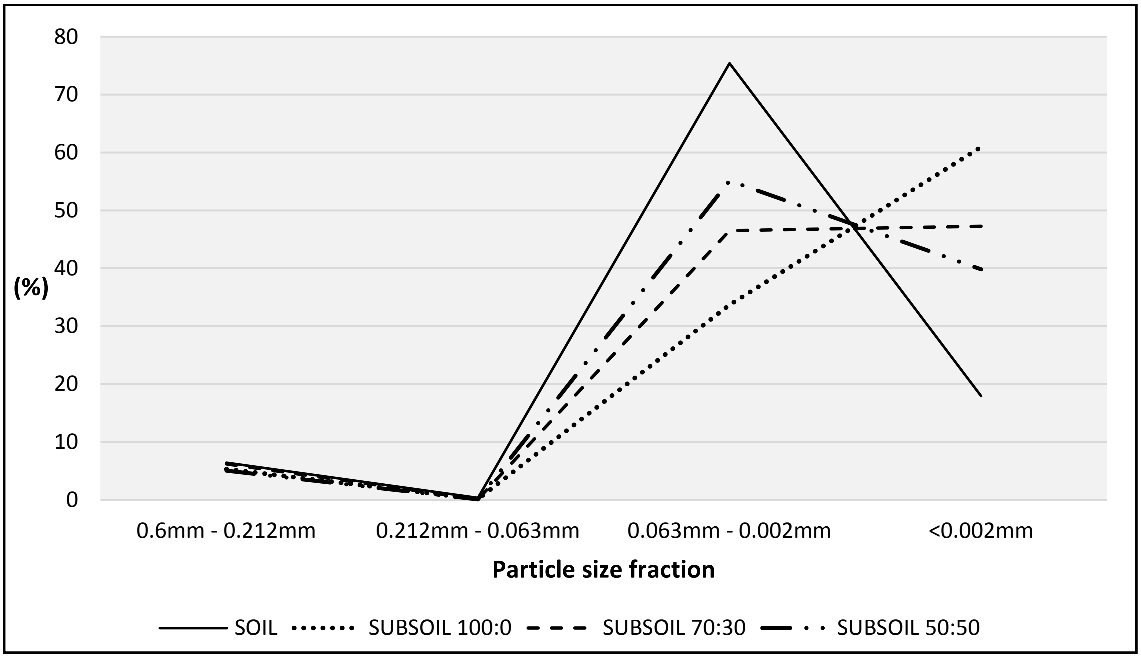

Figure 1 Particle size distribution (PSD) of growing media used in the experiment

3.2 Soil and root analysis

To quantify the root distribution between substrate layers, values for the root mass density (RMD) were used to create a topsoil:subsoil (TS:SS) ratio. Low TS:SS values represent balanced root distribution between the topsoil and subsoil, high values translate into very little or no roots found within the subsoil layer, hence root mass being mostly restricted to the loosened topsoil layer.

During the pot trial, frequency of drying of the pot surface was recorded (FSD), which enabled development of a ranking system in which each of the pots were marked according to how often its surface dried completely. The resulting units ranged from 0 (never dry) to 11 (always dry). Pot surface drying was also evaluated in regards to its position in the glasshouse and the possibility of this having an influence on the FSD; this was proved to have no influence.

Significances of soil and root properties across all three variables are shown in Table 3. The categorical variable with the largest number of significant categories was Treatment.

Table 3 Categorical significant responses for all three variables and their combinations

	RMD		OM		WC		EC		Soil pH		TS:SS	FSD
	TS	SS	TS	SS	TS	SS	TS	SS	TS	SS		
Treatment		**		*	*		*	**		***		
BD		***							*			***
CC	***	***				*					***	**
BD*CC	*	**									*	
Treatment*BD*CC											*	

Mean values significant at *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$; TS=topsoil; SS=subsoil; RMD=root mass density; OM=soil organic matter; WC=water content; EC=electrical conductivity; TS:SS=topsoil:subsoil root mass density ratio; FSD=frequency of surface drying

Treatment had significant effects on most of the measured characteristics. RMD of subsoil was much higher in T2 (0.1 kg m^{-3}) compared to T1 (0.06 kg m^{-3}) and T3 (0.06 kg m^{-3}), which had comparable values. In regards to the highest clay content of T1 (Table 4), values for the soil OM of subsoil were highest in this treatment as well as the WC of topsoil. On the other hand, T1 resulted in weakly acid soil (pH 5.7), compared to the other two treatments, which were alkaline (7.9 - 8.0) (Table 4).

Cover crop significantly ($p \leq 0.001$) influenced RMD in both topsoil and subsoil layers (Figure 2). WC of subsoil was higher where greater RMD–SS was found (Table 5). Balanced root distribution (TS:SS) was noted on rye plants, followed by the grassland mix, least was measured on mustard plants (Table 5). This corresponds with the visual assessment of pots where in most cases, mustard roots did not penetrate into the subsoil layer at all (Figure 5). Cover crop that performed the best in preventing the soil surface from drying was the grassland mix (Table 5).

Bulk density significantly influenced the RMD of subsoil and FSD was higher where high BD was applied (Table 6). Soil pH of the topsoil layer was slightly higher in pots with lower BD (Table 6).

Combination of CC and BD variables significantly influenced RMD of both topsoil and subsoil, hence the TS:SS (Figure 3 Figure 4). Mustard resulted in the lowest RMD in general, whereas rye performed the best (Figure 2,

Table 7). High BD of subsoil layer increases the RMD of topsoil in pots with mustard and rye, however decreases the same characteristic in grassland mixtures.

Across all three variables, the most significant dependence was found within the TS:SS ratio, where the least even root distribution (68.6 ± 21.3) was observed on mustard with BD of 1.3 on treatment T3. Best results were obtained on rye with BD of 1.3 on treatment T3 (3.09 ± 0.64), followed by treatments T2 (3.14 ± 0.67) and T1 (7.14 ± 1.36) on the same variables (Appendix A).

Table 4 Root and soil chemistry response to subsoil treatments

	RMD – SS ($kg\ m^{-3}$)	OM - SS (%)	WC – TS (%)	pH - SS	EC – TS ($\mu S\ cm^{-1}$)	EC – SS ($\mu S\ cm^{-1}$)
T1	0.06^{a}(±0.014.5)	4.37^{b}(±0.31)	0.87^{a}(±0.11)	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)	0.90^{a}(±0.07)	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)	0.61^{b}(±0.03)	7.9^{a}(±0.16)	13.8^{b}(±1.70)	21.3^{b}(±2.16)

Mean values ± SE; values within the column followed by the same letter(s) are not significantly different (Fisher LSD p ≤ 0.05); T1=100:0 Subsoil blend with 100 % silt; T2=70:30 with 70 % silt and 30 % overburden; T3=50:50 with 50 % silt and 50 % overburden.

Table 5 Root and soil chemistry response to cover crops

	RMD - TS	RMD - SS	WC - SS	TS:SS	FSD
Grassland	0.66^{b}(±72.2)	0.06^{b}(±7.61)	1.81^{a}(±0.13)	14.5^{a}(±2.93)	2.50^{b}(±0.40)
Mustard	0.19^{a}(±18.9)	0.01^{a}(±2.85)	1.74^{a}(±0.32)	37.9^{a}(±5.49)	4.89^{a}(±0.65)
Rye	0.98^{c}(±90.7)	0.17^{c}(±15.3)	2.86^{b}(±0.39)	7.09^{b}(±1.27)	4.11^{a}(±0.75)

Mean values ± SE; values within the column followed by the same letter(s) are not significantly different (Fisher LSD p ≤ 0.05)

Table 6 Root and soil chemistry response to different bulk densities

	RMD - SS	pH - TS	FSD
BD 1.3	0.09^{b}(±17.2)	5.8^{a}(±0.03)	2.59^{a}(±0.35)
BD 1.5	0.06^{a}(±11.9)	5.9^{b}(±0.06)	5.07^{b}(±0.57)

Mean values ± SE; values within the column followed by the same letter(s) are not significantly different (Fisher LSD p ≤ 0.05)

Table 7 Root and soil chemistry response to cover crops and bulk densities, combined

COVER CROP	BULK DENSITY	RMD - TS	RMD - SS	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)

Mean values ± SE; values within the same column followed by the same letter(s) are not significantly different

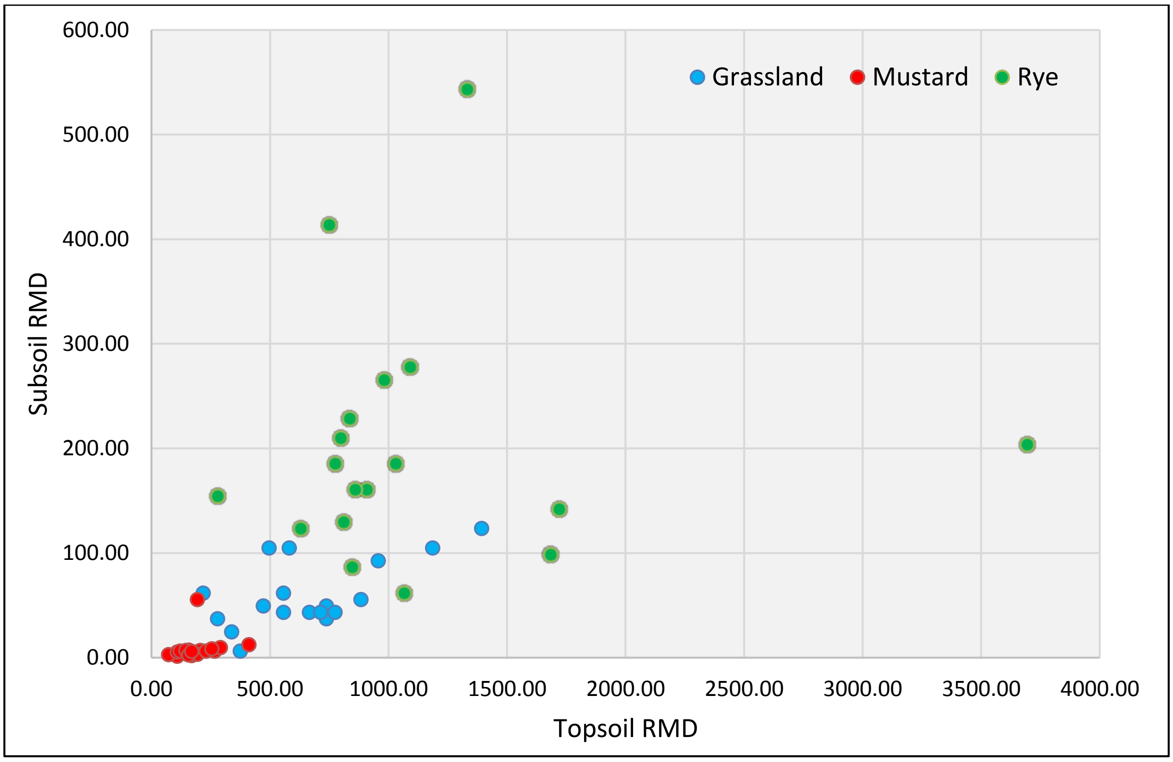

Figure 2 Correlation of RMD (g m^{-3}) of TS and SS

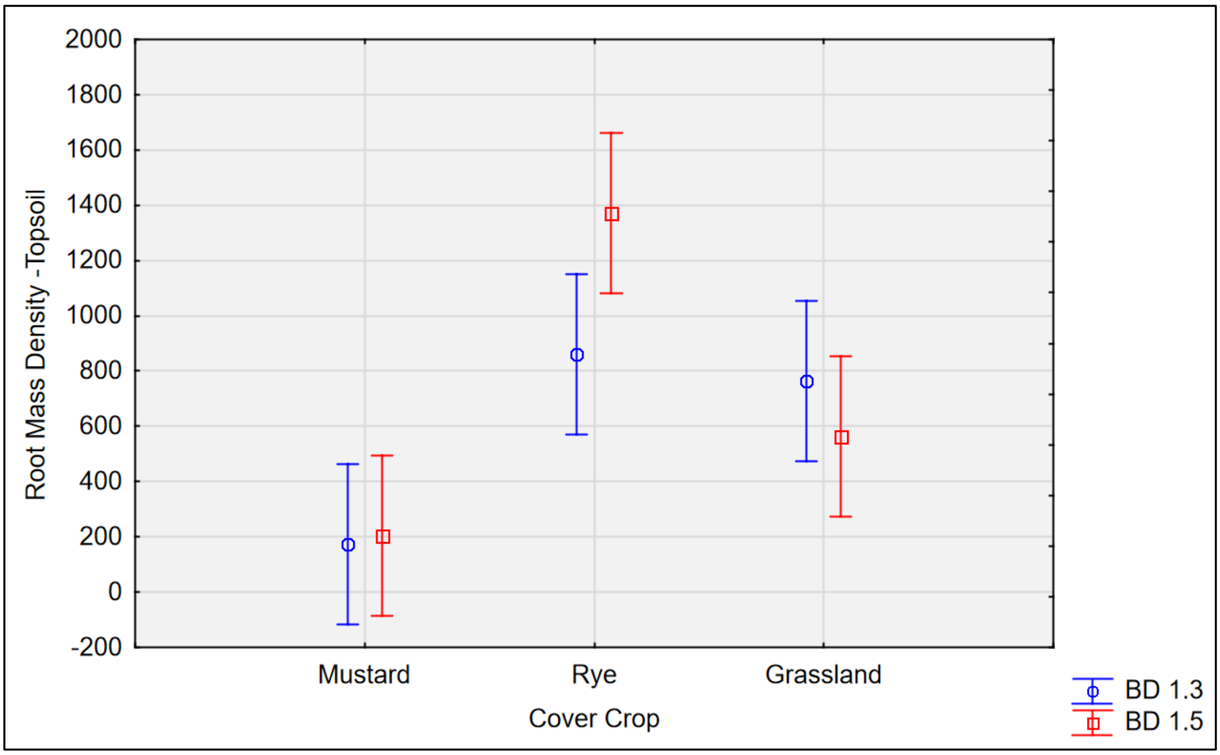

Figure 3 Root mass density (g m^{-3}) of TS - BD*CC significant dependence (Vertical bars denote 0.95 confidence intervals)

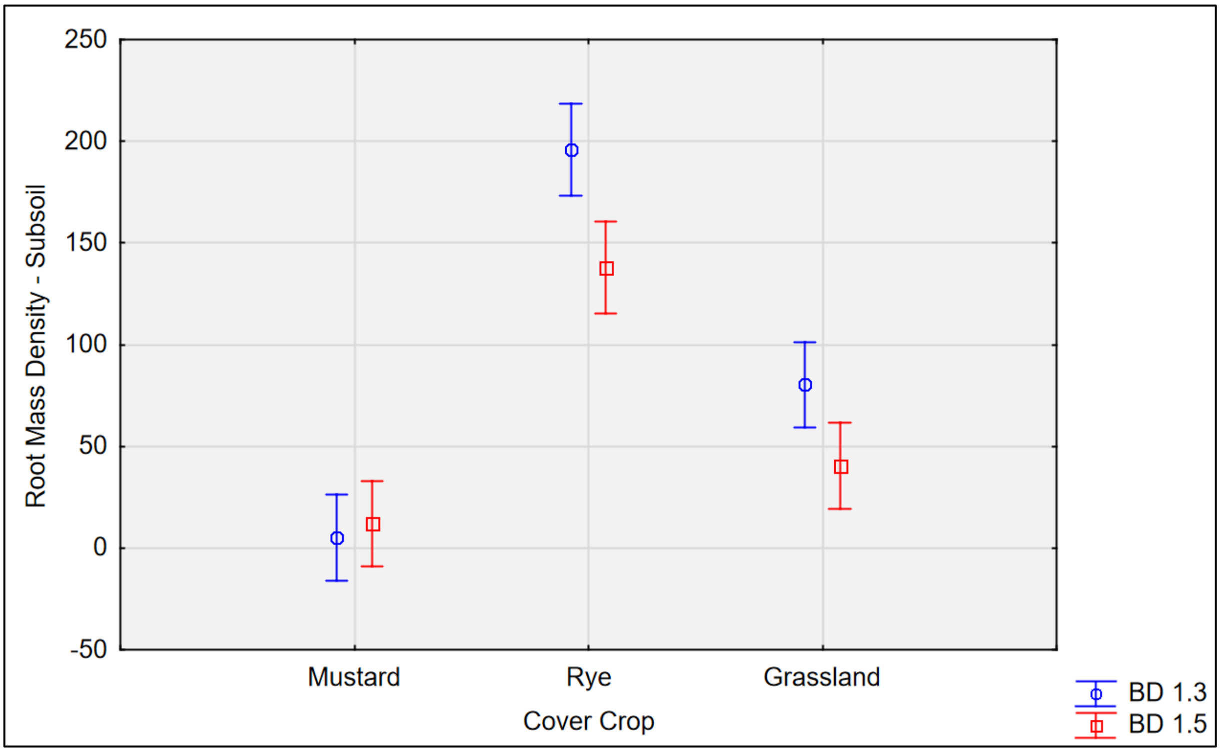

Figure 4 Root mass density (g m^{-3}) of SS - BD*CC significant dependence (Vertical bars denote 0.95 confidence intervals)

3.3 Available N

Cover crops significantly influenced the amount of nitrate (NO_3^-) in both TS and SS, and available N in TS. Different treatments only had effect on the ammonium (NH_4^+). In general, mustard had higher amounts of available N as compared to rye and grass mixture. Treatment T1 had the highest amounts of ammonium (Table 8).

Table 8 Soil N values, significantly dependent ($p \leq 0.05$) on CC and treatments

CC	NO_3^- (mg/kg)		Available N (+) (kgN/ha)	Subsoil treatment	NH_4^+ (mg/kg)
	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)

Mean values ± SE; values within the column followed by the same letter(s) are not significantly different (Fisher LSD $p \leq 0.05$)

3.4 Plant response

First seedlings to emerge were rye, followed by mustard. Tarmac grassland mixture emerged one week after seeding and took approximately two weeks to form some level of soil cover. Mustard buds were visible 30 days into growth (17th July). Average height of Mustard plants in bloom was 38.3 cm. By the end of the experiment, roots of all pot replicates were protruding through the bottom of the pot. In general, roots avoided the subsoil layer by growing in the space between the soil and the pot (Figure 6). Mustard roots were almost always unable to penetrate into the subsoil (Figure 5). Best performance was noted on pots where rye and grass cover crops were used. Grassland seed mixture demonstrated the greatest ability to penetrate through the subsoil layer (Figure 7).

Figure 5 Visual assessment of mustard root development (T3 (50:50), BD 1.5)

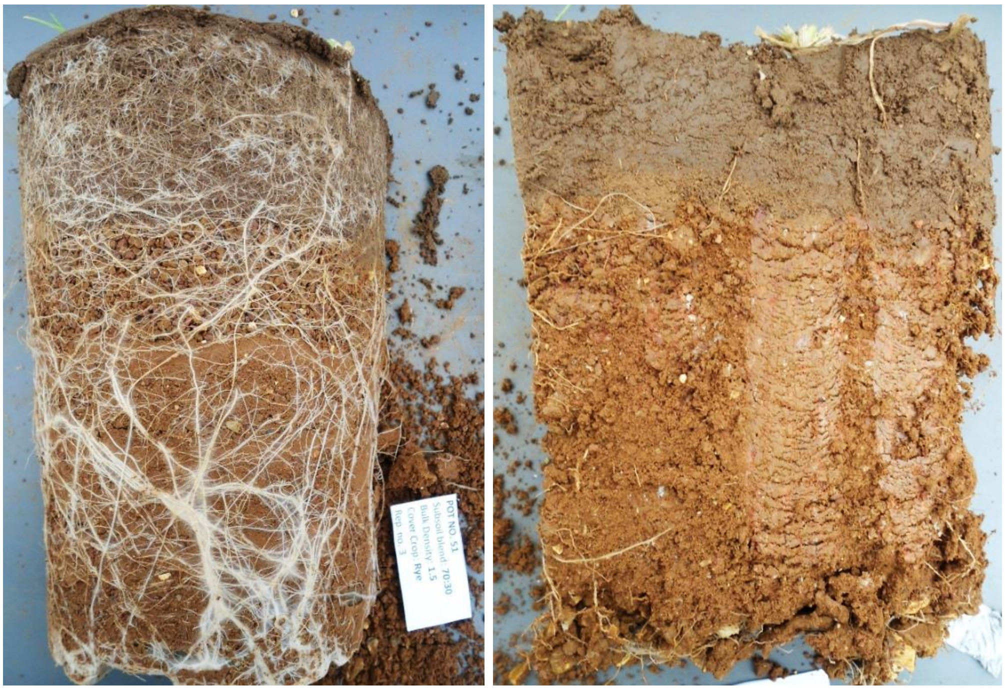

Figure 6 Visual assessment of rye root development (T2 (70:30), BD 1.5)

Figure 7 Detail of root penetration through the subsoil layer – comparison of rye (left) and grassland mix (right) on the same treatments (T3 (50:50), BD 1.5).

3.4.1 Nutrient deficiency

First signs of nutrient deficiency were visible on mustard plants about three weeks after sowing (6^{th} of July 2017). Roughly four weeks into the experiment (12^{th} of July) all mustard plants exhibited serious signs of deficiency. At the same time, rye only started displaying first signs of lack of nutrient. Grassland mixture showed only minor signs of deficiency. At the time of termination of the pot trial, mustard plants were fully exhausted (Figure 8). First nutrient deficiency symptoms indicated nitrogen (N) deficiency (Figure 9). Possible signs of phosphorus (P) and potassium (K) deficiencies on mustard plants followed later (Figure 10).

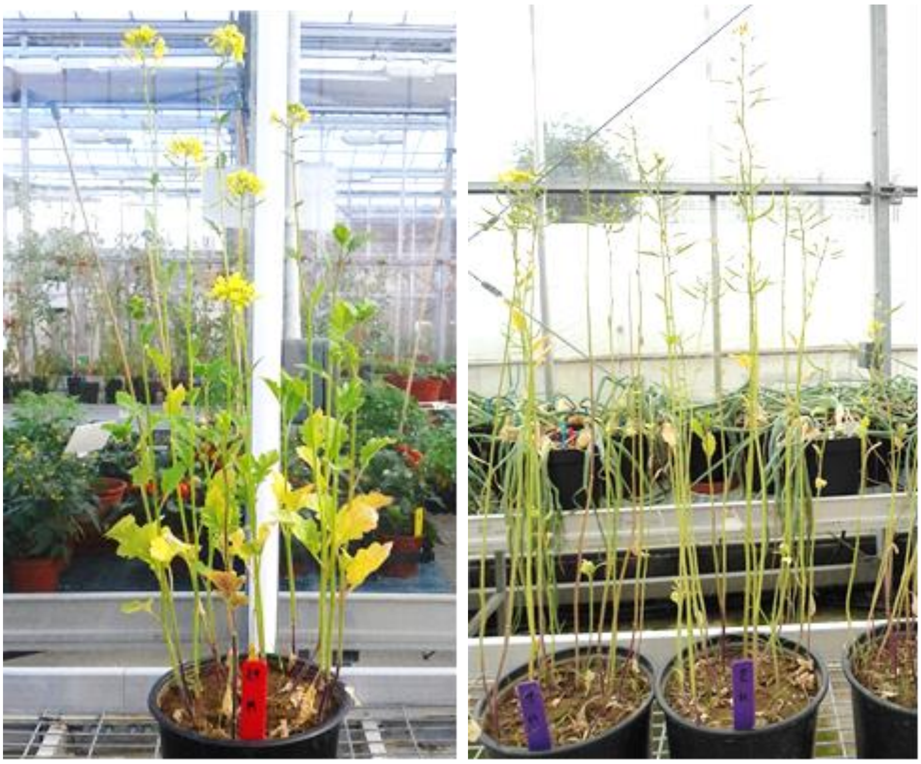

Figure 8 Effects of nutrient deficiency on mustard plants 36 days (left) and 47 days (right) after sowing

Figure 9 Mustard plant showing N deficiency signs – stunned growth and chlorosis on older leaves (27 days) (left) and possible P deficiency signs – purple petioles (35 days) (right) (Kumar and Sharma, 2013; Berry, 2006)

Figure 10 Mustard leaf under possible K deficiency (35 days) (Kumar and Sharma, 2013)

4 DISCUSSION

4.1 Plant response

As stated by Brennan and Acosta-Martinez (2017), frequent cover cropping can have more impact on soil microbiology than using compost, hence this restoration measure can be highly recommended. Cover crops should be selected with special care considering its root growth capabilities, nutrient requirement and pest infestation predispositions.

During the pot trial, mustard plants were affected by various insect species despite being placed in a glasshouse. These were aphids (*Lipaphis erysimi*), mustard leaf miner (*Chromatomyia horticola*) and large white butterfly (*Pieris brassicae*). Other two cover crops had no pest infestation issues. By the end of the pot experiment, roots of all plants were protruding through the bottom of the pot indicating that root growth was restricted, thus roots could not grow up to their potential ability. Mustard resulted in the lowest RMD in general, whereas rye demonstrated the highest RMD values across all three cover crops. High BD increased the RMD of topsoil in pots with mustard and rye, however decreased the topsoil RMD of grassland mixtures. This could be due to the grasses fine root structure, which managed to penetrate into the subsoil layer, hence its root growth was not delimited to the topsoil layer as compared to the rye and mustard. It is important to note that in our pot study, rye roots avoided penetrating the soil by growing through the space around the pot (Figure 6). This is not exceptional as strongly compacted soils are usually only penetrated by roots through cracks and biopores in the soil (Głąb, 2008). This fact has however notably influenced results for the RMD of rye. Vallance and Sonogan (2010) 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. This statement may be of importance in clayey, compacted soils, as were used in our study. Evaluation of the root mass therefore suggests that grassland mixture is the best cover crop option. This is supported by NRCS (2011), claiming that annual and perennial ryegrasses are fast to establish when broadcast, produce great amount of biomass, reduce surface compaction, scavenge nutrients and are also usable as a living mulch. Cresswell and Kirkegaard (1995) also recommend perennial species as those are most effective at biological drilling of subsoil horizons. For example roots of Lucerne, which are extremely fine, can be observed as deep as 2-3 m (Cresswell and Kirkegaard, 1995). Scholefield and Hall (1985) claim that this ability of grasses to penetrate highly compacted soils by becoming constricted can be considered as a compensation of radial pressure. Evidence also suggest that yields of some grasses might be unaffected by compaction (Głąb, 2008; Głąb 2013). Growing rye may however be considered in mixtures with other grass species, or legumes. Rye can also be useful in restoration projects taking place in the summer, 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). As another potential cover crop, NRCS (2011) listed buckwheat, which is one of the fastest growing summer annual plants, tolerating poor soils.

4.2 Soil chemistry

According to results of the particle size distribution, silt contains a large proportion of clay. 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). Based on Hazelton and Murphy (2007) classification of particle fraction contents, T1 clay content can be described as very high (61%), while T3 had a very high silt content (55%). With regards to the highest clay content of T1 (Table 2), the soil organic matter of subsoil was highest in this treatment. T1 and T2 had higher topsoil moisture content, which was probably due to a limited water infiltration into the substrate rich in clay, therefore water remaining mainly within the topsoil layer. T1 also had the highest amount of ammonia, which is again linked to the clay content holding on to nutrients.

In dense soils, pore volume is reduced resulting in less air and less water content in the soil, large pores being completely destroyed and water infiltration reduced, which increases the potential of surface runoff and waterlogging (Wolkowski and Lowery, 2008). Critical bulk density, which is likely to severely affect plant growth and root penetration, is different for different soil textures. For clay loam, the critical value would be higher (BD of 1.6) than for clay (BD of 1.4) (Hazelton and Murphy, 2007). This corresponds with high BD significantly decreasing the RMD of subsoil. Furthermore, higher BD resulted in higher FSD, which suggests that high BD slowed down water infiltration into the soil. In field conditions, high BD of clay soils could result in waterlogging, whereas in a pot trial, water can easily flow in the space between the pot and the soil, therefore smaller amount of water could be trapped within the topsoil layer, resulting in faster moisture depletion in the surface substrate.

Silt used in this experiment had to be processed in order to unify the sampling and growing conditions. However, silt from Blashford quarry contained not only fine particles, but also a coarse fraction of stones and boulders, which is not uncommon for a quarry silt (Harrison et al., 2001). In field conditions, this may positively influence root penetration by creating pores and voids within the clayey substrate.

EC values varied between 9-28 μS cm^{-1}, which is classified as non-saline and is typical for normal surface soils (Hazelton and Murphy, 2007). In regards to the clay content of our subsoil treatments, these values translate as very low with on effect on plants. To accelerate the process of silt-water separation within silt lagoons, some quarries choose to use anionic flocculants (iron and aluminium salts) to help water and silt separation. This could influence EC values of those materials, therefore testing soil for those substances and EC is recommended.

Soil pH may be used as an indicator of suitable grass and crop species (Hazelton and Murphy, 2007). Baize (1993) suggests, that the optimum pH this should be between 6.5 and 7.5. As treatments T2 and T3 resulted in 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, Ni, or Cd (Han, 2007). Mobility of potentially phytotoxic element within the soil also depends on the soil pH (Brady & Weil, 2013). Nevertheless, according to

Hazelton and Murphy (2007), our pH values 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 iron being reduced in pH <7.5, which applies for both T2 and T3.

4.3 Nutrient deficiency

In artificial soils blended with quarry wastes, lack of nutrients should be expected (Mitchell et al, 2004). Nitrogen (N) deficiency was visible on mustard plants as early as 3 weeks into growth. Lack of N is noticeable through retarded growth and changes on leaves. These were first obvious on older leaves owing to nitrogen mobility through the plant, as N is firstly transferred to younger tissues, leaving lower leaves yellow chlorotic, in later stages necrotic (Kumar and Sharma, 2013). This nutrient deficiency was aggravated by buds being visible only a week after. Buds are usually visible after 5 weeks and flowers appear only 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 50-70 cm of height and continues to grow even after that, exceeding 1 m of height. In our case, the average height of mustard plants in bloom was only 38.3 cm 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 an ammonium (NH_4^+) and nitrate (NO_3^-), which is also soluble in water and therefore easily leachable (Hosier and Bradley, 1999). Laboratory results showed that mustard had much higher amount of nitrates in both TS and SS. This suggests that mustard is not effective in scavenging nutrients due to its root structure lacking fine roots. Phosphorus (P) and potassium (K) deficiencies on mustard plants were visible as purple petioles, dwarfed plants (P promotes root development) and marginal and interveinal chlorosis (Berry, 2006; Kumar and Sharma, 2013). Rye and grassland mix were not significantly affected by nutrient deficiencies.

Lack of nutrients should be considered if quarry wastes are to be used as growing media. Results from the research project ‘Minerals from Waste’ suggest, quarry wastes can be successfully used; especially if mixed with a green waste compost (Mitchell et al, 2004).

5 CONCLUSIONS

This study serves as a preliminary assessment of soil structure formation, whether silt, as a waste material derived from sand and gravel processing, could be used as a subsoil medium in cover crop establishment and soil forming process initiation.

Results indicated that silt indeed can be used for this purpose, nevertheless, due to its high clay content, silt blend with some other growing medium is highly advisable. Use of appropriate cover crops is also essential in successful management of soil rehabilitation on newly restored quarry sites.

This experiment has provided a comparison of three cover crop treatments. Contrary to initial beliefs, plants with tap roots performed worst in comparison to grasses with fine roots, hence mustard cannot be recommended as a suitable cover crop for restoration projects where silt is used as a subsoil medium. Both grassland mixture and winter rye performed well, however had different root growth abilities. It can be suggested that improving topsoil/subsoil connectivity could be potentially achieved if used rye and grasses were grown together. Mustard cannot be recommended as a standalone cover crop as it prefers fertile, well drained soils, does not tolerate waterlogging and lacks fine root structure, which is important for nutrient uptake. However, it may be considered as a green manure, to be chopped and incorporated into the few top cm of soil after about 4-8 weeks of growth (Green Manure, 2017). As suggested by Mitchell et al. (2004), blending silt mixtures with green wastes can be recommended in order to prevent any possible nutrient depletion and improve the initial soil structure.

Similar studies should be carried out in order to further investigate long term subsoil and topsoil structural and hydrological connectivity induced by different grass cover crop mixtures. For future studies, growing containers of larger surface area and depth are highly recommended to test silt-cover crop interactions to their fullest potential.

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APPENDICES

Appendix A - Root distribution response

Apx Table 1. Significantly different root distribution across all three variables (treatment, cover crop and bulk density)

TREATMENT	COVER CROP	BULK DENSITY	TS:SS
T1	**Grassland**	**BD 1.3**	10.3[ab](±2.72)
T1	**Grassland**	**BD 1.5**	12.2[ab](±2.40)
T1	**Mustard**	**BD 1.3**	29.8[bc](±4.96)
T1	**Mustard**	**BD 1.5**	41.8[c](±11.8)
T1	**Rye**	**BD 1.3**	9.49[ab](±3.88)
T1	**Rye**	**BD 1.5**	7.14[ab](±1.36)
T2	**Grassland**	**BD 1.3**	8.70[ab](±2.59)
T2	**Grassland**	**BD 1.5**	14.0[ab](±2.23)
T2	**Mustard**	**BD 1.3**	39.3[c](±9.31)
T2	**Mustard**	**BD 1.5**	21.7[abc](±9.23)
T2	**Rye**	**BD 1.3**	3.14[a](±0.67)
T2	**Rye**	**BD 1.5**	11.5[ab](±4.04)
T3	**Grassland**	**BD 1.3**	12.5[ab](±4.39)
T3	**Grassland**	**BD 1.5**	29.3[bc](±16.0)
T3	**Mustard**	**BD 1.3**	68.6[d](±21.3)
T3	**Mustard**	**BD 1.5**	25.8[abc](±5.72)
T3	**Rye**	**BD 1.3**	3.09[a](±0.64)
T3	**Rye**	**BD 1.5**	8.20[ab](±4.49)

Mean values ± SE; Values within the column followed by the same letter(s) are not significantly different (Fisher LSD p ≤ 0.05); T1=100:0 Subsoil blend with 100 % silt; T2=70:30 with 70 % silt and 30 % overburden; T3=50:50 with 50 % silt and 50 % overburden.

Appendix B - Results

Apx Table 2. Laboratory soil and root mass analyses results; excluding results for Soil Mineral Nitrogen (Appendix C)

Pot no.	Subsoil treatment	BD	CC	FSD	Dry weight (g)		RMD (kg m^{-3})		TS:SS	OM (%)		WC (%)		pH		EC (µS cm^{-1})	
					TS	SS	TS	SS		TS	SS	TS	SS	TS	SS	TS	SS
1	T1	1.3	Mustard	2	0.13	0.01	0.16	0.01	21.4	3.31	4.42	0.60	2.17	5.72	5.54		
2	T1	1.3	Mustard	6	0.17	0.01	0.21	0.01	29.5					5.77	6.02		
3	T1	1.3	Mustard	3	0.12	0.01	0.15	0.00	38.6	2.52	3.68	0.60	0.44		5.53	11.6	18.8
4	T1	1.3	Rye	7	0.75	0.26	0.91	0.16	5.66						5.51		
5	T1	1.3	Rye	4	0.85	0.30	1.03	0.19	5.56	3.19	4.83	0.79	6.31	5.81	5.66	7.10	
6	T1	1.3	Rye	5	0.88	0.10	1.07	0.06	17.3	2.71	3.73	1.12	3.67	5.96	5.61		16.0
7	T1	1.3	Grassland	3	0.48	0.17	0.58	0.11	5.54					5.73			
8	T1	1.3	Grassland	3	0.61	0.08	0.74	0.05	15.0	3.25	4.28	1.19	1.79	5.85	5.59		
9	T1	1.3	Grassland	2	0.79	0.15	0.96	0.09	10.3	2.63	3.79	0.20			5.55	6.56	18.1
10	T1	1.5	Mustard	5	0.16	0.01	0.19	0.00	61.5						5.42	9.50	
11	T1	1.5	Mustard	10	0.22	0.01	0.27	0.01	43.1		6.72		1.65	5.66	5.47		
12	T1	1.5	Mustard	7	0.09	0.01	0.11	0.01	20.8		3.52	1.58	0.11	5.68	5.61		21.2
13	T1	1.5	Rye	9	0.71	0.26	0.86	0.16	5.36						5.43	7.67	22.5
14	T1	1.5	Rye	5	0.70	0.14	0.85	0.09	9.81	3.65	5.67	1.12	2.35		5.39		
15	T1	1.5	Rye	7	0.67	0.21	0.81	0.13	6.26	2.53	3.91	0.95	1.87	5.94			
16	T1	1.5	Grassland	3	0.28	0.04	0.34	0.02	13.7						8.07	10.7	
17	T1	1.5	Grassland	4	0.23	0.06	0.28	0.04	7.52	3.43		0.76		6.67	5.50		17.0
18	T1	1.5	Grassland	0	0.55	0.07	0.67	0.04	15.4	2.48	3.54	0.64	2.41	5.80	5.39		
19	T3	1.3	Mustard	3	0.09	0.00	0.11	0.00	88.3						8.07	10.5	16.5
20	T3	1.3	Mustard	2	0.06	0.00	0.07	0.00	26.2		4.15		1.81	5.62	8.07		
21	T3	1.3	Mustard	6	0.14	0.00	0.17	0.00	91.5	2.28	2.28	0.75	1.28	5.70	8.19		
22	T3	1.3	Rye	1	0.66	0.34	0.80	0.21	3.81		2.90		1.51	5.78	8.10		

23	T3	1.3	Rye	2	0.62	0.67	0.75	0.41	1.81	3.63		0.54		5.84	7.63	14.6	17.1
24	T3	1.3	Rye	0	0.69	0.37	0.84	0.23	3.66	2.53	2.40	0.61	2.44		8.08		
25	T3	1.3	Grassland	1	0.61	0.06	0.74	0.04	19.9		5.44		1.94		8.02		
26	T3	1.3	Grassland	2	0.46	0.07	0.56	0.04	12.9	3.55		0.60		6.06	8.04		21.1
27	T3	1.3	Grassland	1	0.41	0.17	0.50	0.11	4.73	2.45	2.25	0.60	1.69		8.06	14.6	
28	T3	1.5	Mustard	1	0.10	0.01	0.12	0.01	19.6						8.10		
29	T3	1.5	Mustard	10	0.19	0.01	0.23	0.01	37.3	3.39		0.55		5.9	8.25		
30	T3	1.5	Mustard	5	0.12	0.01	0.15	0.01	20.6	2.49	2.26	0.46	1.93		8.16	9.44	
31	T3	1.5	Rye	3	0.52	0.20	0.63	0.12	5.10	3.33	4.76	0.78	1.70	6.00	8.05		
32	T3	1.5	Rye	3	1.10	0.88	1.33	0.54	2.45					5.79	8.06		
33	T3	1.5	Rye	3	1.39	0.16	1.68	0.10	17.0	2.34	2.34	0.71	4.14		8.13	12.4	28.3
34	T3	1.5	Grassland	3	0.46	0.10	0.56	0.10	9.02						5.43	21.1	
35	T3	1.5	Grassland	2	0.31	0.01	0.38	0.01	60.8	3.56	3.65	0.52	1.63	5.89	8.01		
36	T3	1.5	Grassland	7	0.64	0.07	0.78	0.04	17.9	2.59	2.17	0.56	1.63	5.88			23.3
37	T2	1.3	Mustard	4	0.13	0.00	0.16	0.00	57.9	3.56	4.82	1.45	3.80	5.73	8.10		
38	T2	1.3	Mustard	2	0.24	0.02	0.29	0.01	30.2					5.66	8.02	8.43	
39	T2	1.3	Mustard	3	0.21	0.01	0.25	0.01	29.8	2.53	3.12	0.83	2.03	5.56			26.9
40	T2	1.3	Rye	1	0.81	0.43	0.98	0.27	3.69	3.61		0.85		5.89	7.88	6.43	
41	T2	1.3	Rye	0	0.23	0.25	0.28	0.15	1.80		4.43		2.53		7.96		
42	T2	1.3	Rye	3	0.90	0.45	1.09	0.28	3.92	2.44	2.86	0.84	3.11	5.69			34.3
43	T2	1.3	Grassland	0	0.18	0.10	0.22	0.06	3.53					5.96	7.94		26.7
44	T2	1.3	Grassland	2	1.15	0.20	1.39	0.12	11.3	3.46	3.46	0.82	2.58	5.66	8.01		
45	T2	1.3	Grassland	2	0.98	0.17	1.19	0.11	11.3	2.43		1.05	1.42		7.97	10.0	
46	T2	1.5	Mustard	9	0.16	0.09	0.19	0.06	3.49	3.36		0.63		5.81	8.02		30.1
47	T2	1.5	Mustard	5	0.34	0.02	0.41	0.01	33.3						8.03	13.0	
48	T2	1.5	Mustard	5	0.14	0.01	0.17	0.01	28.3		3.18	0.96	2.13		8.02		
49	T2	1.5	Rye	8	1.42	0.23	1.72	0.14	12.1	3.60	5.94	0.95	1.93	5.94	7.92		

50	T2	1.5	Rye	2	0.64	0.30	0.78	0.19	4.18					5.91	8.05		
51	T2	1.5	Rye	11	3.05	0.33	3.69	0.20	18.1	2.42	3.09	0.90	2.72			9.08	26.7
52	T2	1.5	Grassland	5	0.39	0.08	0.47	0.05	9.56		4.03		1.33		8.02	14.9	
53	T2	1.5	Grassland	3	0.59	0.07	0.72	0.04	16.5	3.49		0.52		5.95	8.01		22.2
54	T2	1.5	Grassland	2	0.73	0.09	0.88	0.06	15.9	2.40	3.11	1.06	1.69	5.83	7.97		

Appendix C - Soil Mineral Nitrogen

Apx Table 3. Soil mineral nitrogen content

Pot no.	Subsoil treatment	BD	CC	Dry Matter (% w/w)		NO_3^- (mg/kg)		NH_4^+ (mg/kg)		Available N * (kgN/ha)	
				TS	SS	TS	SS	TS	SS	TS	SS
1	T1	1.3	Mustard								
2	T1	1.3	Mustard	84.5		7.61		0.51		30.5	
3	T1	1.3	Mustard		77.7		1.07		1.01		
4	T1	1.3	Rye	91.1		0.28		0.47		2.80	7.80
5	T1	1.3	Rye		82.1		0.08		1.52		
6	T1	1.3	Rye								6.00
7	T1	1.3	Grassland	85.3		0.39		0.84		4.60	
8	T1	1.3	Grassland								
9	T1	1.3	Grassland		81.8		0.07		0.59		
10	T1	1.5	Mustard		80.3		0.47		0.95		2.50
11	T1	1.5	Mustard								5.30
12	T1	1.5	Mustard	88.6		4.78		0.77		20.8	
13	T1	1.5	Rye								
14	T1	1.5	Rye	93.4	85.0	0.96	0.06	0.55	0.50	5.60	
15	T1	1.5	Rye								2.10
16	T1	1.5	Grassland		83.0		0.38		0.84		
17	T1	1.5	Grassland	86.7		0.41		0.74		4.30	4.60
18	T1	1.5	Grassland								
19	T3	1.3	Mustard								
20	T3	1.3	Mustard	85.9	81.1	5.33	0.66	0.67	0.60	22.5	
21	T3	1.3	Mustard								4.70
22	T3	1.3	Rye								
23	T3	1.3	Rye								
24	T3	1.3	Rye	89.2	82.3	2.18	0.06	0.79	0.44	11.1	
25	T3	1.3	Grassland	83.5		0.45		0.97		5.30	1.90
26	T3	1.3	Grassland		80.1		0.47		0.82		
27	T3	1.3	Grassland								4.80
28	T3	1.5	Mustard								
29	T3	1.5	Mustard								
30	T3	1.5	Mustard	86.9	82.0	5.66	0.40	0.54	0.40	23.2	
31	T3	1.5	Rye	83.2	81.6	1.49	0.05	0.65	0.47	8.00	3.00
32	T3	1.5	Rye								2.00
33	T3	1.5	Rye								
34	T3	1.5	Grassland								
35	T3	1.5	Grassland	87.2	82.0	0.69	0.06	1.04	0.34	6.50	
36	T3	1.5	Grassland								1.50

37	**T2**	**1.3**	Mustard		79.3		0.51		0.38		
38	**T2**	**1.3**	Mustard	87.5		4.63		0.78		20.3	3.40
39	**T2**	**1.3**	Mustard								
40	**T2**	**1.3**	Rye								
41	**T2**	**1.3**	Rye	88.0	80.9	2.62	0.07	0.68	0.42	12.4	
42	**T2**	**1.3**	Rye								1.80
43	**T2**	**1.3**	Grassland	84.7		1.09		0.65		6.50	
44	**T2**	**1.3**	Grassland								
45	**T2**	**1.3**	Grassland		81.3		0.07		0.43		
46	**T2**	**1.5**	Mustard	87.5	81.2	7.09	0.63	0.81	0.63	29.6	1.90
47	**T2**	**1.5**	Mustard								4.70
48	**T2**	**1.5**	Mustard								
49	**T2**	**1.5**	Rye		86.1		0.08		0.68		
50	**T2**	**1.5**	Rye	86.4		1.84		0.51		8.80	2.80
51	**T2**	**1.5**	Rye								
52	**T2**	**1.5**	Grassland								
53	**T2**	**1.5**	Grassland	89.9	84.2	0.46	0.07	0.62	0.43	4.10	
54	**T2**	**1.5**	Grassland								1.90

* The available N content (kg/ha) was estimated assuming the 30 cm depth of N profiling