Developing Manufactured Soils for Reclamation of Mined Land in the Boreal Forest Ecosystem

by

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Abstract

The purpose of this study was to manufacture a cover soil that will be suitable to create ‘cover islands’ of native boreal vegetation for reclamation of large mine rock piles generated through open-pit mining activities in the Boreal Shield region north of Lake Superior. Multiple Technosols were manufactured from blends of mill derived organic residuals and finely crushed mine rock. A ten week growth study assessing the performance of the Technosols as growth media for annual ryegrass demonstrated that blends of at least 50% woody residuals and a mixture of finely crushed mine rock could be used to produce a viable growth media. Reclamation plots were constructed in a field setting using two new Technosols manufactured in ratios of 40 and 80% organics using woody residuals and mixed mine rock, applied to 30 or 60 cm depths over a coarse mine rock pile to simulate ‘vegetation islands’. Soil microclimate data and soil pore-water samples collected over one annual cycle demonstrate that increasing organic matter increased soil moisture and concentration of bioavailable plant nutrients. Increasing depth of plots enabled development of a reservoir of available plant moisture below the rooting zone, but did not increase moisture in surface soils. Low survival rates of tickle grass and green alder can mostly likely be attributed to low moisture availability in the surface soils at the time of planting. Technosols composed of 80% woody residuals and deposited to a 60 cm depth could be appropriate for use in reclamation if surface moisture is increased.

Keywords: woody residuals, paper sludge, lysimeters, Technosol, boreal forest, mine rock.

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Chapter 1

1 Introduction

1.1 – Mining & the Use of Cover Soils in Mine Reclamation

The common view of surface mining as damaging to the environment may in part, be attributed to a legacy of environmental neglect. Mining, although detrimental to the environment and to biodiversity, is critical to the economic and social welfare of Canada, with mineral and energy resources constituting more than 30% of Canada's exports (Ontario Mining Association 2013). However, by implementing strategic closure plans that include responsible land reclamation practices, mining companies can substantially minimize negative environmental impacts on mined lands (International Union for Conservation of Nature and Natural Resources *and* International Council on Mining and Metals 2004). Reclaiming mined lands is not only environmentally and socially responsible – it's mandated by the government of Ontario (Mining Act, 2012). Specifically, the Mine Rehabilitation Code, as part of the Ontario Mining Act (2012), states that "All disturbed sites shall be revegetated" and that "The proponent shall restore the site to its former use or condition…" The restoration of mined land can fundamentally be considered an ecosystem reconstruction, with biodiversity and functionality being returned to the disturbed area. Although, the concept of restoration implies reinstating the pre-mining ecosystem, practicalities such as speed of attainment, cost reduction and long-term stability need to be considered in reclamation plans as well (IUC Nature *and* ICMM 2004).

Restoration of the ecological biodiversity and function of mined land commonly begins by returning cover soils to areas that are to be revegetated. Cover soils can provide a suitable substrate for vegetation by increasing organic matter, nutrients and water holding capacity, while re-instating microorganisms that are critical for nutrient cycling (Brown & Naeth 2014). Careful management of soil physical, chemical and biological properties, such as soil pH and fertility, is critical for successful reclamation attempts (Sheoran et al. 2010). Local soils or introduced topsoil are commonly utilized as cover soils in mine land reclamation, however these methods may not be applicable in many circumstances, due to a lack of suitable local substrates, or opposition from stakeholders, and can expand the mine site's industrial footprint considerably. Transportation of cover soils over long distances, from their place of extraction to the mine, increases CO_2 emissions and causes unnecessary disturbance to the ecosystem of origin. An alternative source of cover soils could be found in the by-product of local industry; using these products, mining companies could potentially manufacture a viable soil for use in their reclamation practices in place of traditional methods. Previous studies have investigated the use of industrial waste products as soil amendments (Baker et al. 2011; Beesley & Dickinson 2011; Cohen-Fernández & Naeth 2013; Gagnon & Ziadi 2012; Munksgaard & Lottermoser 2010; Okonski et al. 2003), but less have examined their use for manufacturing a soil (Belyaeva et al. 2012; de Lima et al. 2012; Hafeez et al. 2012; Lehmann & Stahr 2007; Resulović & Čustović 2011; Rokia et al. 2014; Séré et al. 2008).

1.2 – Manufactured Soils

The term 'manufactured soil' has a broad definition that can be extended to include many forms of anthropogenic soils including soils affected by long term industrial processes, agriculture or urbanization (Lehmann & Stahr 2007) or soils which have been constructed purposefully for varying motives (Naeth et al. 2012). Construction of a soil conceptually allows tailoring of soil properties to specific requirements, however construction can be difficult in practice because soil properties are influenced by the nature of the aggregates formed by the biogeochemical interactions in ‘living; soils, a feature that newly manufactured soils initially lack (Paradelo & Barral 2013). Organic material additions or components, such as biosolids, composts, paper and lumber mill wastes, and some inorganic additions such as lime and wood ash can improve specific soil characteristics, provide essential nutrients required for plant growth (Tordoff et al. 2000) and increase organic carbon content essential for microbial metabolic activity (Sheoran et al. 2010; Williamson & Johnson 1991).

1.3 – Barrick Gold Corporation, Hemlo Operations

Barrick Gold Corporation’s Hemlo Operation (Barrick-Hemlo) is located approximately 350 km east of Thunder Bay, Ontario and consists of three sites: David Bell, an underground mine; Williams, an underground and open pit mine, and Newmont/Golden Giant which is currently undergoing reclamation (Barrick Gold Corporation 2013). As the Williams open pit gold mine is nearing the end of its production phase, and thus closure plans are being initiated.

1.31 – Regional Geology and the Native Ecosystem

Barrick-Hemlo operations are located on the Canadian Shield, within the late Archean Hemlo-Heron Bay greenstone belt of the Wawa Subprovince of the Superior Province. The greenstone belt represents an ancient volcanic island arch with the Hemlo deposit located within a metamorphic zone of middle amphibolite facies overlain by meta-sedimentary rocks (Pan & Fleet 1995). The deposit is characterized by dominant potassic, calc-silicate and sulphidation hydrothermal alterations, enriched in arsenic (As), barium (Ba), mercury (Hg), molybdenum (Mo), sulphur (S), antimony (Sb), tellurium (Te), thallium (Tl), and vanadium (V) (Pan & Fleet 1995). Waste rock produced in the open-pit mine has low sulphur content and therefore, there is a low probability of acid mine drainage issues. Any potentially acid generating mine rock will be dealt with separate to the reclamation initiatives outlined in this thesis.

The Boreal Forest ecosystem is dominated by coniferous black spruce (*Picea mariana*), tamarack (*Larix laricina*), balsam fir (*Abies balsamea*), jack pine (*Pinus banksiana*) white pine (*Pinus strobus*), interspersed with deciduous hardwoods of aspen (*Populus* sp.), white birch (*Betula papyrifera*) willow (*Salix* sp.) and alder (*Alnus* sp.) (Elliot-Fisk 1988; Sims et al. 1996; Soja et al. 2007). Native boreal vegetation is adapted to shorter growing seasons and moderate precipitation levels (Molles & Cahill 2008). However, rising global temperatures are predicted to increase the frequency and length of drought periods in this area (Soja et al. 2007). Boreal forest soils are generally classified as shallow Podzols with iron (Fe) and aluminum (Al) being leached from the A horizon, with illuviation into the B horizon (Elliot-Frisk 1988) as it complexes with translocated organic matter, with soluble magnesium (Mg) and calcium (Ca) being removed from both horizons (Larsen 1980). Due to colder temperatures associated with the latitude of the boreal forest, boreal soils have restricted microbiological activity, which limits the effective decomposition of added organic material, resulting in low plant available nutrients and acidic soil conditions (Larsen 1980).

1.32 – Developing Manufactured Soils

The scarcity of suitable local soil material has prompted Barrick to search for alternative sources of cover soils for the extensive mine rock complexes formed on their properties. Barrick-Hemlo is thus supporting research in manufacturing a soil from locally sourced, organic-rich residual materials, that will be suitable for use as growth media for native vegetation to incorporate as ‘cover islands’ for large mine rock piles generated through their open-pit mining. Potential materials for the production of a Technosol for use in mine reclamation at Barrick-Hemlo are finely-crushed, low sulphur mine rock, lumber-mill derived woody residuals, and paper-mill derived primary paper sludge. The crushed mine rock, generated from the open-pit mining activities at the William's mine, can be separated into two subtypes: metasedimentary rock and intermediate volcanic rock. Woody residual materials, comprised of sawdust, bark and off-cuttings of dominantly boreal coniferous trees, was obtained from the (formerly) Domtar, White River Sawmill (White River, ON). Primary paper sludge, a by-product of processing virgin wood fibre, was obtained from the Tembec operations at Terrace Bay Pulp Inc. (Terrace Bay, ON). The objective is to blend these materials, with minimal additional additives to produce a material that will perform as both a cover for the underlying mine rock piles and as a growth medium for the development of a native terrestrial ecology.

As a soil amendment or component, woody residuals (composed of bark, sawdust, and off-cuttings) can greatly increase the organic content of a soil, making them valuable long-term sources of plant nutrients, particularly nitrogen (Sheoran et al. 2010). Smith et al. (1985) found that dry wood residue amendments, admixed in coal mine soils, significantly increased seedling density, canopy cover and plant biomass after two years compared to non-amended soils used for the rehabilitation of mine soils in the northern Great Plains. Paper mill sludge, pulp or biosolids are common soil amendments applied in agriculture (Bellamy et al. 1995; Curnoe et al. 2006; Phillips et al. 1997) and soil remediation (Braun & Beckett 2003; Fierro et al. 1999; Okonski et al. 2003), and recently, has been recognized as a valuable component in Technosol production (Séré et al. 2008). Previous studies have demonstrated that paper mill sludge is effective in reducing transfer of heavy metals from contaminated soil to plants by decreasing their bioavailability (Calace et al. 2000; Calace et al. 2002). With continual applications over several years, papermill biosolids have also been shown to increase crop yield and increase soil organic matter (Gagnon & Ziadi 2012).

1.4 – Objective of the Study

The studies highlighted in this thesis investigate the potential of developing a Technosol for use in mine site reclamation initiatives in the Boreal Forest ecosystem (Northern Ontario, Canada) using lumber-mill derived woody residuals, paper-mill derived primary paper sludge, and finely crushed mine rock as soil components. Chapter 2, a comprehensive literature review on manufactured soils, focuses on development of soil properties influencing fertility, and their application in land reclamation and agriculture. The objective of Chapter 3 is to identify material admixtures that can produce a viable growth medium through a growth study with annual ryegrass (*Lolium multiflorum*). The objective of Chapter 4 is to describe the microclimatological and biogeochemical behaviour of unvegetated manufactured soils in a field setting and relate this to vegetation survival rates.

Chapter 2

2 Manufactured Soils and Amendments in Land Reclamation: A Review

2.1 – Introduction

Reclamation of mined land with the goal of native ecosystem restoration usually starts with returning cover soils to the area to rebuild vegetation diversity and soil function (Brown & Naeth 2014) and, where applicable, to cap and neutralize potential acid generating mine rock. Returning cover soils to mined land provides a suitable substrate for vegetation growth by increasing available organic matter, nutrients and water holding capacity, while re-instating microorganisms that are critical for nutrient cycling (Brown & Naeth 2014). Integrating cover soils also encourages ecological succession toward natural forest more quickly by accelerating the soil formation process which, under natural conditions, can last thousands of years (Scalenghe & Ferraris 2009). A non-traditional method, little investigated in regards to land reclamation, is the use of manufactured or anthropogenic soils as covers. Previous studies have investigated manufactured soils in urban settings and for agricultural use, but few have studied the use of manufactured soils for land reclamation purposes. Recently, industrial and community wastes and by-products have been recognized for their potential as soil amendments (Baker et al. 2011; Beesley & Dickinson 2011; Brown & Naeth 2014; Cohen-Fernández & Naeth 2013; Gagnon & Ziadi 2012; Munksgaard & Lottermoser 2010; Okonski et al. 2003) and recently in Technosol production (Hafeez et al. 2012; Resulović & Čustović 2011; Séré et al. 2010).

This literature review explores the potential for use of manufactured soils for boreal forest ecosystem reclamation, and post-mining activities. The manufactured soil must perform as a cover, for mine rock produced in open-pit mining activities on the Boreal Shield region of Northern Ontario, and as a growth medium for the development of a native terrestrial ecology.

2.2 – Basic Concepts & Definitions

2.21 – Reclamation, Restoration, Rehabilitation & Remediation

Within the field of restoration ecology there is currently no set definition of reclamation, restoration, remediation and rehabilitation, with the terms often used interchangeably, and whose use often varies by country. Terms are defined for clarity's sake, and will be applied as defined for the remainder of the thesis.

Restoration

Cooke & Johnson (2002) stated that restoration refers to reestablishment of the original ecosystem with all structural, functional aspects; however the Society for Ecological Restoration Primer on Ecological Restoration states that an ecosystem has been restored when it "contains sufficient biotic and abiotic resources to continue its development without further assistance or subsidy… [can] sustain itself structurally and functionally… demonstrate resilience to normal ranges of environmental stress and disturbance …interact[s] with contiguous ecosystems in terms of biotic and abiotic flows and cultural interactions" and that "ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Aronson 2004). True restoration to the pre-mining ecosystem is almost always unattainable, however using the original ecosystem as a model for reclamation, and by focusing on re-establishing the land's capacity to capture and retain fundamental resources (energy, water, nutrients, and species), mined lands can approach pre-mining conditions (Cooke & Johnson 2002).

Rehabilitation

Rehabilitation also focuses on the pre-existing ecosystems as a model for recovery, however rehabilitation emphasizes the reparation of ecosystem processes, productivity and services, and not on the re-establishment of ecosystem community composition and structure (Aronson 2004).

Reclamation

Reclamation is a term more commonly used in the mining community, and is considered the general process whereby mined lands are manipulated to enable some form of beneficial or purposeful use (Cooke & Johnson 2002; SER 2014) whether that be ecological, agricultural, or recreational and has previously been defined as "the making of land fit for cultivation" (OED 1971).

Remediation

The term remediation is far less specific to ecological processes or recovery and is focused on environmental clean-up by removing, or neutralizing substances or wastes from a site to prevent or minimize any adverse effects on the environment (Environmental Protection Division 2011).

2.22 – Anthropogenic Soils: Anthroposols, Anthrosols & Technosols

Manufactured soils are blends of soil, soil constituents and other materials that allow for tailoring of soil properties to specific requirements. However, these materials initially lack an aggregated soil structure which will form as the soil ages and/or matures, which can make tailoring a soil for specific properties difficult (Paradelo & Barral 2013). The term ‘manufactured soil’ has a broad definition that can be extended to include ‘anthropogenic’ soils (Lehmann & Stahr 2007) depending on the specific end use of the soil. The first known reference to anthropogenic soils was made by Ferdinand Senft in 1847 when describing soils in urban, industrial and mining environments (Lehmann & Stahr 2007), but was first included in a soil classification system by Dokuchaev who recognized a class of ‘cosmopolitan’ soils in 1896 (Basinski 1959). Anthropogenic soils have been modified, altered or constructed by human activity and as a consequence, have altered pedogenic trajectories from soils formed entirely by natural processes (Naeth et al. 2012). Intensifying urbanization and resource and industrial development is creating and expanding existing areas of anthropogenic soils. These soils may develop as a consequence of indirect anthropogenic activity or may be purposefully constructed or altered to fulfill varying objectives.

Anthroposols. Anthroposols are a soil order recognized by the Australian Soil Resource Information System (ASRIS) and by the French Soil Reference System (FSRS) (Naeth et al. 2012) but remain unrecognized in the World Reference Base (WRB) by the International Soil Reference and Information Center (ISRIC) and by the Food and Agriculture Organization (FAO) (IUSS Working Group WRB 2007). Key criteria in identifying an Anthroposol, as defined by ASRIS, are the presence of artefacts (solid or liquid substances that are created or modified by humans through industrial or artisanal manufacturing process) in the soil profile, or knowledge that the soil parent materials have been made or modified by human action (IUSS Working Group WRB 2007). Anthroposols are currently a proposed order for human modified soils in Canada and are defined as soils having one or more of their natural horizons removed, replaced, added to, or significantly modified by human activities (Naeth et al. 2012). These soils can be constructed deliberately to fulfill soil-oriented purposes or to fulfill some other purpose such as waste burial on landfill sites and may contain artefacts. This proposed Anthroposolic soil order encompasses the WRB recognized soil orders, Anthrosols and Technosols.

Anthrosols. Anthrosols are formed or profoundly modified through long-term human activities. Naeth et al. (2012) simply describe anthrosols as “cultivated soils profoundly influenced by long-term human activity”, specifically citing agricultural use as the main anthropogenic disturbance to these soils. The International Soil Reference and Information Centre (ISRIC) describes Anthrosol formation as a result of long-continued ‘anthropedogenic processes’, citing deep working, intensive fertilization with organic or inorganic fertilizers (without substantial additions of mineral matter), continuous application of earth (sods, sand, earthy manures), irrigation adding substantial quantities of sediment, and wet cultivation involving pooling on the surface soil as outstanding examples of these influences. The Anthrosol parent material can consist of virtually any type of soil, being most abundantly found in areas where pre-existing soils were unsuitable for agriculture (IUSS Working Group WRB 2007).

Technosols. Technosols are soils strongly influenced by human-made material and contain significant amounts of artefacts (IUSS Working Group WRB 2007). The FAO (2006) define Technosols as a soil “whose properties and pedogenesis are dominated by their technical origin.” Strictly defined, a Technosol must have 20% or more (by volume or weighted average) artefacts in the upper 100 cm from the soil surface (or a cemented or indurated layer, whichever is shallower); or a continuous, very slowly permeable to impermeable, constructed geo-membrane of any thickness starting within 100 cm of the surface; or technic hard rock starting within 5 cm of the soil surface and covering 95% or more of the horizontal extent of the soil (IUSS Working Group WRB 2007). These soils can be manufactured for a specific purpose and mostly occur in urban and industrial areas. Certain components of Technosols, such as those resulting from, or being by-products of, industrial processes, have a high risk for toxicity and should be tested before use in environmental applications.

2.23 – Organic Wastes as Components of Manufactured Soils & Soil Amendments

Wastes produced by industry, municipalities and households - woody residuals, paper sludge and pulp, sewage sludge, and municipal solid wastes – can contain a substantial amount of organic material that can be used to return essential plant nutrients to soil (Nason et al. 2007). The addition of soil amendments to post-mine soils can help develop soil structure, and can restore hydrological balance and mineral nutritional capacity (Wong 2003). The effect of a soil amendment will vary with amendment type, with the interaction with the remaining soil environment, including both biotic and abiotic characteristics (Wong 2003). Many soil amendments can also be used to manufacture a soil. In most cases, soil amendments or components can be classified as organic or inorganic. Organic components or amendments can improve specific soil characteristics, provide essential nutrients required for plant growth (Tordoff et al. 2000), increase organic carbon content essential for microbial metabolic activity (Sheoran et al. 2010; Williamson & Johnson 1991), improve water holding capacity and resistance to compaction (Francou et al. 2008; Paradelo & Barral 2013; Soane 1990). According to Soane (1990) organic matter increases the elasticity and resistance of the soil to deformation, which reduces compact-ability. Further, organic matter favours aggregation which in turn increases porosity and decreases bulk density. These effects could be beneficial when amending a soil that has been severely physically degraded, such as mine degraded soils, or when used in manufacturing a soil with highly compactable, inorganic materials. Inorganic amendments can include fertilizers, vermiculite, or gravels and are commonly designed to meet plant nutritional requirements or to improve physical or hydrological properties (Babalola & Lal 1977).

Composts

Composts are essentially a mix of decaying organic matter that can be composed of a multitude of different materials, such as leaves, decomposing vegetation, and or kitchen wastes. These materials are classified as compost because they have undergone the decaying or decomposing process. Compost can be produced using an in-vessel system from biodegradable wastes such as green waste, tertiary treated sewage sludge, and de-inking paper fiber and waste soil (Nason et al. 2007). Most composts contain more phosphorus than nitrogen, so an application slow release mineral N fertilizer within the first year of compost use may be necessary. In reclamation studies using composted waste materials Nason et al. (2007) observed increased biodiversity with an application rate of 500 wet t ha^{-1}, providing 2,100 kg total N ha^{-1} with a maximum of 100 kg N ha^{-1} being immediately available, and 80 kg plant available P ha^{-1}.

Woody residuals

Woody residuals (or “wood waste”) include bark, wood chips, sawdust, and off-cuttings. As a soil amendment or component, woody residuals can greatly increase the organic content of a soil, making them valuable long-term fertilizers, as well as sources of slow release nitrogen (Sheoran et al. 2010). Major sources of woody residuals include municipal solid waste, construction and demolition debris, primary timber processing mill and logging residuals (McKeever 2003). Smith et al. (1985) found that woody residue amendments significantly increased seedling density, canopy cover and plant biomass after two years compared to non-amended soils used for the rehabilitation of mine soils in the northern Great Plains. Brown & Naeth (2014) demonstrated that the use of woody debris in the reclamation process of a mine disturbed forested ecosystem resulted in lower soil available nitrate, and higher volumetric water content when compared to control treatments without woody debris.

Paper Sludge and Pulps

Paper mill sludge and pulp are common soil amendments often applied in agriculture (Bellamy et al. 1995; Curnoe et al. 2006; Phillips et al. 1997) and soil remediation (Braun & Beckett 2003; Fierro et al. 1999; Okonski et al. 2003), has been recently recognized in Technosol production (Séré et al. 2008). Pulp and paper mill primary sludge are primarily composed of wood fibers as the organic component, and may contain some inorganic papermaking fillers, pitch or wood resin, lignin by-products, inert solids rejected during the chemical recovery process, and ash (Ochoa de Alda 2008). The amount of primary sludge produced by mills will vary, as will the composition of the sludges they produce, even if the same pulp and paper manufacturing process is employed (Scott & Smith 1995). Previous studies have demonstrated that paper mill sludge is effective in reducing transfer of heavy metals from contaminated soil to plants through conversion of metals to less bioavailable form (Calace et al. 2000; Calace et al. 2002). With continual applications over several years, paper-mill biosolids were also shown to increase crop yield and soil organic matter levels (Gagnon & Ziadi 2012).

Green waste

Green waste is a biodegradable waste that has not yet been composted, or started to decay or decompose to a great degree. Green wastes mostly consist of yard wastes such as grass or mixed herbage cuttings, weeds, leaves, dead plant material and soil-bound roots (NAWDO 1998). Several studies have demonstrated the benefits of integrating different kinds of composted organic wastes into growing media to promote plant growth. Composted green waste was shown to be equivalent or superior to peat when used at a rate of 50% with perlite (Hartz et al. 1996) and can thus successfully replace peat in vermiculite-peat mixes at rates up to 30% by volume (Bugbee & Frink 1989). However, Hartz et al. (1996) warned that composted green waste is not homogeneous, thus requiring standard evaluation procedures to determine the appropriate end us for a specific composted green waste.

Sewage sludge

Sewage sludge is a product of waste water treatment – depending on the amount of treatment and collection area, different sludges will be produced. Tertiary treated sewage sludge, having undergone more intensive treatments to reduce contaminants and possible toxicity issues, is most often used in land application (Nason et al. 2007). However, sewage sludge may contain significant amounts of endocrine disrupting chemicals that cannot be removed in the treatment process. Sewage sludge has a high content of both organic matter and nutrients, with a large portion of the contained nitrogen and phosphorus in slow release forms (Nason et al. 2007).

Municipal Solid Wastes

Municipal solid wastes are solid wastes generated within a municipality by commercial establishments and households, and are normally collected by the local governing body. Environment Canada states that “MSW refers to recyclables and compostable materials, as well as garbage from homes, businesses, institutions, and construction and demolition sites.” Guidelines set out by Environment Canada also states that approximately 40% of the residential waste produced in Canada is organic and biodegradable, and can therefore be diverted to produce composts or renewable energy. However, some of the components of MSW can contain high amounts of heavy metals – household dust, batteries, disposable household materials, plastics, paints, inks, bodycare products and medicines are household derived products that may be of concern (Smith 2009). Nine years after applications of MSW at rates of 20 and 80 t ha^{-1}, an increase of 10 and 46% in microbial biomass carbon was observed. However, MSW treatments also yielded a low ratio of the soil microbial carbon to soil organic carbon, an indication of metal pollution (Garcia-Gil 2000). In a two-year field trial, Crecchio et al. (2001) demonstrated that MSW compost amendments increased the organic C and total N contents as well as dehydrogenase and nitrate reductase activities of soil. As well as increasing carbon and nitrogen content of soils, MSW compost may also positively influence the yield of certain crops. Convertini et al. (1998), for example, demonstrated that applications of MSW compost increased grain yield of durum wheat.

Biochar

Biochar is a charcoal-like product manufactured through the pyrolysis of biological residues (Beesley & Dickinson 2011). Biochar applications have been shown to improve the fertility of acidic, sandy textured soils by increasing soil pH, soil organic carbon content, and total Ca, K, Mn and P content (Novak et al. 2009). Laird et al. (2010) demonstrated reduced nutrient leaching following biochar application to highly weathered tropical soils. Biochar may also represent a possible carbon sink and enhance carbon storage in soils (Lehmann 2007).

Selecting Appropriate Soil Amendments

When selecting amendments it will be critical to not only look to the literature for guidance, but to also conduct independent analysis of potential materials to determine the appropriateness of an amendment or component for the use in mind. It is sensible to keep an open-mind about the possible uses and limitations to certain soil amendments and manufactured soil components. Published studies frequently demonstrate the beneficial applications of soil amendments, but the reader should be aware that negative results or failed studies have most likely also occurred when using similar amendments and are not always publicized to such a great extent.

2.3 – Soil Properties & their Management

The process of manufacturing a soil allows tailoring of soil properties to meet specific requirements. If the soil is to be used in ecosystem restoration initiatives, the soil can be constructed to reflect the soils of the native ecosystem. This ideal may be difficult because soil properties are influenced by the aggregated structure of soils, which manufactured soils or Technosols initially lack (Paradelo & Barral 2013). Most essentially, a healthy soil will contain sufficient plant available macronutrients and micronutrients, as well as a community of active microorganisms that will promote nutrient cycling within the soil. Soil physical properties, such as structure and texture will affect the water holding capacity of the soil and other parameters critical to plant health. Ideally, soil constituents mix in a manner that induces soil particles to aggregate into a “crumb” structure with air spaces between, from which roots can obtain gas and water. For successful establishment and growth of vegetation, the manufactured soil should be tailored with soil fertility properties as the foremost consideration. This is especially true for boreal forest species that are adapted to the shallow, acidic and generally infertile soils of the boreal shield region and on more fertile soils boreal plant species can be out-competed for resources by faster growing, competitive plant species. Vegetation may also influence specific soil properties. Hakkinen et al. (2010) noted that stands of Scots pine located in the boreal vegetation zone of Finland increased soil C:N ratio of the organic layer by decreasing the nitrogen concentrations in the soil in close proximity to trees. Roots of vegetation may also promote the ‘tonguing’ of overlaying soil horizons into those below, a feature commonly observed in the Ae horizons of Luvisolic and Podzolic soils.

2.31 – Chemical Properties

Soil pH

Soil pH inpacts soil nutrient availability and effects possible metal toxicities, and is a critical factor in controlling which plant species will establish successfully (Nason et al. 2007). For example, phosphorus is most available between pH 6 and 7 (Nason et al. 2007), and becomes fixed at more acidic pH by iron minerals that adsorb water soluble P (Sheoran et al. 2010). Some metals, such as aluminum, are more soluble under acidic conditions, and may become phytoavailable at toxic levels (Barceló & Poschenrieder 2003; Kochian 1995; Sheoran et al. 2010). The balance between decomposer communities is also affected by soil pH. Rousk et al. (2009) found a five-fold decrease in bacterial growth with a corresponding increase in fungal growth when pH was reduced from 8.3 to 4.5. Below pH 4.5 there was universal inhibition of all microbial decomposers.

If acidic soils are desired, pH is commonly lowered through the addition of elemental sulphur (S^o) (Attoe & Olson 1966). However, other amendments shown to lower pH are sulphurous waste products, iron- and aluminum-sulphate, and bracken or pine chip material (Mari et al. 2005; Owen et al. 1999; Roig et al. 2004). However, land application of S^o has been shown to take up to 5 years before the pH reduction occurred on a sandy arable soil (Critchley et al. 2002).

An increase of soil pH may be necessary with lime most commonly being used in reclamation. Lime application was as key component in the success of the reclamation of the Greater Sudbury area (Gunn 1996). Organic residuals provide a high buffering capacity that can increase the pH of acid soils (Nason et al. 2007). Lime stabilized sewage sludge, de-inking paper fiber and construction residuals have also been observed to mitigate soil acidity (Nason et al. 2007). When adjusting soil pH, preliminary trials should be conducted to provide an understanding of the rate and magnitude of pH change and altered availabilities of metals and nutrients.

Soil Fertility

When manufacturing a soil it can be a challenge to develop a fertile, functional soil where nutrients are recycled between plants and soil through a healthy microbial population. Initially when trying to establish vegetation on manufactured soils that are high in organic residuals, nitrogen will most likely be the limiting nutrient, with phosphorus being commonly available in excess when compared to natural soils (Nason et al. 2007). The long term productivity of the system depends on the accumulation rate of soil organic matter, maintaining nitrogen-fixing vegetation and the establishment of an organic-phosphorus pool while avoiding phosphorus fixation (Daniels 1999; Ghose 2005). Maintaining plant available phosphorus in mine spoils is difficult however, because fresh mine spoils are generally low in water soluble phosphorus and as they weather and oxidize they become rich in Fe-oxides that adsorb water soluble phosphorus (Sheoran et al. 2010). By adding organic amendments that have an organic-phosphorus reservoir and a source of slow release nitrogen the conditions of pre-existing soils can be improved. Soil fertility can be improved by mixing high nutrient residuals with low nutrient residuals, incorporating soil-forming material with pre-existing nutrient poor soils. A healthy soil will contain sufficient plant available macronutrients (nitrogen, phosphorus, sulphur, calcium, magnesium and potassium) and micronutrients (iron, manganese, boron, copper, zinc and molybdenum). Micronutrients are required by plants in lesser amounts, with select elements (aluminum, manganese, copper, zinc and lead) severely limiting plant growth when found in excess concentrations in solution (Bradshaw & Chadwick 1980). Although a soil may contain adequate total amounts of plant nutrients, they may be strongly bound in the soil matrix, rendering them inaccessible for plant up-take through the root. Components of the soil that are soluble or loosely adsorbed are more available for plant uptake (Kabata-Pendias 1993). Soils may contain an excess of macronutrients in a bound, unavailable form that may, through weathering and decaying processes, enable a fraction of these nutrients to continually become available. When determining potential toxicities and nutrient availability, Nason et al. (2007) caution against using total soil metal and nutrient concentrations and suggest using phytoavailable concentrations instead. Simple single step extractions using an ion exchange mechanism are commonly used to determine phytoavailable soil fractions (Abedin et al. 2012; Pueyo et al. 2004; Ure 1996; Wang et al. 2004). Additionally, chemical determinations of the soils must be conducted after blending because the complex interactions of the individual components will likely not remain proportional to characteristics of the parent materials after mixing (Nason et al. 2007).

The Nitrogen Cycle

Nitrogen (N), an important component of protein, is often the limiting nutrient in soils. Although some organic soil constituents will contain nitrogen (Nason et al. 2007), it typically is not a component of soil parent material, but rather is supplied to the soil from the atmosphere. Nitrogen-fixing microorganisms, most notably the bacterium *Rhizobium*, which is symbiotically associated with roots of leguminous plants, can reduce atmospheric nitrogen (N_2) to ammonium (NH_4^+) (Zahran 1999). Otherwise, organically sourced nitrogen is converted to ammonium (NH_4^+) by decomposers (Sheoran et al. 2010). The nitrogen from ammonium is utilized by nitrifying microbes, which convert NH_4^+ to nitrite (NO_2^-) which is then converted to nitrate (NO_3^-), the form of nitrogen which is utilized by plants (Sheoran et al. 2010). However, the oxidation of soil nitrogen to NO_3^- may be impeded in acidic soils, which are common in the boreal forest ecosystem. As well, a freshly manufactured soil is likely to be depleted in nitrogen until soil microorganisms responsible for decomposing and cycling nutrients are established and the nitrogen cycle is re-instated (Nason et al. 2007). During vegetation establishment, N fertilizer addition may be required in small, frequent intervals to compensate for the N that is naturally leached from the soil or unavailable in stable organic forms. If soil constituents or amendments are stock piled for extensive periods of time before use, anaerobic conditions will develop below about 1m depth. Under such conditions, an accumulation of ammonium may occur (NH_4^+). When stockpiles have been applied and aerobic conditions reinstated, ammonium can be rapidly transformed to nitrate (NO_3^-) and lost from the soil with the labile organic-N (Davies et al. 1995). During the first two years following reclamation of surface mined soils which had been stockpiled for twelve years, Davies et al. (1995) reported that nitrification rates were lower in reclaimed sites than those in undisturbed sites. After two years fluxes of N in reclaimed sites had returned to levels similar to those in undisturbed sites (Davies et al. 1995). This re-establishment period may be prolonged in areas where the rate of decomposition is retarded or where metal contamination is an issue. The organic soil constituent or amendment will also influence the nitrification rate. Elkins et al. (1984) demonstrated that mine spoils amended with bark rather than topsoil alone, significantly increased soil microbe activity, which in turn, subsequently increased decomposition rat. However, bark amendments also resulted in less available nitrate (NO_3^-) than in spoils which were not amended.

The amount of nitrogen compared to carbon present in a soil is known as the carbon:nitrogen ratio, and also influences soil fertility. Nitrogen is largely present in the soil in organic forms ($R–NH_2$) which are stable and unavailable for uptake by plants. These organic materials are decomposed by soil microbes and fungi which require carbon and nitrogen for metabolic activity (Reichle 1977). Decomposition rates, and subsequently rates of mineralization, immobilization and nitrification, may be N limited if C:N ratio is above 20, and C limited if the ratio is too far below 10 (Bengtsson et al. 2003). Additionally, if soil C:N ratios are too low, much of the excess nitrogen will be lost from the soil via leaching of ammonium (NH_4^+) before it can be converted to nitrate (NO_3^-) and assimilated by plants.

2.32 – Physical Properties

The physical properties of soil will affect almost all other aspects of that soil, including the performance as a growth medium. Soil aggregation influences gas diffusion and porosity; texture influences water holding capacity; compaction influences rooting depth of vegetation. Soils can be composed of a range of materials, each influencing soil physical properties in unique ways.

Soil Texture

Soil texture is an estimate of the relative amount of sand (2.0 - 0.05 mm), silt (0.05 - 0.002 mm), and clay (< 0.002 mm) sized particles in a soil. Gravel sized particles (>2mm) can also be present in a soil, but are not used to determine texture. Soils dominated by sands and gravels will be well drained, but will often have very little nutrient and water holding capacity (Nason *et al*. 2007). At the opposite end of the spectrum, soils dominated by clays will have large nutrient supplies, but limited drainage. Silts are finer textured soils are prone to forming surface crusts

(Sheoran et al. 2010) which reduces water and air infiltration. Loamy textured soils have an ideal particle size distribution (Sheoran et al. 2010) as they combine the favourable characteristics of each sand, silt and clay. Loams contain more nutrients than sandy soils, have better drainage and infiltration than silts, and are easier to till than clay soils.

Soil Aggregation

Soil aggregates are groups of soil particles that bind together more strongly than to adjacent particles, creating pore space between for retention and the exchange of air and water (USDA 1996). Ideally soil constituents mix in a manner so that soil particles are aggregated into a "crumb" structure with spaces between them filled with air, gas and water that plant roots may access. Optimum conditions have a large range in pore size distribution including large pores between aggregates (macro-aggregates) and smaller pores within aggregates (micro-aggregates). Macro-aggregate stability determines macro porosity which affects soil drainage rate and aeration (Sheoran et al. 2010), while micro-aggregate stability is responsible for crumb porosity which determines the amount of water available for vegetation (Davies & Younger 1994).

Soil aggregation controls the soil hydrology and affects soil gas diffusion, but as layers of soils are removed and transported for use elsewhere, compaction will reduce water holding capacity and aeration (Sheoran et al. 2010).

Soil Moisture

Soil particles > 10 mm diameter do not provide capillary water holding capacity, whereas particles < 2 mm provide good capillary water holding capacity. The ability of a soil to retain water is important not only to limit potential drought, but to minimize mineral leaching, most notably that of N. Moisture content of a soil is influenced by stone content, amount of organic carbon, and the texture and thickness of litter layers (Sheoran et al. 2010). Organic content will heavily influence soil moisture content. Hudson (1994) found that, within all textural groups, as organic matter increased from 1 to 3% by in volume the available water capacity approximately doubled. Soil moisture also influences CO_2 fluxes and respiration in soil. Although variation in respiration is mostly explained by soil temperature, respiration has also been shown to be negatively correlated to soil moisture and temperature (Davidson 1998).

Bulk Density

Bulk density, expressed as g/cm^3 or Mg/m^3, is a measure of soil dry weight over soil volume. Bulk density can be used as an indicator of soil compaction and is dependent on soil texture and the composition (percent sand, silt, clay, organic matter, etc.) of the soil, and on the aggregation of the soil particles. Soils with a higher percentage of sand generally have a higher bulk density, while soils with more organic matter have a lower bulk density. The bulk density of most productive natural soils ranges from 1.1 to 1.5 g/cm^3 (Sheoran et al. 2010). High bulk density indicates low soil porosity and increased soil compaction which, in turn, can restrict root growth and limit air and water movement through the soil. Reducing water infiltration by compaction can cause increased runoff and erosion. Highly compacted soils (especially shallow soils common to surface mined sites) do not have the capacity to hold enough plant-available water to sustain healthy plant communities (Sheoran et al. 2010). When applying soils for reclamation, consideration should be given to material loss and increases in bulk density as settling and organic matter degradation occur. Séré et al. (2010) counter intuitively found that bulk density was lowered as their Technosol settled. Within the first 3 years after application, mature compost may lose up to 20% of its mass and unstable compost may lose up to 30% (Nason et al.

2007), observations which could account for lowered bulk density of Technosols several years after application. In general, when remediating brownfield sites and quarries, 20 cm of soil has been an acceptable rooting depth for grasses and trees to provide adequate water, however, this will be greatly influenced by particle size, moisture retention and nutrient status of the specific soil (Nason et al. 2007).

2.33 – Biological Properties

Soils are living communities that require both plants and organisms to develop and maintain the soil ecosystem. Common organisms found in soils include fungi, bacteria, protozoa, mites, millipedes, and worms, with each organism class contributing an important function to sustain the system. Most microorganisms contribute to soil decomposition, the process by which organic matter is broken down into simpler forms of matter. This process permits the recycling of nutrients and develops soil structure. Without the recycling of organic matter in soil systems many nutrients would become depleted.

Soil Microbes

Sites with an active soil microbe community exhibit stable soil aggregation, whereas sites with decreased microbial activity have compacted soil and poor aggregation (Edgerton et al. 1995). Baker et al. (2011) observed that sufficient available carbon is required to support an active microbial community during mine waste reclamation. Microbes obtain the carbon required for their metabolic activity from the organic component of soils (Alexander 1961).

Bacteria

Bacteria play a critical role in organic matter decomposition. Some bacteria can develop symbiotic relationships which will affect soil properties with plants. *Rhizobium* and *Frankia* form endophytic symbiotic relationships with legumes and actinorhizal plants, respectively (Lalonde & Lalonde 1982). Specific to the boreal forest ecosystem, green alder (*Alnus crispa*) develops root nodules that host a strain of the N-fixing bacterium *Frankia* (Chaia et al. 2010). Although actinorhizal symbioses are not obligate for the host (green alder can be grown in greenhouse conditions without nodules) there are no reported cases of non-nodulated green alder in the field (Chaia et al. 2010). Free living and symbiotic rhizo-bacteria are critical for the health of the forest ecosystem; they enhance plant growth directly by providing bioavailable P, fix N in the soil, sequester trace elements for plants, and initiate decomposition of organic matter and nutrient cycling (Sheoran et al. 2010).

Mycorrhizal Fungi

Another very important symbiotic relationship is evident with fungi, in the mycorrhizal association in the roots of many plant species. Mycorrhizal associations can form intracellularly as arbuscular mycorrhizal fungi or extracellularly as ectomycorrhizal fungi. Arbuscular mycorrhizal fungi (AMF) occur in most habitats and environments, and form in most root systems of land plants (Smith & Smith 2011). AMF are essential for survival and growth of plants by contributing to plant nutrient uptake (Sheoran et al. 2010; Smith & Smith 2011), including assisting in the uptake of several forms of soil nitrogen (Mader et al. 2000). Lazcano et al. (2014) demonstrated that AMF were able to decrease allocation of resources to plant root biomass without compromising shoot biomass. They also showed that mycorrhizal plants were able to optimize photosynthetic rates in high soil moisture conditions and were faster to close stomatal openings in response to decreased soil moisture than non-mycorrhizal plants (Lazcano et al. 2014).

As well, soil fungi play a key role in wood decomposition, a process which is vital for carbon and nutrient cycles (Prewitt et al. 2014). Thus, the presence of soil fungi will then influence the effectiveness of this soil component or amendment. However, when soils or soil components are moved and stockpiled, fungal hypha networks will quickly deteriorate (Gould et al. 1996). Soil water potential also affects mycorrhizal viability. Miller et al. (1985) found that when soil water potential is less than -2 MPa, mycorrhizal propagules survive for longer when soil is stored or stockpiled. By keeping stockpiles shallow to increase evaporation of water from soils to the atmosphere, viability of mycorrhizal fungi can be prolonged during storage time. Immediately post-reclamation on opencast coal sites, Williamson & Johnson (1991) observed that mycorrhizal propagule densities declined, but re-established themselves after two years.

2.4 – Pedogenesis

Since anthropogenic soils originate from processes completely removed from those naturally occurring, we can expect their subsequent pedogenic trajectories to be altered as well. As the formation of soil can require up to thousands of years, it is unrealistic to think that by manufacturing a soil material, the reclamation practitioner can create a material that has all the functionality and properties of a natural soil. The speed at which soil horizons develop can be variable, with few papers focused on describing the speed of pedogenesis in manufactured soils. Bini and Gaballo (2006) studied pedogenic trends in a range of aged Anthrosols developed on sulfidic mine spoils in Italy, documenting the thickness of the A horizon developed at approximately 0.1 mm per year. Séré et al. (2010) studied two Technosols aged four years and forty years, on the Italo-French boarder. After four years a differentiated A/C profile had formed, and after forty years a clear O/A/AB/Bw/BC/C profile had differentiated. The areas in which these Technosols were studied have significantly higher mean annual temperature than common in the boreal forest, which has limited microbial activity due to lower temperatures. The difference in climate may influence the rate at which soils age.

2.5 – Summary

Reuse of waste materials whenever possible, to achieve sustainable and economical land reclamation is. There is no technical reason why composts, woody residuals, paper sludge and pulp, green waste, sewage sludge, municipal solid waste and biochar cannot be used in creating or amending soils for use in land reclamation. When handled and mixed correctly, organic wastes could be diverted from the landfill to manufacture soils for use as cover soils or growth media to help restore the ecosystems of post-industrial sites. Composts and organic wastes supply essential plant nutrients in organic forms, and re-instate microorganisms critical for nutrient cycling, thus increasing soil fertility. The addition of organic matter will also decrease soil bulk density, increase porosity and water holding capacity and promote soil aggregation. If organic wastes need to be stored and stockpiled before use in land reclamation initiatives, they should be held in smaller, shallower piles if possible to maintain microbial populations and processes which are essential for creating a functional soil.

Chapter 3

3 Assessing Technosols manufactured from industrial by-products as a growth medium using annual ryegrass (*Lolium multiflorum*)

Constructing a soil out of locally sourced, industrial by-products for use as cover soils in the reclamation of damaged lands could reduce the environmental impacts associated with traditional land reclamation methods, and will allow mining companies to tailor soil properties to specific site or use requirements. Woody residuals and primary paper sludge have been used in agricultural and reclamation applications as soil amendments to improve soil fertility (Nason et al. 2007). Specifically, a study conducted by Phillips et al. (1997) demonstrated improved soil condition by increasing soil organic carbon, after a three year application of paper sludge on agricultural fields. When wood residues were used as an amendment on mine spoils, improved plant establishment and growth were attributed to improvements in water holding capacity (Sheoran et al. 2010). These popular soil amendments may possibly be used to manufacture a soil for reclamation applications in the boreal forest ecosystem. The objective of this study was to produce a suitable growth medium from an admixture of woody residuals, primary paper sludge and two sub-types of non-acid generating finely crushed mine rock. The study was guided by the following hypotheses: Quantities of total and bioavailable plant nutrients will be higher in Technosols containing higher amounts of organic constituent; Water holding capacity will be higher in Technosols that contain higher amounts of organic constituent; Ryegrass grown in lower organic content Technosols will have lower shoot biomass and higher root biomass than ryegrass grown in higher organic Technosols.

3.1 – Methods

3.11 – Materials and Technosol Ratios

Technosols consisted of one organic constituent (primary paper sludge or woody residuals) and one mineral constituent (finely crushed metasedimentary or intermediate volcanic mine rock). Woody residuals obtained from the Domtar White River Sawmill contained sawdust, bark and off-cuttings of dominantly boreal coniferous trees. Primary paper sludge, produced by the manufacture of virgin wood fibre, was also obtained from Terrace Bay Pulp Inc. (Terrace Bay, ON). The intermediate volcanic and metasedimentary mine rock co-exist in the Williams open-pit mine at the Barrick Gold Corporation's Hemlo operation, but were separated for the purpose of this study. The mine rock was crushed to a size range 1 cm - 2 mm in diamater. Primary paper sludge and woody residuals were combined with finely crushed intermediate volcanic mine rock or finely crushed metasedimentary mine rock in organic percentages of 0, 25%, 50% and 75% and thoroughly homogenized. Each Technosol blend was replicated three times and assigned to block A, B, or C (Figure 1).

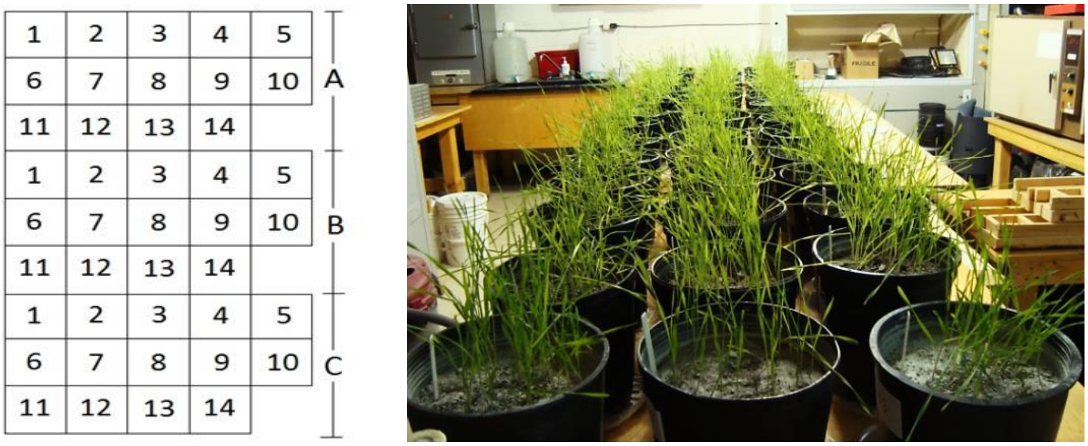


Figure 1. (L) Randomization matrix where numbers 1-14 indicate pot position within one of the three replicate blocks (A, B, C). Pots were assigned a number within the replication block randomly and rotated weekly; (R) Pots in position within matrix.

3.12 – Plant Establishment & Growth

Rye grass germination was tested on each soil mixture over a period of four days by distributing seeds on moistened Technosols in a covered petri-dish. Successful germination events (of twenty five seeds), as demonstrated by emergence of seedling, were noted (Table 1).

Table 1. Germination counts (of 25) of annual ryegrass on Technsols, made with metasedimentary or intermediate volcanic mine rock, woody residuals or primary paper sludge, over a period of four days. Percentages indicate the amount of organic component in the soil.

	Metasedimentary Mine Rock							**Intermediate Volcanic Mine Rock**						
		Woody Residuals			**Paper Sludge**				**Woody Residuals**			**Paper Sludge**		
	0%	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**	**0%**	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
A	24	21	25	25	19	25	24	25	23	24	-	23	25	23
B	23	24	25	23	25	22	24	23	24	24	24	24	25	25
C	25	24	24	23	25	25	25	24	24	24	24	24	23	25
Av	24	23	24.7	23.7	23	24	24.3	24	23.7	24	24	23.7	24.3	24.3

Soils were placed into 4.21 L planting pots (17.5 cm depth and 17.5 cm diameter). Holes were punctured in the bottom of each pot to allow for water drainage. Fifty annual ryegrass (*L. multiflorum*) seeds were sown in each soil mixture following the addition of 500 mL of full strength Hoagland solution. Although not native to the boreal forest ecosystem, annual ryegrass was used in this study because the short lived grass is frequently used in reclamation to stabilize newly placed soils. There are also numerous studies which document the responses of ryegrass to different growth conditions (Baker et al. 2011; Hannaway et al. 1999; Hunt 1975; Jiang & Fry 1998). Annual ryegrass was grown in an indoor growth facility over a period of ten weeks with full light spectrum hydroponic lights for twelve hours per day. Deionized water was administered three times weekly for the duration of the experiment. For the first five weeks, 500 mL of deionized water was administered three times a week to replicate spring precipitation events of Northern Ontario. Over weeks 6-10 the administered 250 mL deionized water (3 times weekly) replicated summer-like conditions and reduced water loss from the bottom of the pots. At the beginning of the sixth week, the ryegrass was thinned to 15 stems per pot, with both roots and shoots of the grasses being removed from the pot for mass and chemical analysis. At the end of the growth period, remaining roots and shoots were destructively harvested. Roots were cleaned with deionized water to remove soil debris.

3.13 – Sample Analysis

Roots and shoots were separated and dried for 24 hrs at 105°C before determining dry mass of roots and shoots. Soil samples from each pot were collected and dried for 24 hrs at 105°C. Soil pH was measured in water and a neutral salt solution (0.1M $CaCl_2$) (Carter 1993). Soils were also analyzed for oxidation potential (Eh) (5.0 g sample and 10 mL water) and electrical conductivity (EC) (1:2 water ratio). For the metal quantification, a 0.50 g soil sample was digested with 10 mL of a 10:1 ratio of HF/HCl, heated to 110°C for 3.5 hrs in an open 50 mL Teflon™ tube in a programmable digestion block to dryness, cooled prior to the addition of 7.5 mL of HCl and 7.5 mL of HNO_3 with heating to 110°C for another 4 hrs to dry gently. The dried residues were then heated to 110°C for 1 hr following the addition of 0.5 mL of HF, 2 mL of HCl, and 10 mL of HNO_3 to reduce solution volume to 8–10 mL. On cooling, the solution was brought to 50 mL with ultrapure water for subsequent analysis by plasma spectrometry. A 0.20 g plant sample was used for the estimation of total metal concentrations following the same procedure. Bioavailable metals in the growth media were estimated by extracting 5.0 g of mineral material (crushed pure metasedimentary or pure intermediate volcanic rock) or 2.0 g of Technosol with 20 mL of 0.01 M $LiNO_3$ in a 50-mL centrifuge tube in a shaker under ambient lighting conditions for 24 hrs at 20°C (Abedin et al. 2012). The pH ($LiNO_3$) of the suspension was measured prior to centrifugation at 3,000 rpm for 20 min, with filtration of the supernatant through Whatman 42 filter paper into a 20 mL polyethylene tube and made to volume with deionized water. The filtrate was preserved stored at approximately 3°C for analysis by ICP-MS. The quality control program completed in an ISO 17025 accredited facility (Elliot Lake Research Field Station of Laurentian University) included analysis of duplicates, Certified Reference Materials (CRMs), Internal Reference Materials (IRMs), and procedural and calibration blanks, with continuous calibration verification and use of internal standards to correct for any mass bias. All concentrations were calculated in mass/mass dry soil (or plant) basis. CNS (carbon, nitrogen, sulphur) analysis was conducted using the LECO™ CNS 2000 instrument: samples were combusted in an oxygen stream with evolved gases quantified by infrared absorption. Soil moisture characteristic curves were constructed for each Technosol using a Soil Moisture Corporation™ pressure plate system set at 0.1, 0.333, 1.0, 2.0, 4.0, 8.0, and 15.0 MPa of pressure.

3.14 – Calculations and Statistical Analysis

Calculations and statistical analysis were carried out using R 3.0.2 (The R Foundation for Statistical Computing 2013). Shapiro-Wilk's test was used to assess normality, and Bartlett's test for homogeneity of variance. Biomass data passed homogeneity of variance assumptions, but most did not meet the normal distribution assumptions. Normal distribution of root and root:shoot biomass data ($p > 0.05$), but not shoot biomass data was obtained by log transformation. Log transformation improved the distribution of shoot biomass data best when several transformations were compared (shoots 5 weeks: $p = 0.013$; shoots 10 weeks: $p = 0.025$). A two-way analysis of variance (ANOVA) and Pearson and Spearman correlations were used to analyze root and shoot biomass data and nutrient concentration data. Significance was determined at $p \leq 0.05$. ANOVA was followed by Tukey's HSD test when a significant difference was detected. Samples that contained elemental concentrations below detection limits were excluded from statistical analysis, as opposed to employing common substitution of some fraction of the detection limit in place of the non-detect.

3.2 – Results

3.21 – Parent Materials

Although the finely crushed mine rock had approximately neutral pH when measured in H_2O and $CaCl_2$, there was considerable difference in chemical composition (Table 2). The organic constituents of the soils in this study differed significantly in pH, with woody residuals yielding a neutral $pH_{(H2O)}$ of 6.5 and primary paper sludge a basic $pH_{(H2O)}$ of 9.9. The organic constituents also varied considerably in elemental composition, with woody residuals containing higher amounts of both macro and micro-nutrients (Table 2).

Table 2. Select properties and total elemental concentrations of soil constituents used to produce soil blends.

Properties	**Intermediate Volcanics**	**Metasediments**	**Primary Paper Sludge**	**Woody Residuals**
pH (H_2O)	8.8	8.9	9.9	6.5
pH ($CaCl_2$)	7.5	7.4	8.7	6.3
Nutrient Elements				
Carbon (%)	1.16	0.05	21.7	36.9
Nitrogen (%)	0.04	0.04	0.04	0.04
Carbon: Nitrogen	27.6	12.8	517	99.2
Sulphur (%)	0.41	0.003	0.10	0.03
P (ppm)	514	444	513	425
Ca (%)	1.85	1.07	9.23	1.52
Mg (%)	0.58	0.30	0.29	0.16
K (%)	2.22	1.76	0.13	0.20
Fe (%)	1.56	1.61	0.07	0.53
Zn (ppm)	78.2	65.8	34.1	89.1
Mn (ppm)	365	220	309	538
Cu (ppm)	21.8	37.1	7.20	9.43

3.22 – Ryegrass Biomass

Thinned Harvest Samples: Weeks 1-5. Shoot dry mass over all treatments ranged from 0.268 g to 0.964 g (Table 3). The highest mean shoot dry mass was achieved by treatment 3-0% (0.848 g ± SE 0.076) and the lowest was yielded by treatment 2-75% (0.454 g ± SE 0.038). No significant difference in dry shoot mass was detected when all treatments were compared separately (Figure 2). Dry shoot mass yield was significantly different between soils grouped based on rock type ($F_{1,36} = 4.15$, $p < 0.05$). A significant interaction between rock type and organic type used in the Technosols existed ($F_{2,36} = 6.27$, $p < 0.005$) (Figure 3). Treatments containing intermediate volcanic rock yielded higher shoot dry mass than treatments containing metasedimentary rock. Treatments that contained intermediate volcanic rock without an organic constituent yielded significantly higher shoot dry mass than all other treatment groupings, while treatments that contained metasedimentary rock without an organic constituent yielded the lowest shoot dry mass (Table 4).

Table 3. Above and below ground biomass (g) and root:shoot ratio of annual ryegrass grown for 5 weeks on Technosols made of mine rock, woody residuals and primary paper sludge. A, B and C indicate replicates of each treatment; average (Av) and standard error (SE) are italicized.

	Metasedimentary Mine Rock							**Intermediate Volcanic Mine Rock**						
	+ Woody Residuals				**+ Paper Sludge**			**+ Woody Residuals**				**+ Paper Sludge**		
	0%	25%	50%	75%	25%	50%	75%	0%	25%	50%	75%	25%	50%	75%
Roots														
A	0.257	0.143	0.215	0.195	0.140	0.243	0.161	0.280	0.264	0.208	0.149	0.160	0.167	0.175
B	0.169	0.131	0.166	0.125	0.090	0.185	0.167	0.264	0.152	0.120	0.155	0.091	0.136	0.189
C	0.281	0.210	0.153	0.155	0.190	0.200	0.115	0.401	0.179	0.147	0.134	0.116	0.168	0.138
Avg	*0.236*	*0.161*	*0.178*	*0.158*	*0.140*	*0.209*	*0.148*	*0.315*	*0.199*	*0.158*	*0.146*	*0.122*	*0.157*	*0.167*
SE	*0.034*	*0.025*	*0.019*	*0.020*	*0.029*	*0.018*	*0.017*	*0.043*	*0.034*	*0.026*	*0.006*	*0.020*	*0.011*	*0.015*
Shoots														
A	0.657	0.575	0.545	0.615	0.525	0.902	0.385	0.964	0.601	0.698	0.806	0.586	0.544	0.544
B	0.268	0.519	0.527	0.585	0.435	0.584	0.516	0.873	0.495	0.547	0.492	0.509	0.515	0.535
C	0.475	0.515	0.486	0.532	0.550	0.549	0.462	0.705	0.596	0.416	0.446	0.512	0.700	0.607
Avg	*0.467*	*0.536*	*0.520*	*0.578*	*0.504*	*0.678*	*0.454*	*0.848*	*0.564*	*0.554*	*0.581*	*0.536*	*0.586*	*0.562*
SE	*0.113*	*0.019*	*0.017*	*0.024*	*0.035*	*0.112*	*0.038*	*0.076*	*0.035*	*0.082*	*0.113*	*0.025*	*0.058*	*0.023*
Root:Shoot														
A	0.392	0.249	0.395	0.316	0.266	0.270	0.419	0.290	0.440	0.297	0.185	0.272	0.306	0.321
B	0.631	0.252	0.315	0.213	0.206	0.317	0.324	0.302	0.307	0.220	0.314	0.179	0.263	0.353
C	0.590	0.407	0.315	0.291	0.345	0.365	0.248	0.569	0.301	0.353	0.300	0.226	0.240	0.227
Avg	*0.538*	*0.303*	*0.342*	*0.274*	*0.272*	*0.317*	*0.331*	*0.387*	*0.349*	*0.290*	*0.266*	*0.226*	*0.270*	*0.301*
SE	*0.074*	*0.052*	*0.027*	*0.031*	*0.040*	*0.028*	*0.049*	*0.091*	*0.045*	*0.039*	*0.041*	*0.027*	*0.020*	*0.038*

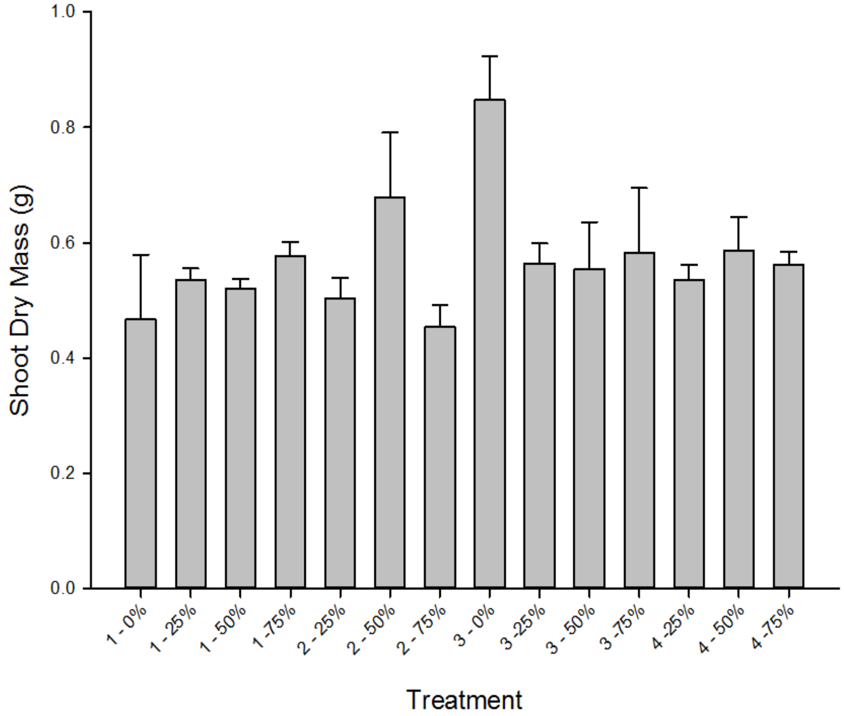


Figure 2. Ryegrass shoot dry mass yields after 5 weeks of growth in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. Treatments were not significantly different. n = 3 for each treatment.

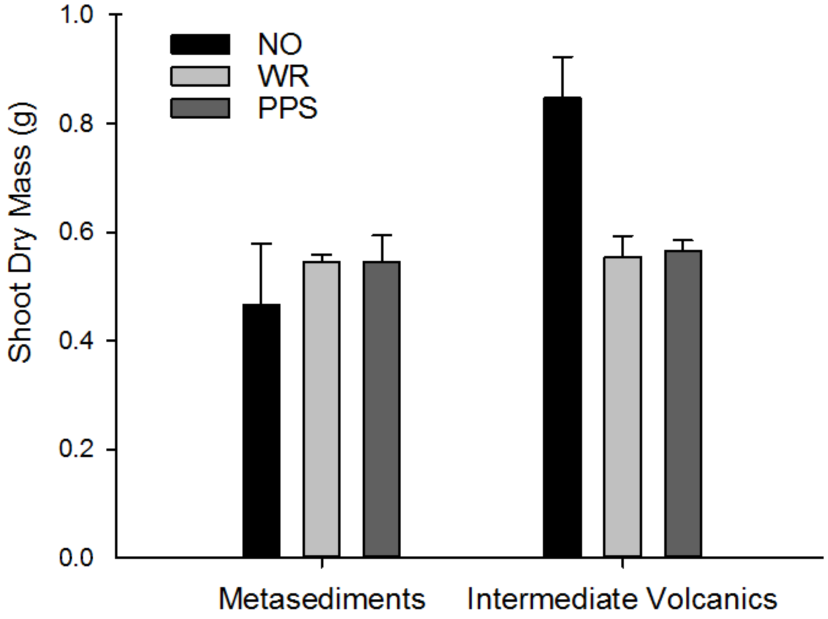


Figure 3. Shoot dry mass of ryegrass after 5 weeks of growth in Technosols made with finely crushed metasedimentary or intermediate volcanic mine rock, containing no organic constituent (NO), woody residuals (WR) or primary paper sludge (PPS). Standard error bars are shown. n = 3 for each of the non-organic groups, n = 9 for each organic group.

Table 4. Root and Shoot Dry Mass (g) and Root:Shoot Ratio of annual ryegrass grown for 5 weeks and 10 weeks. Means are shown for treatment groupings based on soil constituents: metasedimentary rock (MS), intermediate volcanics (IV), no organics (NO), woody residuals (WR) and primary paper sludge (PPS). Standard error italicized.

Grouping by:	**Five Weeks of Growth**						**Ten Weeks of Growth**					
	Root (g)		Shoot (g)		Root:Shoot		Root (g)		Shoot (g)		Root:Shoot	
Rock Constituent												
MS	0.175	*0.010*	0.534	*0.026*	0.339	*0.024*	0.154	*0.020*	0.516	*0.037*	0.324	*0.054*
IV	0.180	*0.015*	0.604	*0.031*	0.298	*0.019*	0.176	*0.021*	0.552	*0.046*	0.320	*0.030*
Organic Constituent												
NO	0.028	*0.030*	0.657	*0.105*	0.462	*0.062*	0.283	*0.031*	0.915	*0.062*	0.314	*0.036*
WR	0.167	*0.009*	0.555	*0.021*	0.304	*0.016*	0.147	*0.021*	0.535	*0.020*	0.276	*0.033*
PPS	0.156	*0.009*	0.553	*0.026*	0.287	*0.014*	0.137	*0.019*	0.414	*0.017*	0.354	*0.060*
Rock & Organic Constituents												
MS + NO	0.236	*0.034*	0.467	*0. 112*	0.538	*0.074*	0.819	*0.095*	0.819	*0.095*	0.312	*0.075*
MS + WR	0.166	*0.011*	0.544	*0.013*	0.306	*0.022*	0.535	*0.032*	0.535	*0.032*	0.253	*0.047*
MS + PPS	0.166	*0.016*	0.545	*0.049*	0.307	*0.022*	0.396	*0.025*	0.396	*0.025*	0.399	*0.012*
IV + NO	0.315	*0.043*	0.848	*0.076*	0.387	*0.091*	1.01	*0.028*	1.010	*0.028*	0.317	*0.031*
IV + WR	0.167	*0.015*	0.567	*0.042*	0.302	*0.024*	0.535	*0.026*	0.535	*0.026*	0.299	*0.048*
IV + PPS	0.149	*0.010*	0.561	*0.021*	0.265	*0.018*	0.415	*0.021*	0.415	*0.021*	0.343	*0.052*

Root dry mass ranged from 0.090 g to 0.401 g over all treatments (Table 3), with the highest mean root dry mass being observed in treatment 3-0% (0.315 g ± SE 0.043) and the lowest by treatment 4-25% (0.122 g ± SE 0.020). Dry root mass was significantly different between Technosols ($F_{13,28} = 3.30$, $p < 0.005$) (Figure 4) resulting from treatment 3-0% yielding significantly higher root dry mass than treatments 2-25% ($p < 0.01$), 2-75% ($p < 0.05$), 3-50% ($p < 0.05$), 3-75% ($p < 0.05$), 4-25% ($p < 0.005$). Dry root mass was significantly different between Technosols grouped based on organic constituent ($F_{2,36}= 12.1$, $p < 0.001$), with no detectable interaction between rock type and organic type used in the soils. Treatments with no organic constituents yielded higher root dry mass than treatments that contained woody residuals ($p < 0.001$) or primary paper sludge ($p < 0.001$) (Figure 5 & Table 4). Root:Shoot ratio ranged from 0.179 to 0.631 over all treatments (Table 3). The highest root:shoot ratio was observed in treatment 1-0% (0.538 ± SE 0.074) and the lowest in treatment 4-25% (0.226 ± 0.027). Root:shoot ratio was significantly different between Technosols ($F_{13,28} = 2.18$, $p < 0.05$) (Figure 6) resulting from treatment 1-0% having a significantly higher root:shoot ratio than treatment 4-25% ($p < 0.01$). Root:shoot ratio was significantly different when treatments were grouped based on organic constituent ($F_{2,36=}$ 8.545, $p < 0.001$). Treatments that contained an organic constituent yielded a significantly lower root:shoot ratio than the pure metasedimentary mine rock treatment (1-0%) (Figure 7).

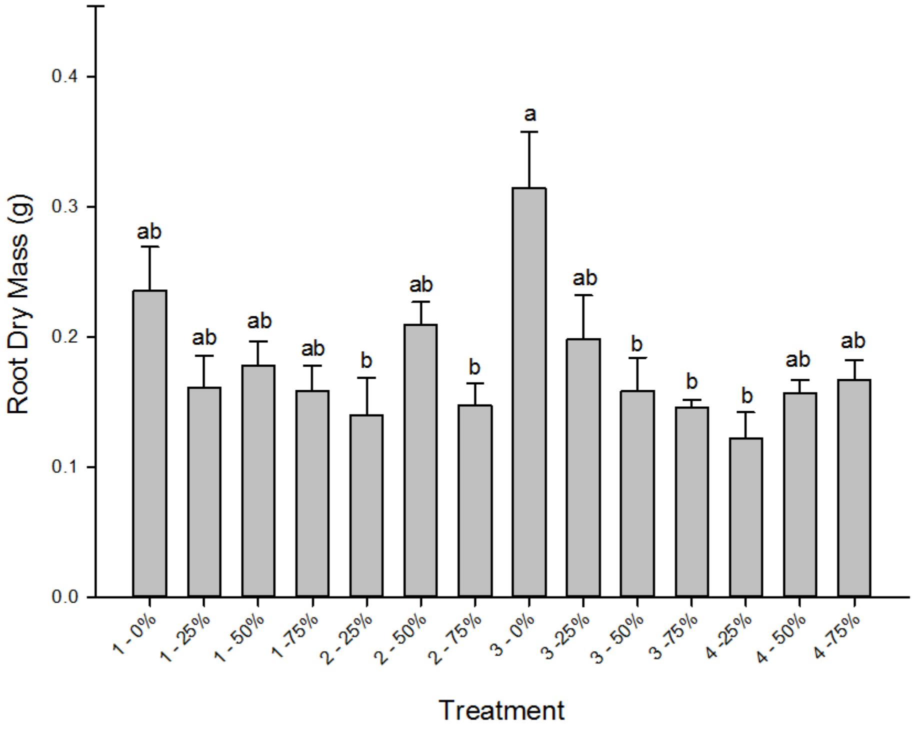


Figure 4. Root dry mass yields of ryegrass after 5 weeks of growth in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. Letters indicate significant differences between treatments. n = 3 for each treatment.

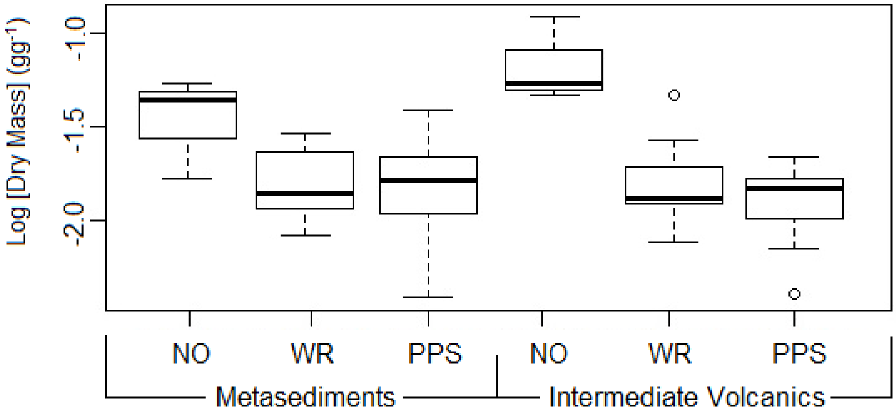


Figure 5. Log [Root Dry Mass] of ryegrass grown for 5 weeks in Technosols made with finely crushed metasedimentary or intermediate volcanic mine rock, containing no organic constituent (NO), woody residuals (WR) or primary paper sludge (PPS). Whiskers represented as Q1 – 1.5IQR and Q3 + 1.5IQR. n = 3 for each of the non-organic groups, n = 9 for each organic group.

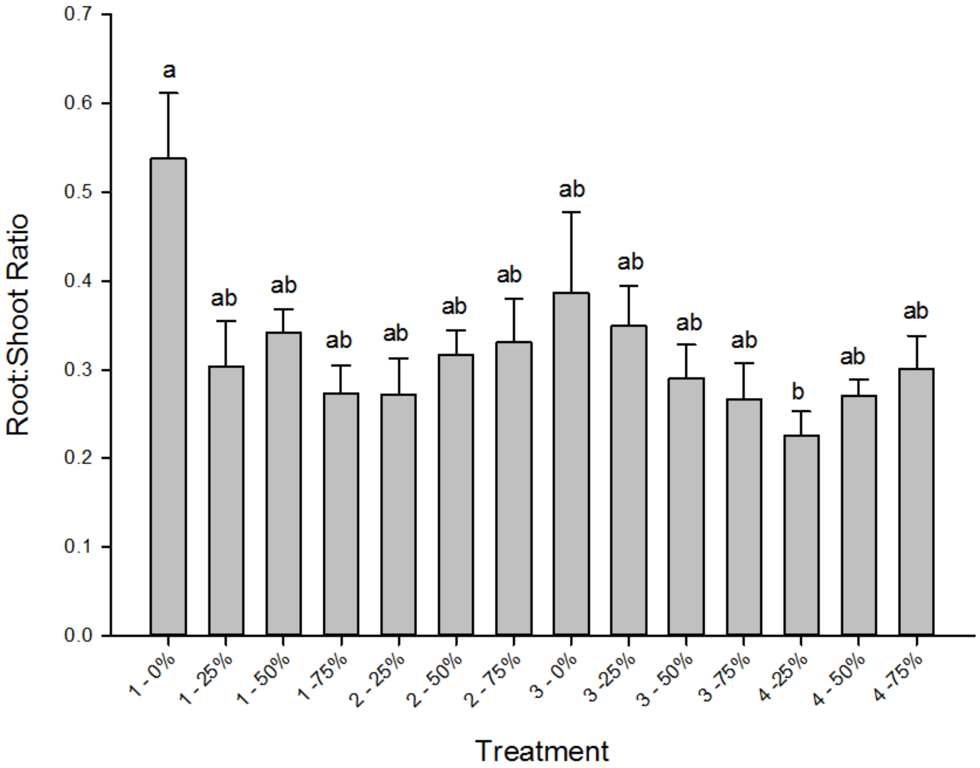


Figure 6. Ryegrass root:shoot ratios after 5 weeks of growth in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. Letters indicate significant differences between treatments. n = 3 for each treatment.

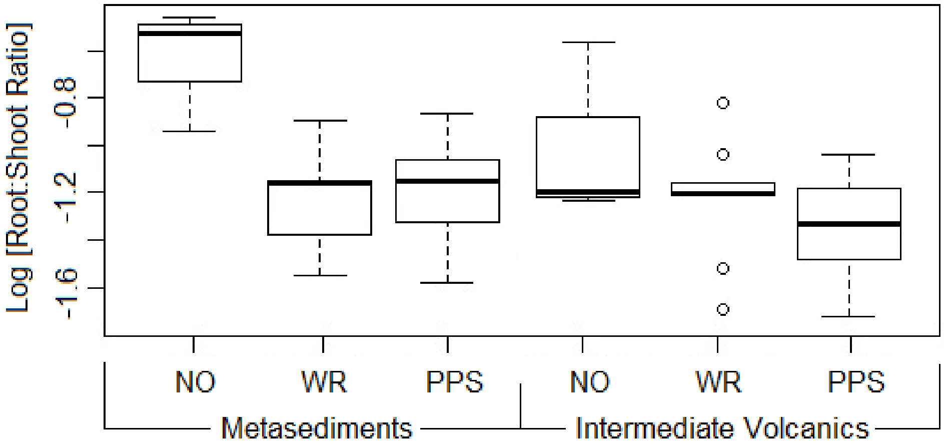


Figure 7. Log [Root:Shoot Ratio] of ryegrass grown for 5 weeks in Technosols made with finely crushed metasedimentary or intermediate volcanic mine rock, containing no organic constituent (NO), woody residuals (WR) or primary paper sludge (PPS). Whiskers represented as Q1 – 1.5IQR and Q3 + 1.5IQR. n = 3 for each of the non-organic groups, n = 9 for each organic group.

There was a significant correlation (Pearson) between the amount of organic constituent in the soil to the root:shoot ratio ($p < 0.05$, $r = -0.335$) (Figure 8). When soils with different organic constituents were compared separately, there was a strong negative correlation between the amount of woody residuals in a soil and the root:shoot ratio of ryegrass grown in that soil ($p < 0.005$, $r = -0.5770$) (Figure 8). There was no correlation between amount of primary paper sludge in a soil and the root:shoot ratio of ryegrass grown in that soil. There was no significant effect of organic ratio on the dry mass yields of shoots or roots.

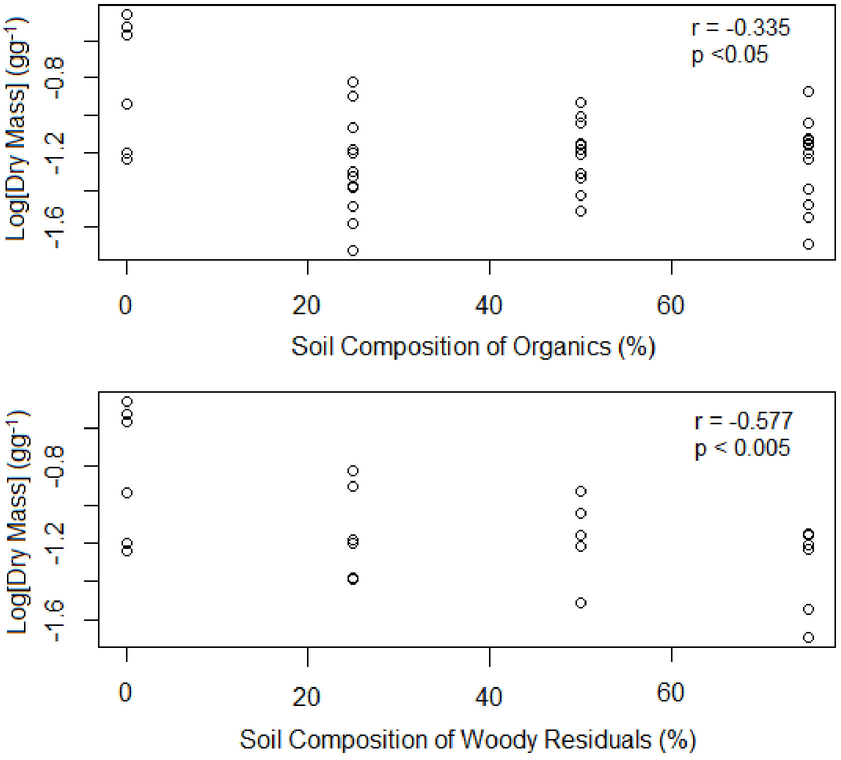


Figure 8. Log [Root:Shoot Ratio] over increasing amounts of organic constituent (top) and woody residuals (bottom) in the Technosols based on ryegrass root and shoot yields after 5 weeks of growth. n = 42 (top); n = 24 (bottom).

Final Harvest Samples: Weeks 6-10. Shoot dry mass ranged from 0.298 g to 1.062 g over all treatments (Table 5). The highest mean shoot dry mass was achieved by treatment 3-0% (1.062 g ± SE 0.028) and the lowest was yielded by treatment 2-50% (0.371 g ± SE 0.037).

Table 5. Above and below ground biomass (g) and root:shoot ratio of annual ryegrass grown for 10 weeks on Technsols made of mine rock, woody residuals and primary paper sludge. A, B and C indicate replicates of each treatment; average (Av) and standard error (SE) are italicized

	Metasedimentary Mine Rock							**Intermediate Volcanic Mine Rock**						
	+ Woody Residuals				**+ Paper Sludge**			**+ Woody Residuals**				**+ Paper Sludge**		
	0%	25%	50%	75%	25%	50%	75%	0%	25%	50%	75%	25%	50%	75%
Roots														
A	0.177	0.088	0.170	0.294	0.107	0.053	0.061	0.301	0.386	0.125	0.223	0.138	0.227	0.110
B	0.209	0.120	0.078	0.173	0.162	0.150	0.131	0.365	0.110	0.144	0.167	0.178	0.126	0.235
C	0.356	0.138	0.072	0.049	0.145	0.107	0.386	0.291	0.110	0.178	0.029	0.085	0.092	0.073
Av	*0.248*	*0.115*	*0.106*	*0.172*	*0.138*	*0.103*	*0.193*	*0.319*	*0.202*	*0.149*	*0.140*	*0.134*	*0.148*	*0.139*
SE	*0.055*	*0.015*	*0.032*	*0.071*	*0.016*	*0.028*	*0.099*	*0.023*	*0.092*	*0.016*	*0.058*	*0.027*	*0.041*	*0.049*
Shoots														
A	0.987	0.534	0.532	0.616	0.441	0.406	0.487	1.062	0.720	0.471	0.477	0.453	0.379	0.373
B	0.657	0.563	0.500	0.412	0.509	0.410	0.377	0.964	0.466	0.563	0.537	0.396	0.552	0.414
C	0.812	0.417	0.728	0.517	0.333	0.298	0.304	1.005	0.517	0.507	0.557	0.390	0.438	0.342
Av	*0.819*	*0.504*	*0.587*	*0.515*	*0.428*	*0.371*	*0.389*	*1.010*	*0.568*	*0.514*	*0.524*	*0.413*	*0.457*	*0.376*
SE	*0.095*	*0.046*	*0.072*	*0.059*	*0.051*	*0.037*	*0.053*	*0.028*	*0.078*	*0.027*	*0.024*	*0.020*	*0.051*	*0.021*
Root:Shoot														
A	0.179	0.165	0.319	0.478	0.243	0.130	0.125	0.283	0.535	0.265	0.469	0.304	0.599	0.295
B	0.318	0.213	0.155	0.420	0.318	0.366	0.348	0.379	0.237	0.257	0.311	0.449	0.228	0.568
C	0.439	0.331	0.099	0.094	0.435	0.360	1.270	0.289	0.214	0.351	0.053	0.219	0.210	0.212
Av	*0.312*	*0.236*	*0.191*	*0.331*	*0.332*	*0.285*	*0.581*	*0.317*	*0.329*	*0.291*	*0.278*	*0.324*	*0.346*	*0.358*
SE	*0.075*	*0.049*	*0.066*	*0.120*	*0.056*	*0.078*	*0.351*	*0.031*	*0.104*	*0.030*	*0.121*	*0.067*	*0.127*	*0.107*

There was a significant difference in Shoot dry mass yield when all treatments were compared separately ($F_{13,28} = 8.675$, $p < 0.001$). Treatment 1-0% (metasedimentary with no organics) yielded significantly higher shoot dry mass than all treatments containing primary paper sludge as the organic constituent, excluding treatment 4-50%; treatment 3-0% (intermediate volcanic with no organics) yielded significantly higher shoot dry mass than all treatments that contained organics (Figure 9). When treatments were grouped based on organic constituent, there was a significant difference in shoot dry mass yield ($F_{2,36} = 58.2$, $p < 0.001$). All pairs of treatments that contained different organic constituents had significantly different dry mass yields, and despite difference in rock type, pairs with similar organic treatments did not yield a significantly different shoot dry mass (Figure 10). Treatments containing no organic constituent yielded higher biomass, on average than treatments containing woody residuals ($p < 0.001$) or primary paper sludge ($p < 0.001$) as the organic constituents (Table 4). Treatments that contained woody residuals as the organic constituent yielded significantly higher dry shoot biomass than treatments containing primary paper sludge as the organic constituent ($p < 0.001$). Root dry mass ranged from 0.029g to 0.365 g over all treatments (Table 5). There was no significant difference in root dry mass yield when all treatments were compared (Figure 11). When treatments were grouped based on organic type there was a significant difference in root dry mass yield ($F_{2,36} = 5.21$, $p < 0.05$), with treatments containing no organic constituents yielding significantly higher root dry mass than treatments containing either woody residuals ($p < 0.05$, 0.147 g ± SE 0.021) or primary paper sludge ($p < 0.05$, 0.137 g ± SE 0.019) as the organic constituents (Figure 12).

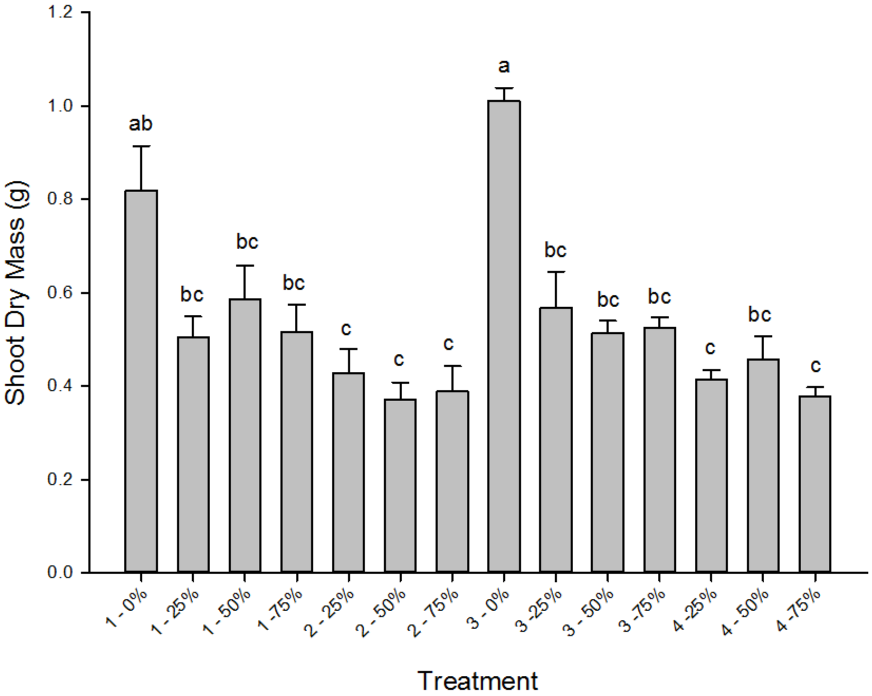


Figure 9. Ryegrass shoot dry mass yields after 10 weeks of growth in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. Letters indicate significant differences between treatments. n = 3 for each treatment.

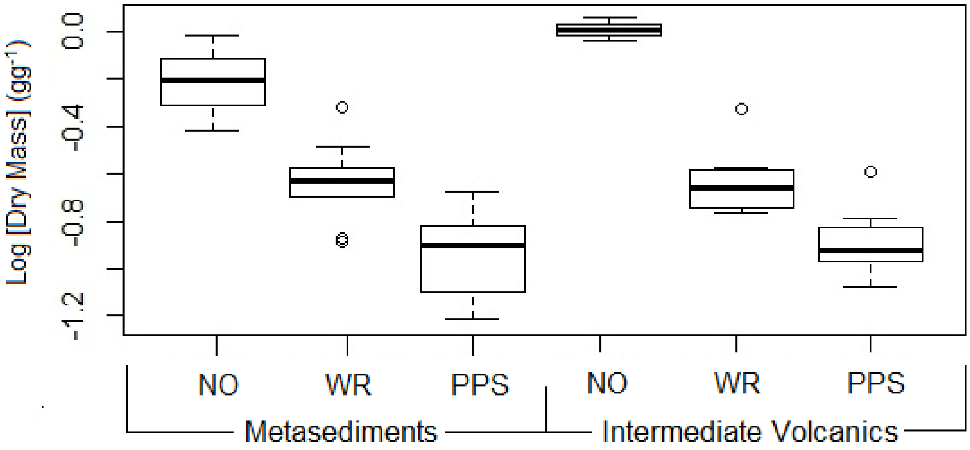


Figure 10. Log [Shoot Dry Mass] of ryegrass grown for 10 weeks in Technosols made with finely crushed metasedimentary or intermediate volcanic mine rock, containing no organic constituent (NO), woody residuals (WR) or primary paper sludge (PPS). Whiskers represented as Q1 – 1.5IQR and Q3 + 1.5IQR. n = 3 for each of the non-organic groups, n = 9 for each organic group.

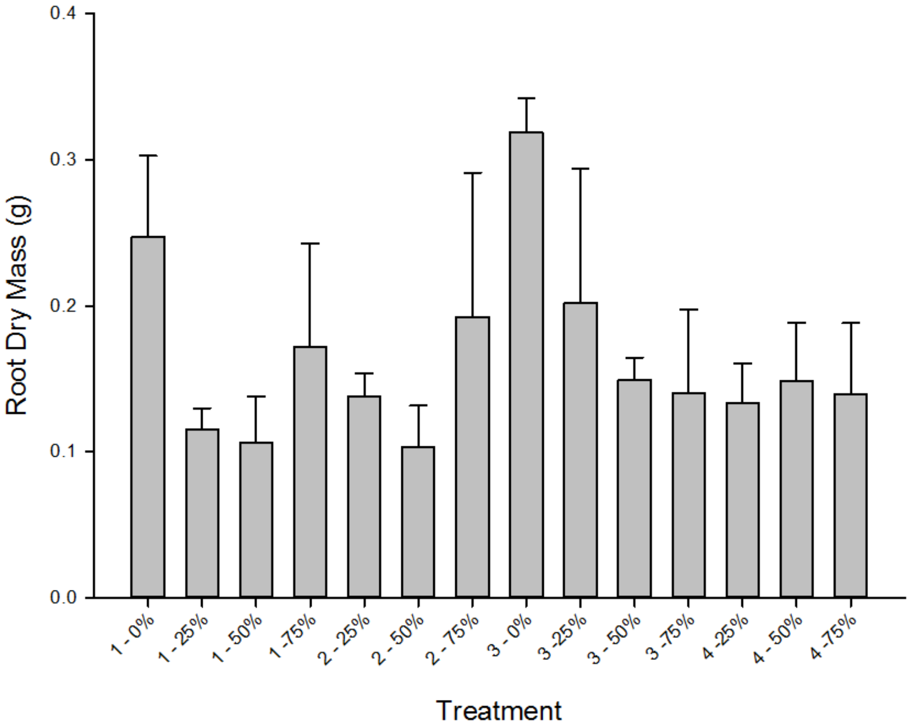


Figure 11. Ryegrass root dry mass yields after 10 weeks of growth in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. Treatments were not significantly different. n = 3 for each treatment.

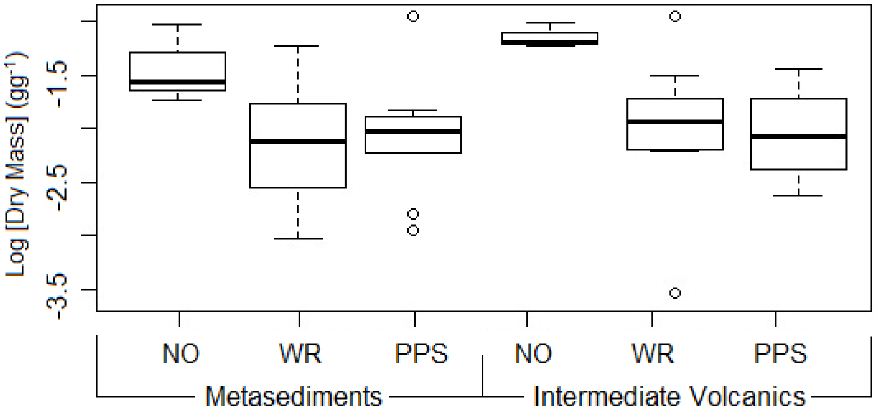


Figure 12. Log [Root Dry Mass] of ryegrass grown for 10 weeks in Technosols made with finely crushed metasedimentary or intermediate volcanic mine rock, containing no organic constituent (NO), woody residuals (WR) or primary paper sludge (PPS). Whiskers represented as Q1 – 1.5IQR and Q3 + 1.5IQR. n = 3 for each of the non-organic groups, n = 9 for each organic group.

Root:Shoot Ratio ranged from 0.053 to 1.27 over all treatments (Table 5). There was no significant difference in root:shoot ratio when treatments were compared separately (Figure 13), or by groupings based on rock, organic or rock and organic constituents (Figure 14). There was no significant effect of organic ratio on the dry mass yields of shoots or roots or on the root:shoot ratio.

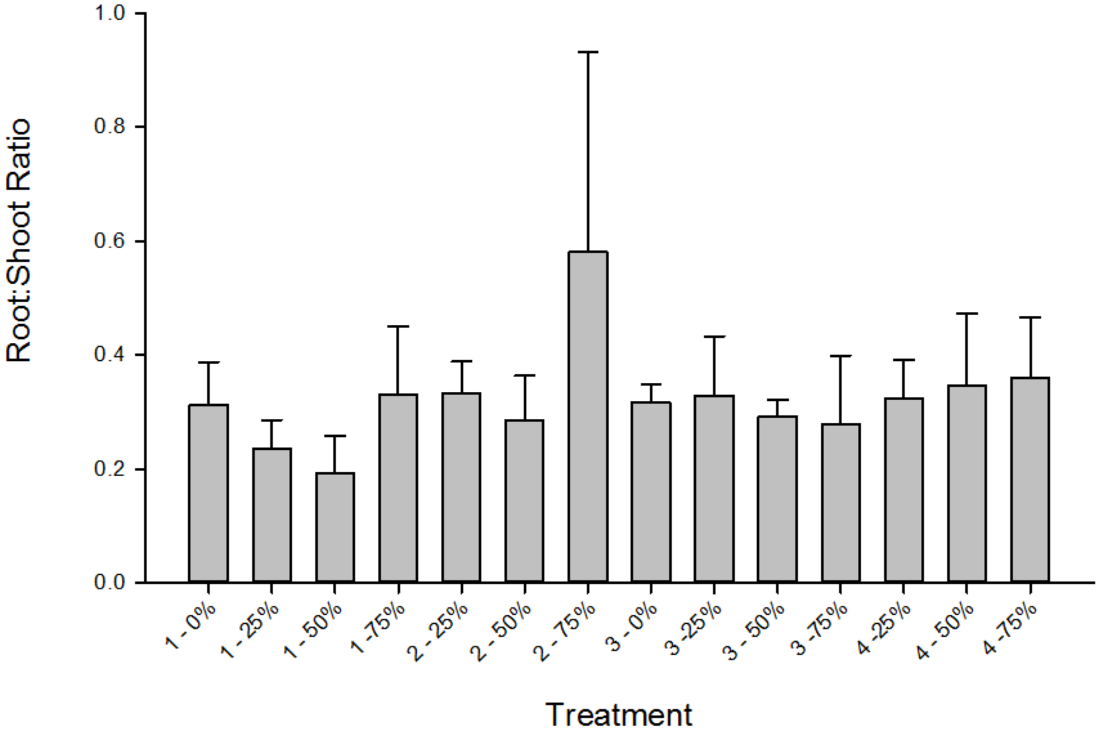


Figure 13. Ryegrass root:shoot ratios after 10 weeks of growth in Technsols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. Treatments were not significantly different. n = 3 for each treatment.

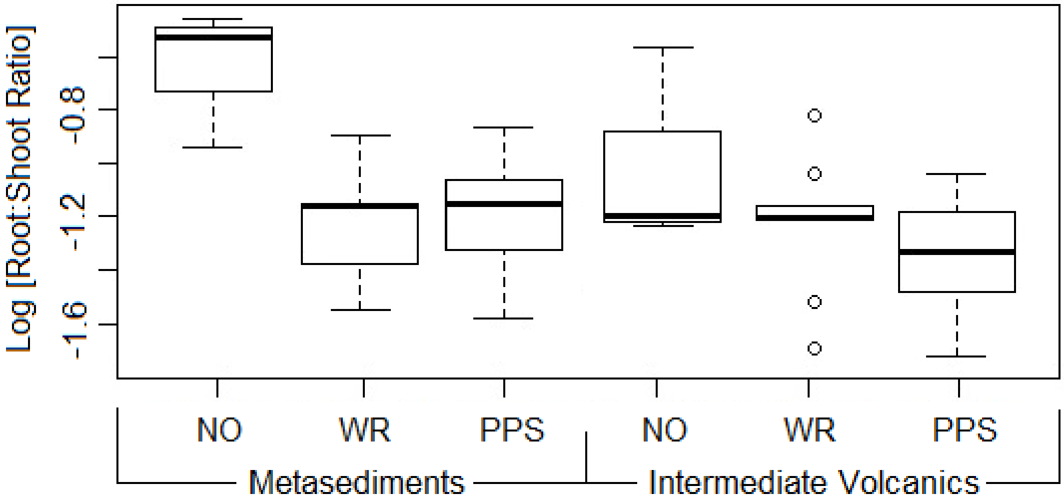


Figure 14. Log [Root:Shoot Ratio] of ryegrass grown for 10 weeks in Technosols made with finely crushed metasedimentary or intermediate volcanic mine rock, containing no organic constituent (NO), woody residuals (WR) or primary paper sludge (PPS). Whiskers represented as Q1 – 1.5IQR and Q3 + 1.5IQR. n = 3 for each of the non-organic groups, n = 9 for each organic group.

3.23 – Soil Moisture

As the amount of organic material present in the Technosol increased, so too did the soil moisture retention of the soil at a given matric suction (Figure 15 & A1). Field capacity, determined at a matric potential of -0.333 MPa, and permanent wilting point, determined at a matric potential of -15 MPa, were higher in soils constructed with woody residuals than in soils constructed with primary paper sludge, or those that contained no organic constituents (Table 6).

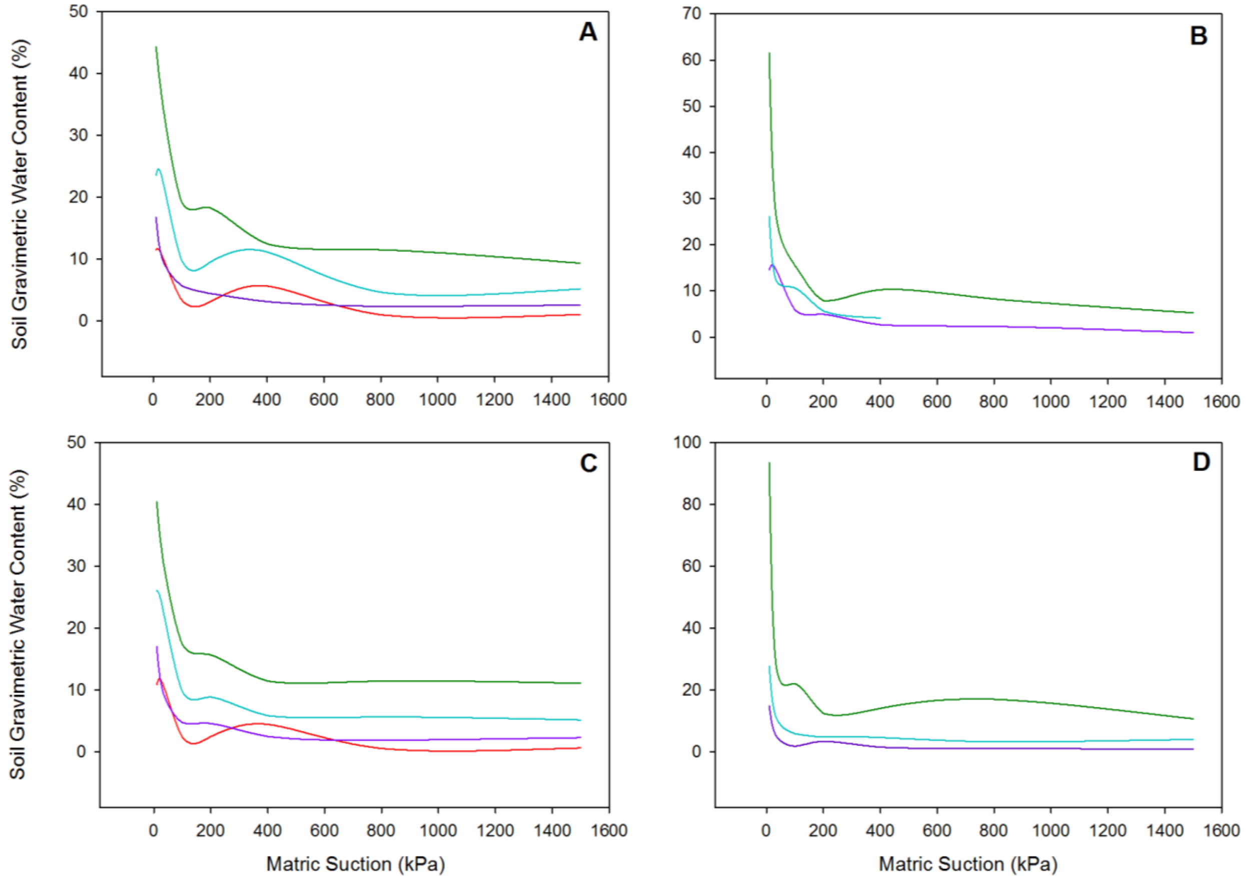


Figure 15. Soil moisture characteristic curves for Technosols composed of metasedimentary mine rock and woody residuals (A), metasedimentary mine rock and paper sludge (B), intermediate volcanic mine rock and woody residuals (C) and intermediateve volcanic mine rock and paper sludge (D). Soils containing 0% organics (red), 25% organics (purple), 50% organics (blue) and 75% organics (green) are shown. n = 3 for each Technsol.

Table 6. Average soil moisture values at matric potentials from -0.333 MPa to -15 MPa for Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. n = 3 for each Technosol.

	Gravimetric Water Content (%)		
Technosol	**Field Capacity** (-0.333 MPa)	**Permanent Wilting Point** (-15 MPa)	**Plant Available Water**
1-0%	10.34	1.04	9.29
1-25%	9.86	2.57	7.29
1-50%	22.74	5.18	17.56
1-75%	35.09	9.34	25.75
2-25%	14.66	0.95	13.71
2-50%	12.42	1.94	10.48
2-75%	26.51	5.26	21.25
3-0%	10.73	0.63	10.10
3-25%	9.47	2.30	7.17
3-50%	22.70	5.17	17.54
3-75%	30.70	11.10	19.60
4-25%	5.31	0.81	4.49
4-50%	11.24	4.04	7.20
4-75%	28.41	10.69	17.72

3.24 – Soil Fertility & Plant Nutrient Accumulation

Soils the contained primary paper sludge had a higher pH and cation exchange capacity (CEC) than soils that contained woody residuals as the organic constituent (Table 7). Increasing the amount of woody residuals in the soil lowered soil pH from approximately 8.6 (no woody residuals) to 6.8 (75% woody residuals), and increased CEC values. Increasing the amount of primary paper sludge in the soil increased soil pH from approximately 8.6 (no paper sludge) to 9.5 (75% primary paper sludge) and increased CEC values**.** Woody residuals contained more carbon or ‘organic matter’ than primary paper sludge (Table 7).

Table 7. Soil fertility parameters of Technosols manufactured from finely crushed metasedimentary (1&2) and intermediate volcanic (3 & 4) mine rock and woody residuals (1 & 3) and primary paper sludge (2 & 4) with ranges indicated by shading*.

Sample	Organic Matter	Phosphorus P ppm		Percent Base Saturations				K/Mg Ratio	pH	CEC
		Bicarb	Bray-P1	%P	%K	%Mg	%Ca		pH	meq/100g
1-0%	0.1	4	4	-	2.6	7.3	88.4	0.36	8.6	15.9
1-25%	2.5	4	5	-	2.4	8.2	87.4	0.29	7.7	15.7
1-50%	6.0	5	7	1	2.2	7.8	88.2	0.28	7.4	15.5
1-75%	16.4	7	11	1	1.5	7.0	83.4	0.21	6.9	17.3
2-25%	0.8	5	7	1	2.4	9.9	84.5	0.24	8.9	16.9
2-50%	3.4	9	15	1	1.6	11.6	81.8	0.14	9.3	29.2
2-75%	13.5	22	25	2	1.4	14.3	78.3	0.10	9.5	46.0
3-0%	0.1	2	1	-	0.6	3.7	95.1	0.16	8.9	33.5
3-25%	1.4	2	1	-	0.6	3.4	95.4	0.18	7.7	37.7
3-50%	5.7	4	4	-	0.6	4.0	95	0.15	7.3	37.9
3-75%	21.5	6	9	1	0.8	4.4	90	0.18	6.8	28.5
4-25%	0.9	4	3	-	0.8	4.9	92.5	0.16	9.3	38.9
4-50%	4.6	6	13	1	0.7	8.5	88	0.08	9.3	40.9
4-75%	8.9	7	10	1	0.7	10.2	84.6	0.07	9.4	42.6

* Very Low, Low, Medium, Good

Nutrients. Soil carbon (C) and nitrogen (N) concentrations increased as the amount of organic constituent increased in the Technosol, but were both present in greater amounts in woody residuals than primary paper sludge (Figure 16).

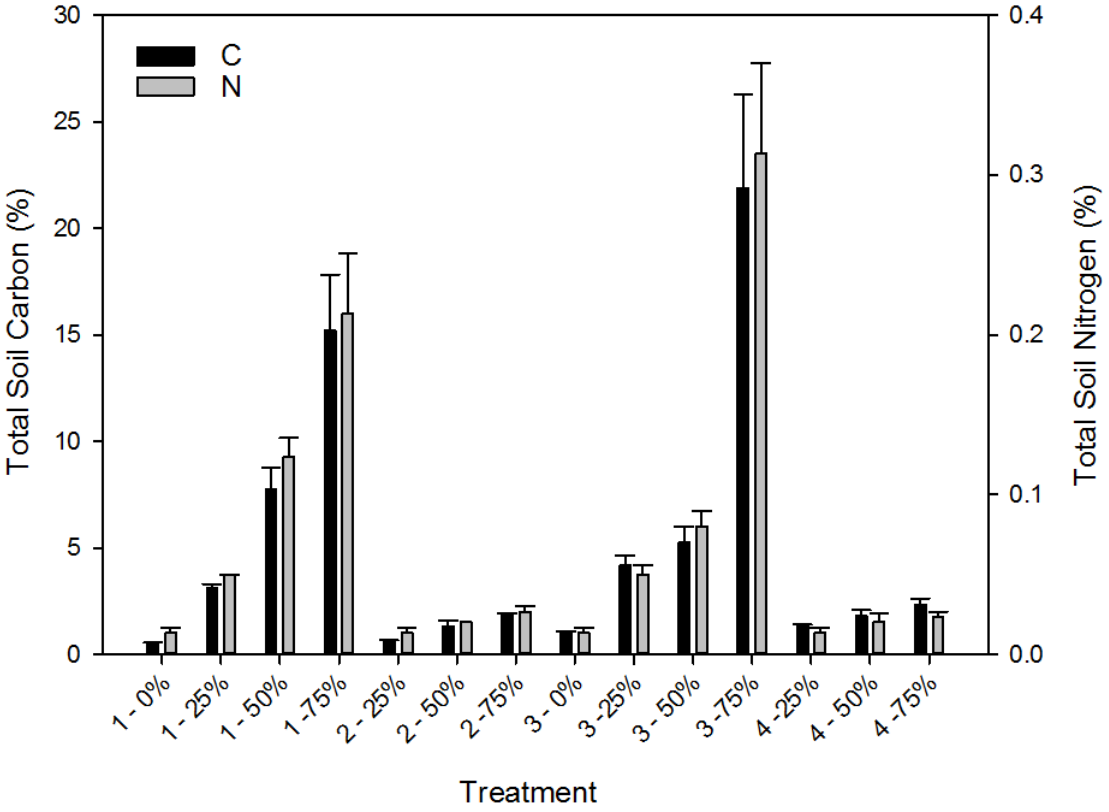


Figure 16. Total soil carbon and nitrogen in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

Soil total sulphur (S) concentrations were much higher in Technosols that contained intermediate volcanic mine rock than in Technosols that contained metasedimentary mine rock, and increased more significantly as the amount of woody residuals in a Technosol increased than primary paper sludge (Figure 17).

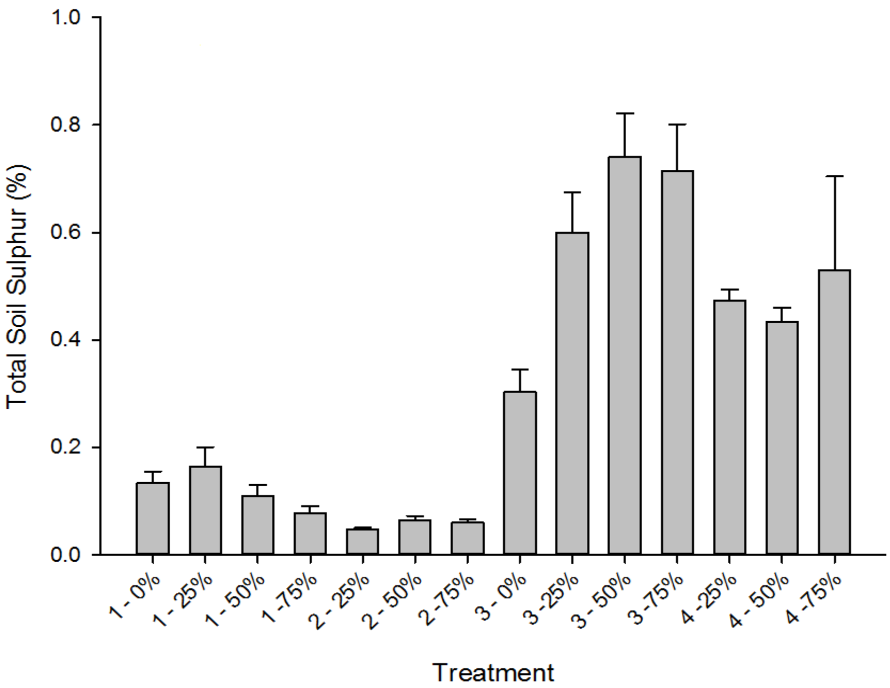


Figure 17. Total soil sulphur in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

Calcium (Ca) was more biologically available in soils that contained woody residuals than in soils that contained primary paper sludge, although there was more total Ca present in soils that contained primary paper sludge (Figure 18). Ca was also present in higher total amounts in soils that contained intermediate volcanic mine rock, than in soils that contained metasedimentary mine rock. Magnesium (Mg) was more biologically available in soils that contained primary paper sludge, than in soils that contained woody residuals, although there was slightly more total Mg present in soils that contained woody residuals (Figure 19). The Ca:Mg ratio based on total Ca and Mg ranged from 3.55 – 7.34 for all Technosols (Table A1), but when Ca:Mg ratio was based on bioavailable concentrations of Ca and Mg, the Ca:Mg ratio was much lower in Technosols constructed with primary paper sludge (1.36 – 4.60) and higher in Technosols that contained woody residuals (10.70 – 14.47) (Table A2).

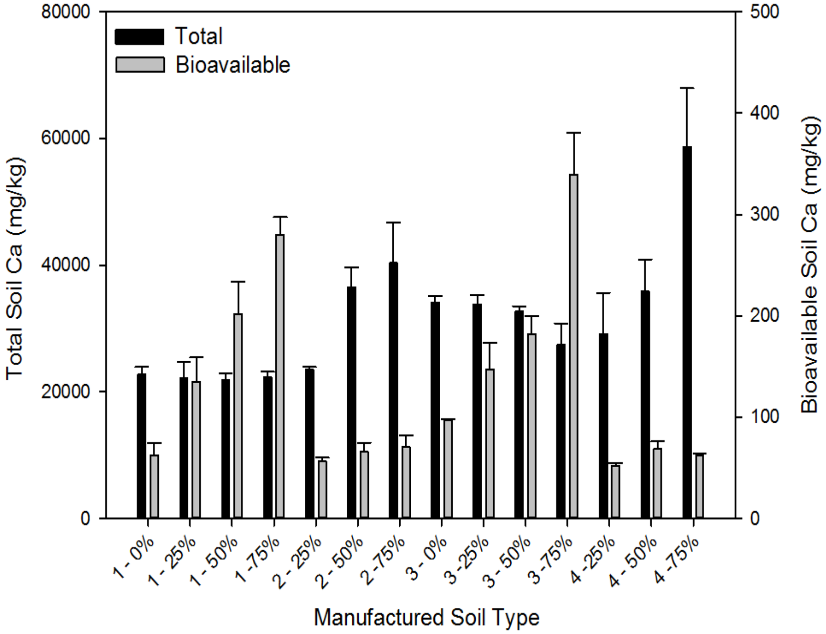


Figure 18. Total and bioavailable soil Ca in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

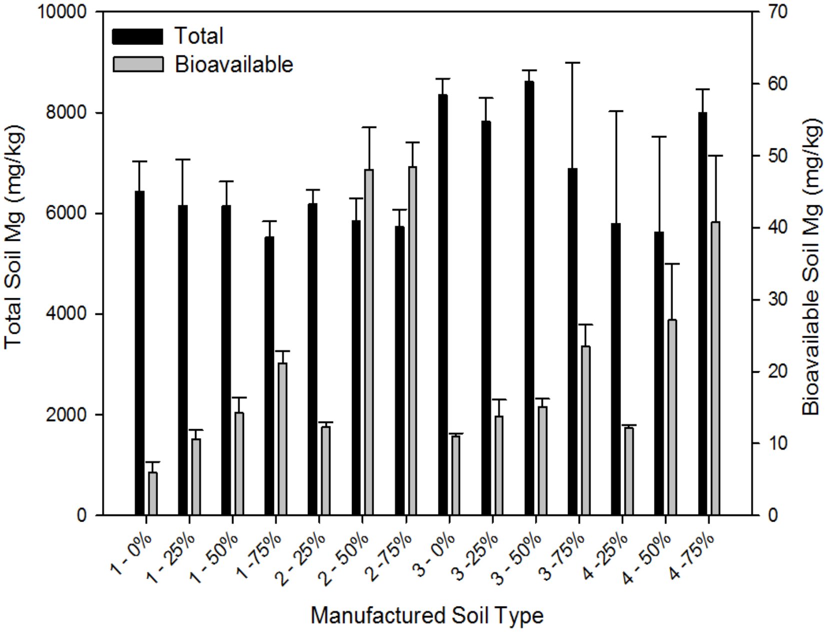


Figure 19. Total and bioavailable soil Mg in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

Phosphorus (P) was more biologically available in soils that contained woody residuals (Figure 20). Potassium (K) was present in higher total and bioavailable amounts in soils that contained intermediate volcanic mine rock than metasedimentary mine rock (Figure 21). Soil fertility results reflect the trends in total and bioavailable macronutrients described above. Ca was present in all soils in sufficient amounts (Table 8); Mg was present in sufficient amounts soils that contained metasedimentary mine rock (Table 8); P was not biologically available in sufficient amounts in any soils (Table 8); K was present in sufficient amounts in soils that contained metasedimentary mine rock and 50% or 75% woody residuals (Table 8).

Sufficiency ranges adapted from Mills & Jones (1996) and Plank & Donohue (2000) indicated that ryegrass was able to obtain sufficient amounts of Ca, Mg, and K from all soils after five and ten weeks of growth (Table 9 & 10). Ryegrass was able to obtain sufficient amounts of P in all soils after 5 weeks of growth, but after 10 weeks of growth, only ryegrass grown in soils that contained woody residuals obtained sufficient amounts of P (Table 9 & 10).

Copper (Cu) and iron (Fe) were more biologically available in soils that contained primary paper sludge than in soils that contained woody residuals (Figure 22 & 23). Manganese (Mn) was more biologically available in soils that contained primary paper sludge when the mine rock constituent of the soil was metasedimentary; Mn was more biologically available in soils that contained woody residuals when the mine rock constituent of the soil was intermediate volcanic (Figure 24). Mn was present at higher total amounts in soils that contained woody residuals compared to primary paper sludge, and intermediate volcanic mine rock, compared to metasedimentary mine rock. Zinc (Zn) was present at higher total amounts in soils that contained woody residuals compared to primary paper sludge (Figure 25).

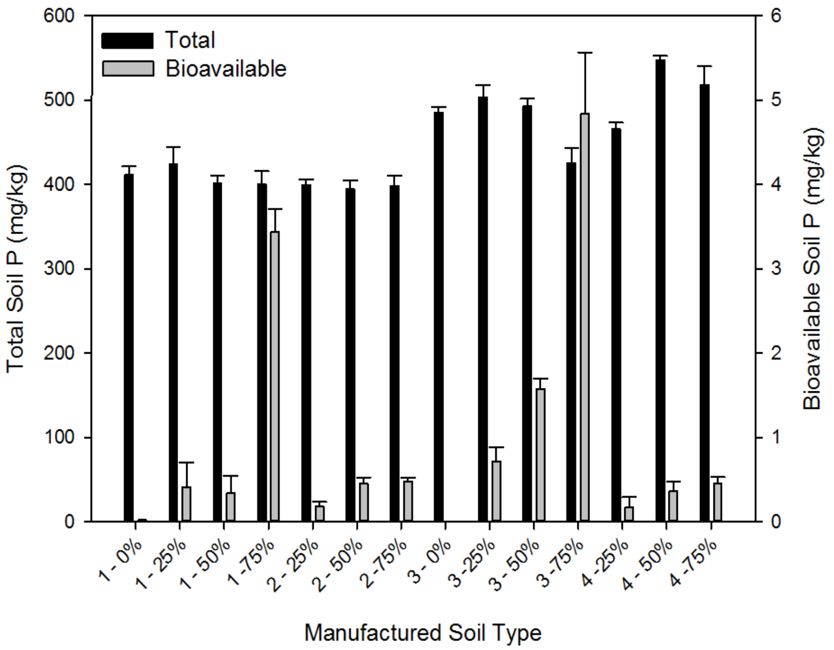


Figure 20. Total and bioavailable soil P in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

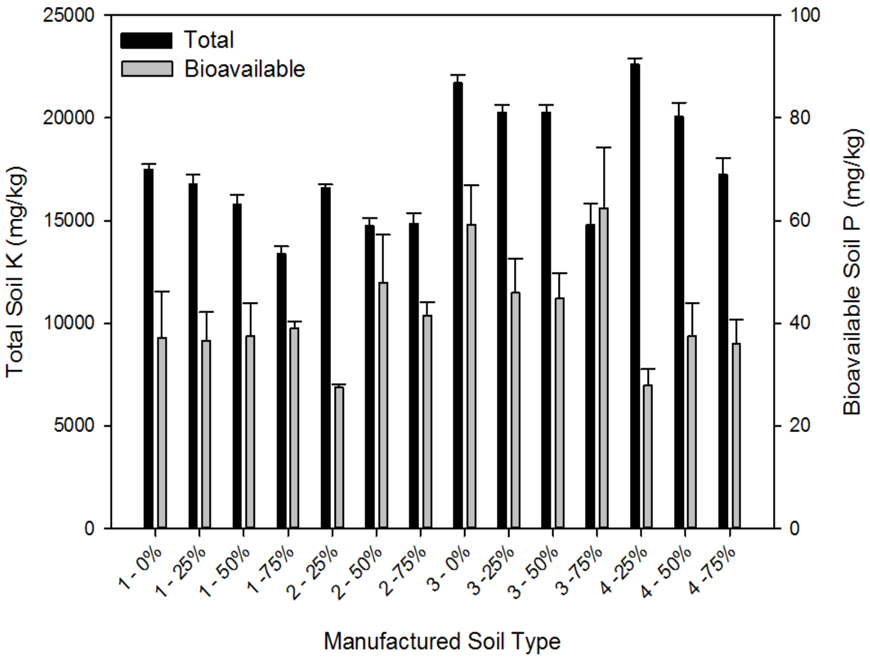
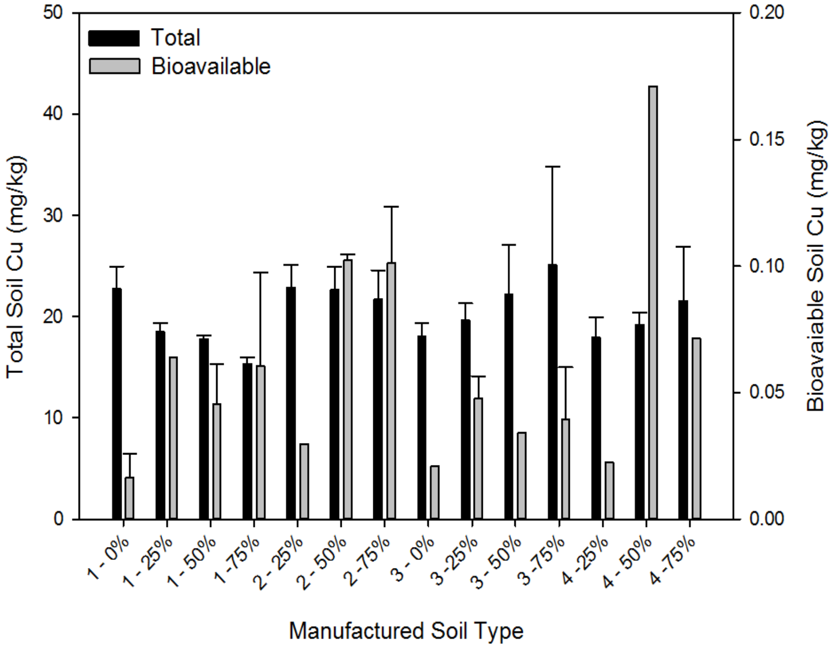


Figure 21. Total and bioavailable K soil in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.



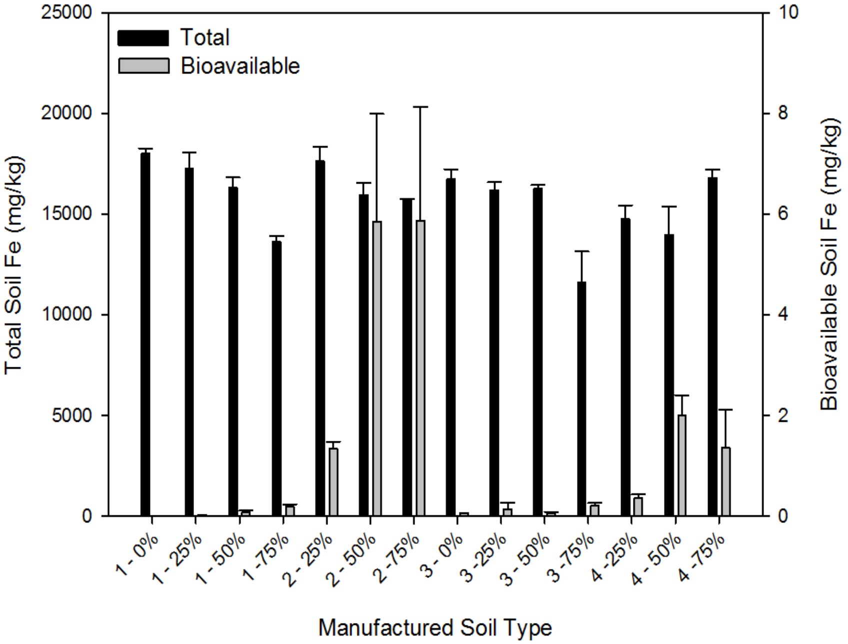


Figure 22. Total and bioavailable soil Cu in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

Figure 23. Total and bioavailable soil Fe in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

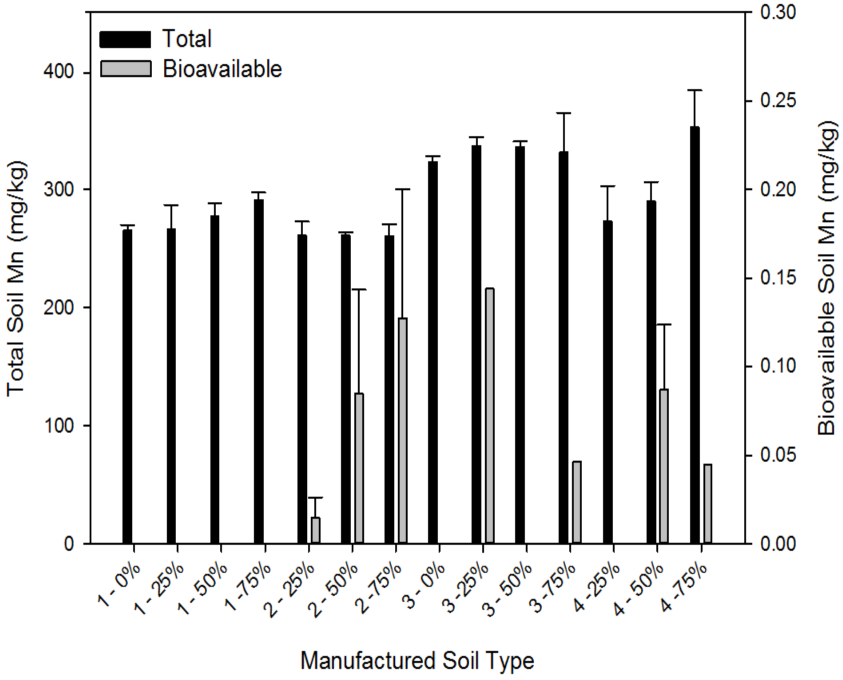


Figure 24. Total and bioavailable soil Mn in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

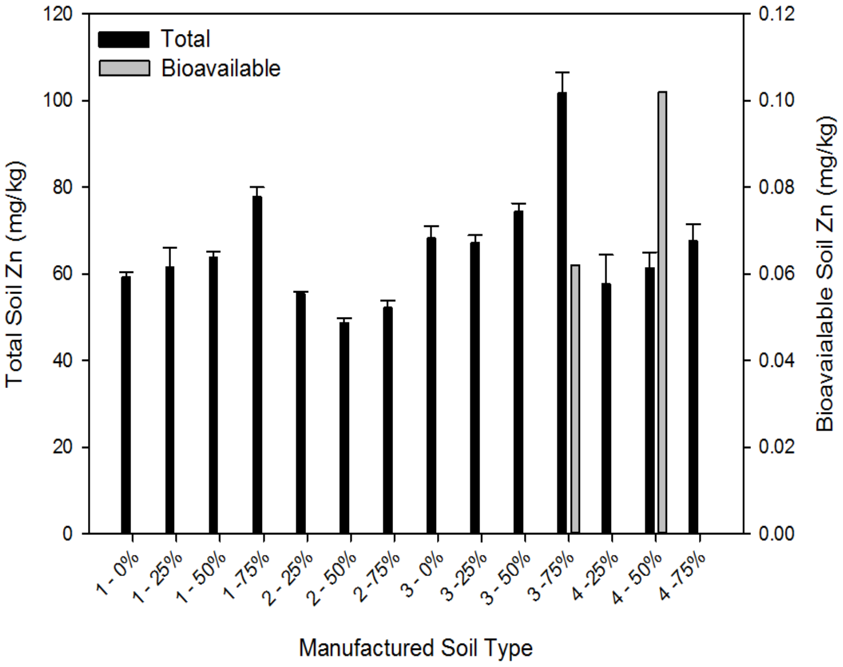


Figure 25. Total and bioavailable soil Zn in Technosols made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. Standard error bars are shown. n = 3 for each Technosol.

Soil fertility results reflect the trends in total and bioavailable macronutrients described above. Cu was present in sufficient amounts in soils that contained metasedimentary mine rock (except for those soils with 75% organics) and in soils that contained intermediate volcanic mine rock and woody residuals (Table 8); Fe, Mn and Zn were present in sufficient concentrations in all soils (Table 8). Sufficiency ranges adapted from Mills & Jones (1996) and Plank & Donohue (2000) indicated that ryegrass was able to obtain sufficient amounts of Cu, Fe, and Zn from all soils after five and ten weeks of growth (Table 9 & 10). Ryegrass was also able to obtain sufficient amounts of Mn in all soils after 5 weeks of growth, but after 10 weeks of growth, only ryegrass grown in soils that did not contain woody residuals obtained sufficient amounts of Mn (Table 9 & 10).

Above ground plant biomass was negatively correlated (Spearman) to bioavailable soil Mg ($p < 0.001$, $r = -0.524$), Cu ($p < 0.005$, $r = -0.656$) and Fe ($p < 0.001$, $r = -0.550$) (Figure 26). Below ground plant biomass was negatively correlated (Pearson) to total soil Mg ($p < 0.01$, $r = 0.46$), K ($p < 0.05$, $r = 0.32$) and Fe ($p < 0.05$, $r = 0.31$) (Figure 27).

Table 8. Soil fertility values for select macro and micro nutrients in Technosols manufactured from finely crushed metasedimentary (1&2) and intermediate volcanic (3 & 4) mine rock and woody residuals (1 & 3) and primary paper sludge (2 & 4) with ranges indicated by shading*.

	Potassium	**Magnesium**	**Calcium**	**Sulfur**	**Zinc**	**Manganese**	**Iron**	**Copper**
Sample	**K ppm**	**Mg ppm**	**Ca ppm**	**S ppm**	**Zn ppm**	**Mn ppm**	**Fe ppm**	**Cu ppm**
1-0%	159	140	2820	11	5.0	19	197	0.7
1-25%	146	155	2740	20	5.6	22	164	0.5
1-50%	134	145	2730	14	7.4	27	162	0.5
1-75%	99	145	2880	10	10.2	33	127	0.4
2-25%	156	200	2850	37	4.2	15	184	0.5
2-50%	187	405	4780	104	4.3	21	196	0.5
2-75%	256	790	7200	196	6.0	46	278	0.2
3-0%	80	150	6370	26	1.3	52	105	0.5
3-25%	93	155	7200	51	3.1	63	100	0.5
3-50%	92	180	7200	25	7.4	60	92	0.6
3-75%	93	150	5120	17	12.2	54	92	0.5
4-25%	114	230	7200	62	1.9	54	135	0.2
4-50%	105	415	7200	104	2.8	43	118	0.3
4-75%	119	520	7200	135	3.8	49	106	0.2

*Very Low, Low, Medium, High, Very High

Table 9. Plant accumulation of select macro and micro nutrients in the shoots of ryegrass harvested after 5 weeks of growth. Sufficiency ranges are indicated and values that fall below, within or above the sufficiency range are indicated by shading*.

	Macronutrients				**Micronutrients**			
	Ca (%)	**Mg (%)**	**K (%)**	**P (%)**	**Cu (ppm)**	**Fe (%)**	**Mn (ppm)**	**Zn (ppm)**
Metasediments								
+Woody Residuals								
0%	0.61	0.25	6.17	0.40	11.47	0.07	102.90	39.73
25%	0.79	0.23	5.96	0.49	10.42	0.06	70.57	60.10
50%	0.95	0.23	5.80	0.54	9.04	0.06	57.20	55.23
75%	1.05	0.24	5.87	0.62	10.13	0.05	46.67	73.60
+ Paper Sludge								
25%	0.48	0.60	5.58	0.45	12.81	0.06	144.00	44.73
50%	0.83	0.80	5.00	0.39	11.13	0.20	177.33	36.90
75%	0.37	0.75	5.88	0.43	9.28	0.05	165.67	39.53
Intermediate Volcanics								
+Woody Residuals								
0%	0.58	0.35	6.77	0.26	9.90	0.06	117.93	22.03
25%	0.89	0.26	5.90	0.48	10.06	0.06	74.23	60.13
50%	0.97	0.25	6.05	0.58	11.30	0.05	64.30	79.60
75%	1.09	0.24	6.31	0.71	8.60	0.05	54.50	71.20
+ Paper Sludge								
25%	0.74	0.83	5.58	0.40	11.65	0.13	137.67	38.80
50%	0.58	0.89	5.78	0.42	9.03	0.11	209.67	37.17
75%	0.51	0.89	6.02	0.42	12.27	0.07	191.67	45.37
Sufficiency Range	0.20 – 1.00	0.14– 1.00	2.50– 5.00	0.20 – 0.50	4.5 – 15	0.003 – 0.02	20 – 150	18 – 70

*Below range, within range, above range

Table 10. Plant accumulation of select macro and micro nutrients in the shoots of ryegrass harvested after 10 weeks of growth. Sufficiency ranges are indicated and values that fall below, within or above the sufficiency range are indicated by shading*.

	Macronutrients				**Micronutrients**			
	Ca (%)	**Mg (%)**	**K (%)**	**P (%)**	**Cu (ppm)**	**Fe (%)**	**Mn (ppm)**	**Zn (ppm)**
Metasediments								
+Woody Residuals								
0%	0.85	0.26	4.74	0.11	6.95	0.08	176.00	23.73
25%	1.38	0.28	4.99	0.26	6.14	0.07	107.57	57.20
50%	1.46	0.22	4.00	0.25	5.27	0.05	58.17	39.37
75%	1.63	0.24	4.35	0.36	7.50	0.05	47.53	68.73
+ Paper Sludge								
25%	0.73	0.68	3.31	0.15	7.14	0.08	261.33	26.70
50%	0.76	1.24	2.70	0.13	10.67	0.18	480.33	32.00
75%	0.53	1.06	2.89	0.12	8.16	0.05	537.33	27.50
Intermediate Volcanics								
+Woody Residuals								
0%	0.82	0.34	5.40	0.11	6.91	0.05	265.33	14.67
25%	1.28	0.25	4.06	0.23	5.81	0.04	103.53	62.43
50%	1.21	0.22	4.03	0.24	5.68	0.04	61.03	42.27
75%	1.51	0.22	3.94	0.34	4.63	0.05	48.37	53.90
+ Paper Sludge								
25%	0.70	0.95	3.72	0.13	8.02	0.09	282.33	23.70
50%	0.97	1.11	3.42	0.14	7.42	0.12	427.33	23.23
75%	0.63	1.07	2.85	0.13	8.55	0.06	525.00	34.47
Sufficiency Range	0.20 – 1.00	0.14– 1.00	2.50– 5.00	0.20 – 0.50	4.5 – 15	0.003 – 0.02	20 – 150	18 – 70

*Below range, within range, above range

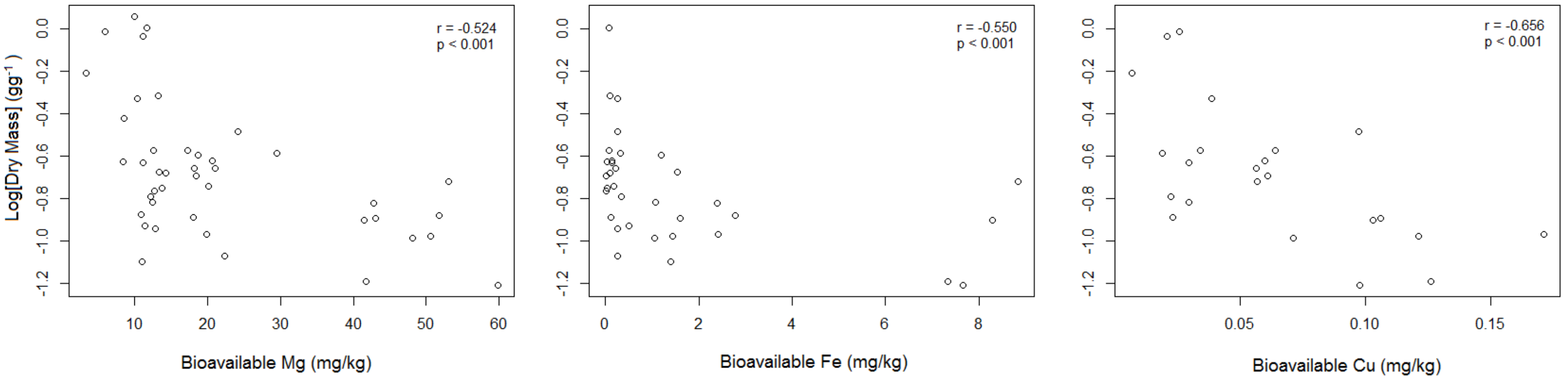


Figure 26. Significant correlations (Spearman) of the shoot biomass of ryegrass grown in Technosols for 10 weeks, to bioavailable soil Mg, Cu, and Fe. n = 42.

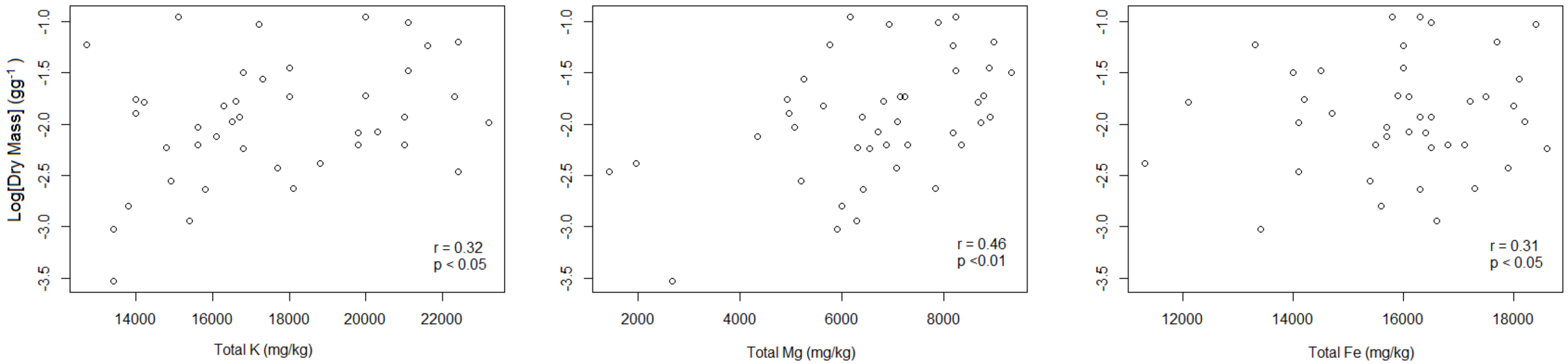


Figure 27. Significant correlations (Pearson) of the root biomass of ryegrass grown in Technosols for 10 weeks, to total soil K, Mg, Fe. n = 42.

3.3 – Discussion

The chemical data indicating elevated levels of plant nutrients and more neutral pH of the woody residual parent material, suggest that the most successful growth medium blends with woody residuals would most likely be predicted; woody residuals had a more neutral pH and a lower C:N ratio than primary paper sludge. Although paper sludge contained fractionally more total macronutrients than woody residuals, the pH of the primary paper sludge could render the reserve of nutrients potentially less bioavailable. The pH of the primary paper sludge (8.5-9.5) is higher than the optimal pH range of many plants, including annual ryegrass which prefers soils at pH 5.5-7.5 but tolerates a range of soil pH from 5.0 to 7.8 (Hannaway et al. 1999) and boreal forest vegetation which prefers more acidic soils (Larsen 1980). Total and bioavailable analysis of the Technosols do show that soils containing primary paper sludge had less bioavailable nutrients (P, N, S, Ca, K, Cu) than soils containing the same amounts of woody residuals (Figure 16, 17, 18, 20, 21, 22). Although intermediate mine rock had higher total and bioavailable concentrations of nutrients than metasedimentary mine rock, both rock types had similar pH values and water holding capacities. If a substantial amount of organics needed to be added to the mine rock to produce a viable soil, differences in the total nutrient concentrations of the soil will more heavily be influenced by the actual organic constituent used, or by any interactions resulting from the mixing of the rock and organic constituents.

3.31 – Thinned Harvest Biomass

During the first 5 weeks of the experiment, 500 mL of water was administered to each pot, three times weekly. The water, even with drainage through the bottom, was sufficient to prevent the soil from drying out completely before the next watering event. Thus, despite the Technosols having different water holding capacities (Figure 15), the watering regime should have prevented water availability from becoming a limiting resource during the first 5 weeks of the study. After 5 weeks of growth, there were no significant differences in above ground biomass yield when treatments were compared separately, but when they were grouped based on their soil constituents above ground biomass was significantly different depending on the rock constituent used and its interaction with the organic constituent. Interestingly, the highest above ground biomass developed on pure intermediate volcanic mine rock, with the lowest yield from soils of pure metasedimentary mine rock. Ryegrass grown in pure metasedimentary mine rock also had the highest below ground biomass yield and thus, the highest root:shoot ratio, which indicate that Technosols of pure metasedimentary mine rock performed least favourably as a growth medium out of all Technosols tested. Differences in below ground biomass between the two pure mine rock treatments probably resulted from differences in nutrient availability. Soils containing only metasedimentary mine rock had significantly lower above ground biomass and significantly higher below ground biomass than soils consisting of only crushed intermediate volcanic mine rock. The bioavailability of macronutrients (S, Ca, Mg, K) was much lower in soils consisting only of metasedimentary mine rock (Figure 17, 18, 19 & 21).

Although ryegrass grown in pure intermediate volcanic mine rock had the highest above ground biomass yield, this material also had the second highest below ground biomass yield, and the second highest root:shoot ratio of the soils tested, when grouped based on soil constituents (Table 5). This indicates that although these Technosols were able to produce a large amount of above ground biomass, they had to develop an extensive root system to acquire adequate below ground resources to do so. Poorter and Nagel (2000) state that plants will shift their biomass allocation towards parts of the plant that will help acquire limiting resources; a phenomenon termed the functional equilibrium hypothesis. In the case of limiting below ground resources, such as nutrients or water, plants will shift biomass allocation towards the roots; a shift is reflected in higher root:shoot ratios. When three different strains of perennial ryegrass were grown in ‘high’ and ‘low’ nutrient treatments, in all cases, root weight obtained from plants grown in the low nutrient treatment was higher than those grown in high nutrient treatments (Vose 1963). In this study, differences in root biomass between high and low nutrient treatments were also reflected in elevated root:shoot ratios in low nutrient treatments. Although the use of soils in reclamation that will promote the development of extensive root systems, which could reduce soil erosion and promote soil stability, may seem beneficial, the attainment of these benefits may compromise growth conditions which may also be sacrificing a sound base for the long term development of a sustainable and productive ecosystem.

Technosols that did not contain and organic component also had lower levels of plant nutrients (P, K, Mg, Ca, S, N, Zn and Mn) than Technosols composed of at least 25% organics. Non-organic soils, and soils that contained 25% organics had much lower levels of plant available water than soils that contained at least 50% and 75% of an organic constituent (Table 6). Moisture retention is particularly important in the rooting zone where increased soil moisture will help with root survival in drought conditions. In general, organics retain more moisture (in the form of capillary water) than sandier soils that have larger grain sizes and tend to be more well-drained (Eash et al. 2008). The capability of the Technosol to retain adequate soil moisture will be critical in field application on exposed and dry slopes.

When an organic constituent was added to metasedimentary mine rock, nutrient availability increased substantially. Primary paper sludge increased availability of Mg (Figure 19), with woody residuals increasing the availability of Ca and K (Figure 18 & 21). Paper sludge also increased the amount of bioavailable Mg in soils containing intermediate volcanic mine rock, which initially had higher amounts of bioavailable Mg than metasedimentary mine rock. However the bioavailable Mg increase was not as great as that in soils that contained metasedimentary mine rock. As woody residuals were added to the two rock types Ca availability increased dramatically in soils that contained metasedimentary mine rock, its availability was almost equal to that in soils that contained intermediate volcanic mine, even though intermediate volcanic mine rock contained higher amounts of bioavailable Ca in 0% organic blends. These changes in nutrient availability may help explain the interaction effect between rock and organic type on shoot biomass produced by ryegrass after 5 weeks of growth. However, this interaction was more likely deemed statistically significant because of the drastic difference in shoot biomass production between the non-organic soils. When soils were grouped based on rock and organic constituents, shoot biomass yield was not significantly different in treatments that contained organics but soils containing only metasedimentary mine rock produced significantly less shoot biomass.

The interaction effect between rock and organic type of a Technosol may have resulted from large changes in CEC and pH as primary paper sludge or woody residuals were added to the two subtypes of mine rock. Primary paper sludge increased soil CEC and pH; increasing the amount of woody residuals in the soil did not seem to increase soil CEC in any significant manor, although it lowered pH to near neutral ranges (optimal for ryegrass production). Additions of primary paper sludge to mine rock caused the pH to increase above the optimal range for ryegrass production, but also increased the CEC of the soil, which in turn increased the soil’s capacity to hold nutrients. Significantly lower below ground biomass yields were observed in soils that contained organics; specifically, when primary paper sludge was added to metasedimentary mine rock (increased an initially low CEC at the cost of a high pH) and the addition of woody residuals to intermediate volcanic mine rock induced no change to a high CEC, but decreased soil pH to the optimal level. Additions of woody residuals always improved soil quality, possibly by decreasing soil pH. Primary paper sludge only improved soil quality when CEC was initially low. The existence of a negative correlation between the amount of woody residuals in a soil and the root:shoot ratio, and the absence of a correlation between primary paper sludge and root:shoot ratio, support the concept of a trade-off between pH and CEC as organics were added to a soil. Although increasing the CEC of soils with primary paper sludge could be beneficial if a pH range of 8-10 was desirable, Technosols manufactured with this organic constituent would be unsuitable for use in the boreal forest ecosystem where indigenous vegetation is adapted to acidic soils. If soils with a more neutral or higher pH were used in this area, invasive or non-native plant species may be able to establish there, and out-compete native vegetation. For primary paper sludge to be considered as a viable component of Technosols that will be used in the boreal forest ecosystem, an amendment that would decrease pH must also be applied. Elemental sulphur is an option which could be ecologically feasible, as it would lower soil pH to the desirable range, and increase sulphur levels in the Technosols which are lacking in this essential nutrient. However, the addition of this amendment may not be economically feasible, and may also cause other critical nutrients (such as N, P, K, Mg, and Ca) to become less bioavailable if soil pH drops below 5.5 (Lucas & Davis 1961). Other studies examining papermill biosolids and paper sludge as soil amendments have reported a wide range of pH values from 6.9 to 8.4 (Battaglia et al. 2007; Calace et al. 2002a, 2003; Gagnon & Ziadi 2012; Ochoa de Alda 2008; Okonski et al. 2003). Although the primary paper sludge investigated in this study may not be appropriate to manufacture soils for use in the boreal ecosystem due to high pH values, if primary paper sludge was obtained from other sources, it may have different chemical properties required to be a viable soil component.

3.32 – Final Harvest Biomass

After 5 weeks of growth the watering regime was reduced from 500 mL of water three times a week to 250 mL of water three times a week. As the frequency of watering remained consistent, with soils that did not contain organics not having the moisture retention capacity to hold 250 mL of water at any given watering event, especially when receiving 500 mL from weeks 1-5, there was no real change to the watering regime for plants grown in these soils. Water was a growth limiting factor from the start for non-organic soils, a condition remaining consistent throughout the experiment. However, soils that contained organics were able to hold more than 250 mL of water the reduction in the volume of water administered induced moisture limitations for plants grown in soils containing organics. Since the watering regime was changed halfway through the experiment, and some soils contained plants already adapted to these growth conditions, we cannot directly compare treatments to each other and infer responds to an environment with less water availability. Thus, plants that had already developed an extensive root system in the first 5 weeks of the experiment in soils containing no organics, would have the means necessary to acquire limited resources (i.e. water), while plants that did not develop such extensive root systems in the beginning phase of the experiment (soils containing organics) would have to redirect energy to this task. Further, during the 6-10 week period of the growth experiment, the chamber temperatures became quite high, reaching up to 30°C. These increased temperatures, along with the reduced watering regime may have caused plants to go from lush and green to drooping and yellow (Figure 28).

Figure 28. Physical condition of annual ryegrass before thinning (L) and before final harvest (R).

Ryegrass samples harvested at the end of the 10 week growth period had significant different below ground biomass when soils were grouped based on organic type. The ryegrass grown in soils that contained organics were expected to develop more extensive root systems to acquire sufficient amounts of water as resources became limited. Soils that contained no organics still yielded the highest root biomass. This seems logical, because organic soils had higher water holding capacity and nutrient availabilities which would not require such an extensive root system to capture the necessary water and nutrients, as those in non-organic soils. Water resources became the most limiting resource, with soils drying completely dried before the following watering event. Given the hot conditions, it is not surprising that plants did yellow and dry due to extremely stressful conditions.

Significantly greater above ground biomass was obtained from soils that did not contain organics. As the ryegrass grown in non-organic soils already had an extensive root system developed, plants were able to allocate more energy into generating productive above ground biomass. Ryegrass grown in organic soils had to expend energy in root development, consequently limiting above ground biomass production to suffer as a consequence. Larcher (1975) notes that developing root systems will divert energy from development of above ground biomass. The results of this study show that most of the Technosols that had significantly lower root biomass production in the first five weeks of the growth study also had significantly lower shoot biomass during the last five weeks of the growth study (Figure 4 & 9), as these plants suddenly had to divert energy into developing more extensive root. These results are in agreement with the findings of Larcher (1975) who demonstrated that ryegrass grown in soils that had significantly higher root biomass during weeks 1-5, also had significantly higher shoot biomass during weeks 6-10.

As root development was not significantly different after five weeks in soils that contained organics, we may be able to conclude that woody residuals out performed primary paper sludge as an organic soil constituent, based on the significantly higher shoot biomass yield from the soils containing woody residuals (Figure 10). Although ryegrass root:shoot ratios were not significantly different between soils containing different organics, indicating that plants in all soils were experiencing stress that resulted in allocation of biomass proportionally to the same areas. Given equal allocation, more total biomass yields from one type of soil would indicate a more successful growth medium. Woody residuals may have been a more successful organic soil constituent than primary paper sludge because of increased amounts of available phosphorus (Figure 20), carbon, nitrogen (Figure 16) and sulphur (Figure 17). Although woody residuals had very low levels of manganese, this macronutrient is not required by plants as large a quantity as the macronutrients such as P, S and N. Vose (1963) found that increased nitrogen will decrease root:shoot ratio by greatly increasing above ground biomass, and could be contributing to differences in shoot biomass yields from week 6-10 in our experiment. Jupp and Newman (2014) demonstrated that during drought, perennial ryegrass ceased uptake of phosphorus, even when there were adequate amounts in the soil. After 10 weeks of growth, nutrient sufficiency ranges indicated that plants were taking up less phosphorus than needed, even when soils contained adequate amounts. Only ryegrass grown in soils that contained woody residuals obtained sufficient amounts of phosphorus. Jupp and Newman (2014) concluded that the ability of the plant to take up nutrients was the main cause of reduced phosphorus uptake during drought rather than reduced bioavailability of nutrients, although both were affected by drought. These results point to the importance of organic matter in soils to increase soil water holding capacity during times of drought. Soils that contained primary paper sludge had slightly lower water holding capacities than soils that contained woody residuals, and also had lower amounts of phosphorus. These two factors, along with increased levels of select macronutrients in soils that contained woody residuals could have resulted in increased shoot biomass of ryegrass grown in soils that contained woody residuals.

Significant negative correlations between bioavailable Mg, Cu, and Fe and the above ground biomass harvested after 10 weeks of growth may have been caused by a shift in biomass allocation during the 6-10 week growth period. Thus, as the availability of Mg, Cu, and Fe increased shoot biomass decreased, an observation possibly due to the fact that during the 6-10 week growth period, biomass was being primarily accumulated in the roots, rather than the shoots, of plants grown in soils that contained organics. The correlation between bioavailable soil Fe and shoot biomass is heavily influenced by data from four samples only (Figure 26). These data correspond to samples from the 2-50% and 2-75% soil, which contain metasedimentary mine rock and primary paper sludge. As previously discussed, the ryegrass grown in these soils (containing primary paper sludge) increased their shoot mass the least during this latter time period, due to limiting below ground resources. Soils containing primary paper sludge also contained the most amounts of Mg and Cu (Figure 19 & 22).

Below ground biomass was positively correlated to total soil Mg, K and Fe but not to bioavailable soil Mg, K, or Fe (Figure 27). The bioavailable concentration of an element is the amount of a nutrient that is available in the soil for plants to access and use for biomass production, whereas a total elemental concentration is the total amount of a specific nutrient in the soil, including the large fraction that is not bioavailable. Functionally, biomass production should logically be correlated to bioavailable concentrations of elements. Thus there was probably no causal relationship between total soil Mg, K or Fe and root biomass, especially since all ryegrass accumulated sufficient amounts of Mg, K, and Fe throughout the entire growth period (Table 9 & 10). However, total Mg and K were present at greater amounts (Figure 19 & 21) in soils that did not contain organics, coincidentally the soils that also had the highest root biomass yields (Figure 11).

3.33 – Conclusions, Implications and Recommendations

Although the quantity and distribution of water administered during this experiment was modelled after precipitation events of Northern Ontario, the watering events were spaced at regular intervals with set volumes delivered at each event. In the field, precipitation events may be irregular in both frequency and amount. Although soils were assessed under laboratory conditions and may behave differently in a field setting, results of this experiment can be used to predict how these soils will perform in an applied setting. Under drought conditions Technosols must contain sufficient organic matter to increase water holding capacity, to help sustain plant growth. In this experiment, the Technosols must contain at least 50% organics had greater water holding capacity than soils that contained 25% or less organic material. Any future land reclamation work should also take into consideration the changing environmental climate which brings the possibility of more prolonged and frequent drought periods which will influence plant community composition and colonization. Therefore manufacturing a soil with higher organic content is recommended.

The blending of woody residuals decreased the pH of the Technosol to a neutral range, and provided sufficient amounts of nutrients to sustain plant growth. Primary paper sludge did improve selected soil properties by drastically increasing soil CEC, but the increasing amounts of primary paper sludge also increased soil pH to a level that is not appropriate for application in the boreal forest ecosystem. The use of elemental sulphur to decrease the pH of Technosols manufactured with primary paper sludge is not an economically feasible option for a large-scale reclamation project. Thus the primary paper sludge alone is not recommended to manufacture soils for land reclamation initiatives in the boreal forest ecosystem.

Woody residuals and finely crushed mine rock have been identified as a viable components of Technosols developed for use in boreal land reclamation initiatives. Woody residuals provided adequate amounts of bioavailable plant nutrients at an appropriate pH. Future studies could investigate decomposition and incorporation rates of the organic soil component, with focus on enhancing functional microbial processes that encourage nutrient cycling and soil aggregation. Technosols should contain over 25% organics to ensure retention of sufficient plant available water during periods of reduced precipitation, although organic ratios of 50% or higher may be more fitting to certain field conditions. Both types of finely crushed mine rock examined in this study could be used in future to manufacture soils. Given that both mine rock subtypes coexist in the open pit mine, and results indicated no significant difference in biomass production when similar organic blends were compared between rock types, the cost of separation may not be necessary and both rock types can be used when manufacturing soils for reclamation. Future studies should investigate the effect of producing different particle size distribution of the crushed mine rock on water holding capacity, nutrient availability and selected physical and chemical properties.

The results of this study indicate that Technosols comprised of 50% volume or higher of woody residuals and blends of finely crushed mine rock can form an effective growth media by increasing both water holding capacity and concentrations of essential plant nutrients to result in increased shoot biomass and decreased root:shoot ratios of annual ryegrass.

Chapter 4

4 Soil Moisture and Temperature Regime of two Spolic Technosols manufactured for Mine Reclamation in the Boreal Forest Ecosystem

In this study, woody residuals and finely crushed mine rock were used to produce two Technosols comprised of a 40% and 80% organic component, based on the laboratory growth study (Chapter 3). The Technosols were incorporated into field lysimeters which allowed the monitoring of soil moisture, temperature and water potential. These measurements, in conjunction with soil pore water samples, were used to describe the behaviour of the Technosols void of vegetation and provide a reference base for these soil regimes as select boreal forest vegetation is transplanted on to the field lysimeters in future seasons. The study was guided by the following hypotheses: Technosols that contained higher amounts of organics would have increased levels of soil moisture throughout the soil profile due to the increased field capacity of the Technosol; Technosols of greater depth would have increased levels of soil moisture at depth due to reduced evaporation; Soil moisture will be less dynamic as depth within the soil profile increases; Technosols that contain higher amounts of organics will have increased levels of plant nutrients; Technosols that contain higher amounts of bioavailable plant nutrients and higher soil moisture within the rooting zone will have higher rates of vegetation survival.

4.1 – Methods

4.11 – Field Lysimeter Construction

Twelve reclamation plots were constructed on the former Golden Giant mine site at Barrick Gold Corporation’s Hemlo Operations, in July 2012. Plot construction was conducted as follows:

A 5 m x 5 m berm was constructed and lined with an impermeable geomembrane fitted with a drainage tube connected to a large holding vessel for flow through water sampling. The membrane was covered with a layer of pea gravel and backfilled with mine rock (40 – 100 cm in diameter), so that a raised pile of mine rock was formed, about one meter in height. The coarse mine rock pile was levelled, capped with approximately 15 cm of gravel to the level of the berm using smaller gravel sized (< 2 cm in diameter) crushed mine rock. This raised base of the reclamation plot had an area of approximately 5 m x 5m. Plots were then capped with a Technosol raked out level to 30 or 60 cm depths (Figure 29).

Figure 29. (L) Base of a reclamation plot, showing the front drainage tube to collect percolation waters. (R) Depositing a Technosol on the top of the reclamation plot.

4.12 – Technosol Materials and Construction

Two Technosols were constructed by combining woody residuals (Domtar White River Sawmill, White River, ON) with finely crushed mine rock (Williams Mine, Barrick Gold, Hemlo, ON) in organic ratios of 40% and 80% by volume. A preliminary laboratory growth study (Chapter 3) demonstrated that finely crushed mine rock and woody residuals were potentially viable materials to produce a Technosol for use in mine land reclamation. The study also guided in the decision to include organics at 40% and 80% volume in Technosol production. The woody residuals obtained from the (formerly) Domtar White River Sawmill consisted of sawdust, bark and off-cuttings of dominantly boreal coniferous trees. Intermediate volcanic and metasedimentary mine rock co-exist in the Williams open-pit mine at Barrick Gold Corporation's Hemlo operation. Each Technosol was constructed independently. Materials and Technosols were thoroughly homogenized using a front loader. Material volume was measured using a full bucket (approximately 0.96 m^3) of a 426C Caterpillar from Tormont. The following Technosol treatments were produced with the given material volume ratios:

1. 40% organic Technosol at 30 cm thickness: 4 buckets woody residuals and 6 buckets finely crushed mine rock
2. 80% organic Technosol at 30 cm thickness: 8 buckets woody residuals and 2 buckets finely crushed mine rock
3. 40% organic Technosol at 60 cm thickness: 8 buckets woody residuals and 12 buckets finely crushed mine rock
4. 80% organic Technosol at 60 cm thickness: 16 buckets woody residuals andf 4 buckets finely crushed mine rock

Each Technosol was deposited at the corners and middle of each reclamation plot and levelled to 30 or 60 cm depth using hand rakes (Figure 30). A soil depth of 30 cm was selected as 20 cm rooting depth is generally adequate for both tree and grass growth in reclaimed brownfield sites (Nason et al. 2007), with some settling being assumed to happen within the first year after application. The 60 cm soil depth was not simply a doubling of the 30 cm depth treatment. Each treatment, but was designed to provide a greater rooting volume, enhance moisture storage, and allow for depth reduction on consolidation following decomposition of the organic material. Each treatment was replicated three times, with a total of twelve reclamation plots being constructed. A site diagram is provided in the Appendix (Figure A2).

Figure 30. Technosols for each cell were produced independently. (L) Finely crushed waste rock and wood waste were combined in volume ratios using a backhoe to yield desired soil. (R) Technosols were deposited on to field lysimeter cells and hand raked to 30 or 60 cm thickness.

4.13 – Sensor Installation

In each plot, one tension plate lysimeter (UMS, SPG120 Leachate Sampling Plate), one MPS-2 water dielectric potential/temperature sensor (Decagon Devices), and two (30 cm deep Technosol plots) or three (60 cm deep Technosol plots) 5TM soil temperature/moisture sensors (Decagon Devices) were installed (Figure 31). Locations of each sensor and logger within the plots can be found in the Appendix (Table A4).

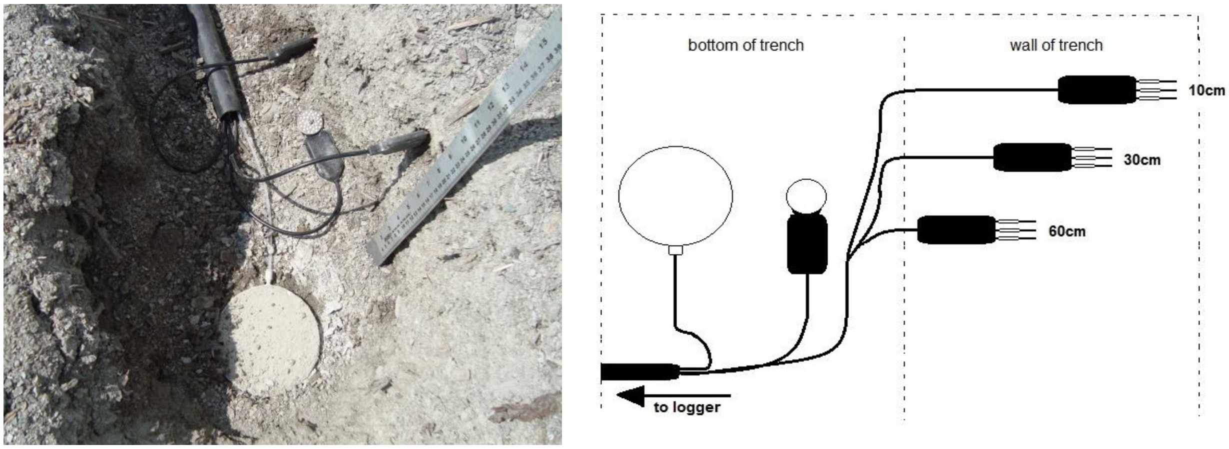


Figure 31. Image and schematic of sensor and lysimeter installations within Barrick reclamation plots (depths indicated). The tension plate lysimeter is the circular white apparatus and is laid flat on the bottom of the excavated trench. The MPS-2 water potential/temperature sensor is the black sensor with the white circular head and lays flat on the bottom of the excavated trench. The 5TM soil moisture/temperature sensors are the black sensors with prongs, embedded into the wall of the trench at select depths.

MPS-2 and 5TM sensors were monitored with Em50 series data loggers and ECH$_2$O software (Decagon Devices)., with the individual 5TM sensors were calibrated for each Technosol material as outlined by Decagon Devices application note “Calibrating ECH2O Soil Moisture Sensors” (Cobos & Chambers 2010). Raw soil moisture measurements were converted to volumetric water content (m^3/m^3) from the following equations:

1. VWC = 0.0003*Raw + 0.0369 (*80% organics Technosol*)

2. VWC = 0.0002*Raw + 0.0384 (*40% organics Technosol*)

After allowing the Technosol to settle and consolidate for three weeks, a trench was excavated from the front or side edge to the center of each reclamation plot to the rock interface. Tension plate lysimeters were soaked in deionized water for 24 hours before installation on a level soil surface, 5 cm above the mine rock/soil interface. A thin tubing system was connected to each plate lysimeter for water sampling. MPS-2 water potential/temperature sensors were installed on a level soil surface above the mine rock/soil interface. 5TM soil moisture/temperature sensors were installed vertically into the trench wall at depths of 10 cm, 30 cm and 60 cm (if applicable). All water extraction tubing and sensor cables were encased in protective pipe. The sensor wires were connected to an Em50 data logger to log soil temperature, moisture and water potential measurements at up to 30 minute intervals. After sensor and plate lysimeter installation, the trench was carefully filled and gently compacted by hand (over sensor location) approximately every 5 cm.

4.14 – Water Sampling and Data Acquisition & Processing

Soil pore water samples were collected from the tension plate lysimeter system on the following dates: 24/10/2012, 20/07/2013, 13/08/2013, 28/10/2013. Tension plate lysimeters were sampled by applying 0.8 MPa pressure to the system with a hand pump and allowing sample to collect under tension overnight. All water samples were chilled for shipment to the Elliot Lake Research Field Station (ELRFS) analytical facility at Laurentian University for a suite of analyses including: anions, TIC/TOC, N-species, and a suite of up to 50 elements by ICP techniques (Figure 32).

Figure 32. (L) Suction plate lysimeter systems were pressurized with a hand pump to collect water samples contained within the Technosol. (R) Water samples collected via tension plate lysimeters being prepared for transportation to ELFRS for analysis.

Soil microclimate data (temperature, moisture and water potential) was downloaded from Em50 data loggers as .dxd and .xls files on the following dates: September 20th, 2012; October 24th, 2012; July 20th, 2013; August 9th, 2013; August 13th, 2013; and October 28th, 2013. Data loggers were set to record soil microclimate data at varying intervals depending on the season: thirty minute intervals from August 20, 2012 – July 19, 2013; two minute intervals from July 19, 2013-July 21, 2013; five minute intervals from July 21 – October 28, 2013; thirty minute intervals from October 28, 2013 – present. In mid-November 2012 multiple sensor wires were detached from several data loggers. Thus, data from the three replicate plots of each treatment were compiled and averaged to form a composite reclamation plot for the purpose of describing soil microclimate data responses to regional climatic conditions. Field capacity and permanent wilting point of the soils were estimated using soil moisture values obtained from soil retention curves of Technosols studied in (Chapter 3) and bulk densities estimated in a laboratory setting. Values for the 80% organic Technosol were estimated from soils composed of 75% woody residuals; values for the 40% organic Technosol were estimated from averaging values obtained from soils composed of 25% and 50% woody residuals.

Weather data recorded by a station at the tailings facility at Barrick – Hemlo provided by the company was used to identify periods of heavy precipitation (06/07/2013 – 14/07/2013 and 25/08/2013 – 29/08/2013), prolonged drought (26/06/2013 – 06/07/2013), and average precipitation events (10/06/2013 – 21/06/2013) that were matched to the moisture and temperature regime of the Technosols on the reclamation plots. Data processing and graphical analysis of soil microclimate data were carried out using R version 3.0.2 (The R Foundation for Statistical Computing 2013). A two-way analysis of variance (ANOVA) was used to determine differences in nutrient concentration of pore water samples with significance assessed at $p \leq 0.05$.

4.15 – Sample Analysis

Water samples were analyzed for total organic carbon, anions (PO_4^{-3}, Cl^-, NO^{3-}) using IC, ammonia (NH_4^+) by Testmark Labs and dissolved elements by ICP-MS. Routine agronomic soil tests were completed (A&L Canada Laboratories). Soil pH was measured in water and a neutral salt solution (0.1M $CaCl_2$) (Carter 1993). Soils extracts were also analyzed for Eh (5.0 g sample and water to form paste), EC (1:2 water ratio). For the estimation of total metal concentrations in the Technosols, a 0.50 g soil sample was treated with 10 mL of a 10:1 ratio of HF/HCl, heated to 110°C for 3.5 h in an open 50 mL Teflon™ tube in a programmable digestion block to dry down samples, followed by the addition of 7.5 mL of HCl and 7.5 mL of HNO_3 and heating to 110°C for another 4 h to dry gently. The samples were then heated to 110°C for 1 h following the addition of 0.5 mL of HF, 2 mL of HCl, and 10 mL ofHNO_3 to reduce sample volume to 8–10 mL. On cooling, the samples are made to 50 mL with ultrapure water for subsequent analysis by plasma spectrometry. Bioavailable metals were estimated by extracting 5.0 g of soil (pure metasedimentary or pure intermediate volcanic) or 2.0 g of soil (all blended soils) with 20 mL of

0.01 M $LiNO_3$ in a 50-mL centrifuge tube in a shaker under ambient lighting conditions for 24 h at 20°C (Abedin, *et al*. 2012). The pH ($LiNO_3$) of the suspension was measured prior to centrifugation at 3,000 rpm for 20 min, with filtration of the supernatant through Whatman 42 filter paper into a 20-mL polyethylene tube and made to volume with deionized water. The filtrate was preserved at approximately 3°C for analysis by ICP-MS. The quality control program completed in an ISO 17025 accredited facility (Elliot Lake Research Field Station of Laurentian University) included analysis of duplicates, Certified Reference Materials (CRMs), Internal Reference Materials (IRMs), and procedural and calibration blanks, with continuous calibration verification and use of internal standards to correct for any mass bias. All Technosols and waste material concentrations were calculated in mass/mass dry soil basis.

4.16 – Seeding and Vegetation Transplants

Agrostis scabra (Tickle Grass) seeds and *Alnus viridis* (Green Alder) shrubs were planted on two of the three replicate plots on July 21st, 2013 and August 12th, 2013. Plots that were selected for vegetation were 1A, 1C, 2B, 2C, 3B, 3C, 4A, 4C, while plots 1B, 2A, 3A and 4B were used as controls. Tickle grass seed was obtained from *Wild About Flowers* (Okotoks, AB). Seed viability was tested on a damp paper towel with almost 100% germination. On July 21st, 2013, following measurement of actual plot surface area (Table A5), seed was weighed to ensure an application rate of 2 g/m^2. Seeds were dispersed evenly with a Scotts® HandyGreen® II Hand-Held Spreader by walking across the plot multiple times in opposing paths. Following seeding, the plot surface was lightly scarified with a coarse tined garden rake. Tickle grass seed was re-sown on to vegetated plots on August 13th, 2013 in the same method as previously stated.

One hundred and fifty individual green alder shrubs, ranging from 10 – 30 cm in height were collected from a recently disturbed sandy soil site, located at UTM coordinates 16U 0643543 5357348 adjacent to Highway 17. Spades were used for excavation with soil left surrounding the root mass during transportation (Figure 33). On August 13th, 2013 sixteen individual green alder seedlings were planted in each of the vegetated plots in a 4x4 grid (Figure 34).

Figure 33. (L) Location of green alder collection site along Hwy 17 near White River, ON. (R) Removal of individual green alder with spades.

Figure 34. Plot schematic with individual green alder represented by a sphere in a 4x4 configuration with field view of actual plots after planting. Each position in plot is labelled from 1-16 starting in the front right hand corner.

Soil was gently shaken from the root mass of each sampling before being planted into the plots to ensure the roots were bare. The green alder planting grid was initiated 25 cm from the edge of each plot to reduce edge effects. The height of the individual green alder was measured to the closest centimeter using the tallest stem (Table A6). Sixteen additional green alder shrubs were excavated and re-planted in a 4 x 4 configuration at the transplant site, with heights of individuals were recorded (Table A6).

4.2 – Results

4.21 – Field Capacity, Permanent Wilting Point and Plant Available Water

The field capacity of Technosols composed of 40% organics was calculated to be at approximately 0.14 m^3/m^3 soil moisture; permanent wilting point was calculated to be at approximately 0.03 m^3/m^3 soil moisture. Technosols composed of 80% organics had a field capacity calculated to be approximately 0.17 m^3/m^3 soil moisture and a permanent wilting point of approximately 0.05 m^3/m^3 soil moisture.

4.22 – Soil Moisture and Temperature Regime

Annual Trends

Plot 1 Soil Moisture (40% organic Technosol of 30 cm depth; Figure 35). Soil moisture at a 10 cm depth in the plot ranged from approximately 0.110 - 0.140 m^3/m^3, and did not exceed 0.150 m^3/m^3 except when following an extreme precipitation event (see October 2012). Soil moisture at a 30 cm depth in the plot ranged from approximately 0.110 - 0.140 m^3/m^3 and at any given time, soil moisture at a 30 cm depth was consistently lower than soil moisture at a 10 cm depth in the plot. The wetting and drying patterns in at a 30 cm depth mirrored those that occurred at a 10 cm depth, with a slight lag and less extreme oscillations. Soil moisture remained consistently above the permanent wilting point (0.04 m^3/m^3) at both 10 and 30 cm depths.

Plot 1 Soil Temperature (40% organic Technosol of 30 cm depth; Figure 36). Soil temperature followed a diurnal pattern at both 10 and 30 cm depths. Temperature increased steadily into the middle of August, and continued to decrease steadily at both depths into the late fall. Soil temperatures at a 10 cm depth ranged from approximately 5 – 28°C in the growing season, with peak temperatures less than one degree below air temperatures recorded for the same time periods. Soil temperatures at a 30 cm depth ranged from approximately 8 – 23°C. Temperatures reached peak values approximately 3 hours later at a 30 cm depth than at a 10 cm depth. Responses to changes in air temperature were much less extreme at a 30 cm depth than at a 10 cm depth. During the growing season, soil temperatures at a 10 cm depth were consistently higher than temperatures at the 30 cm depth during the day, but the opposite was true during the night. During the late fall, soil temperatures stayed elevated at the 30 cm depth while temperatures at the 10 cm depth decreased with the surrounding air temperature. Soil temperatures reached below freezing at 10 and 30 cm depths in early November 2012 decreasing to -28°C and -22°C at 10 and 30 cm depths, quite rapidly in the middle of January. Soil temperatures began to increase rapidly in March 2013, and rose above freezing by the end of April 2013.

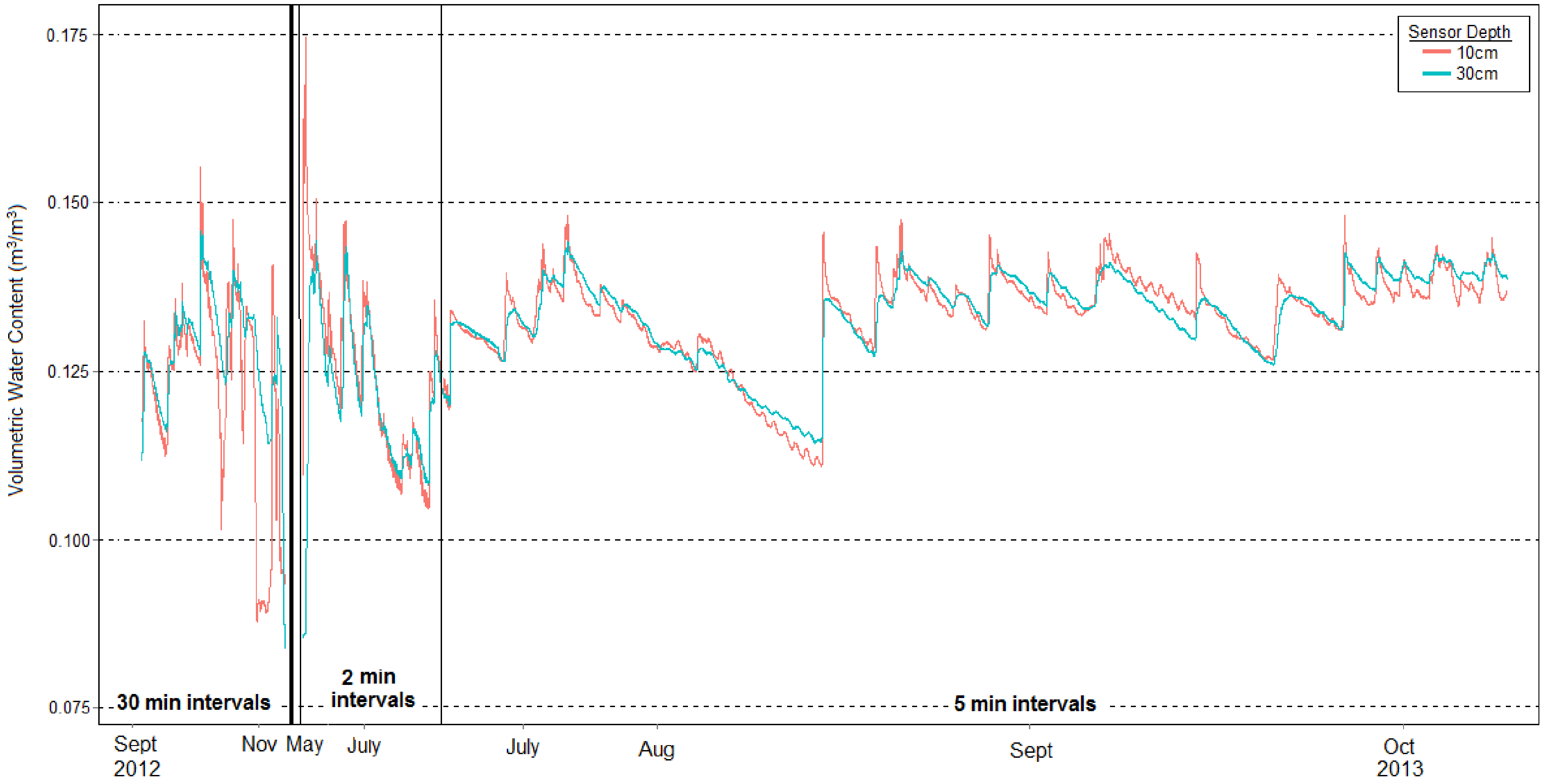


Figure 35. Soil moisture regime of reclamation plots of 40% organic Technosols of 30 cm depth. Measurement intervals are indicated. Soil moisture readings between December and April 2013 are not shown, as sensors cannot read 'moisture' when water is in solid phase. n =3.

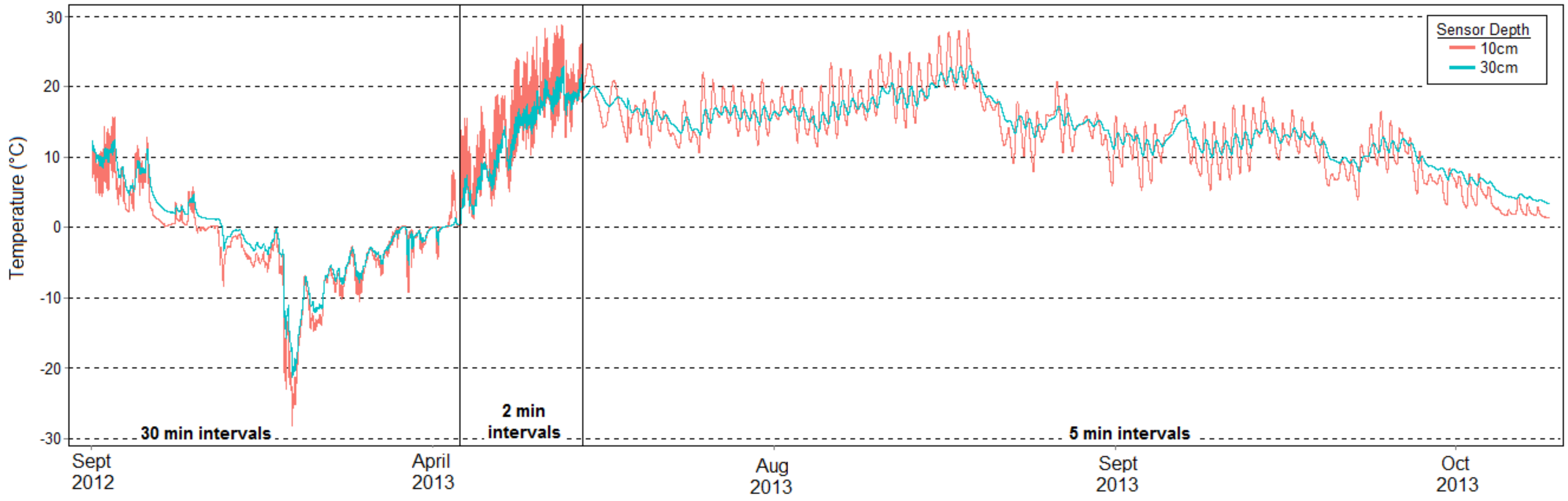


Figure 36. Soil temperature regime of reclamation plots of 40% organic Technosols of 30 cm depth. Measurement intervals are indicated. n =3.

Plot 2 Soil Moisture (80% organic Technosol of 30 cm depth; Figure 37). Soil moisture at a 10 cm depth ranged from approximately 0.170 – 0.250 m^3/m^3. Responses to precipitation events were not as rapid or extreme at a 10 cm depth in Plot 2, as those observed at a 10 cm depth in Plot 1. Soil moisture at a 30 cm depth ranged from approximately 0.145 - 0.200 m^3/m^3, peaking at approximately 0.225 m^3/m^3 during times of heavy precipitation. At any given time, soil moisture at a 30 cm depth was consistently lower than soil moisture at a 10cm depth. Patterns in wetting and drying at a 30 cm depth mirrored those that occurred at a 10 cm depth with a slight lag in response time to precipitation events and less extreme fluctuations. There was also a much larger difference between soil moisture at 10 and 30 cm depths in Plot 2 than in Plot 1. Soil moisture remained consistently above the permanent wilting point (0.10 m^3/m^3) at both 10 and 30 cm depths.

Plot 2 Soil Temperature (80% organic Technosol of 30 cm depth; Figure 38). Soil temperature followed a diurnal pattern at both 10 and 30 cm depths. Temperature increased steadily into the middle of August, and continued to decrease steadily at both depths into the late fall. Soil temperatures at a 10 cm depth ranged from approximately 8 – 23°C in the growing season. Peak temperatures were approximately 5 degrees below air temperatures recorded for the same time periods. Soil temperatures at a 30 cm depth ranged from approximately 12 – 21°C, reaching peak values approximately 4-5 hours later at a 30 cm depth than at a 10 cm depth. Responses to changes in air temperature were much less extreme at a 30 cm depth than at a 10 cm depth. During the growing season soil temperatures at a 10 cm depth were consistently higher than temperatures at a 30 cm depth during the day, with opposite trend during the night. During the late fall, soil temperatures stayed elevated at a 30 cm depth while temperatures at a 10 cm depth decreased steadily with the surrounding air temperature drop. Soil temperatures were below freezing at 10 and 30 cm depths in the middle of November 2012 and decreased rapidly to -23°C and -17°C at 10 and 30 cm depths, in the middle of January 2013. Soil temperatures started to increase rapidly in March 2013, and rose above freezing by the end of April 2013.

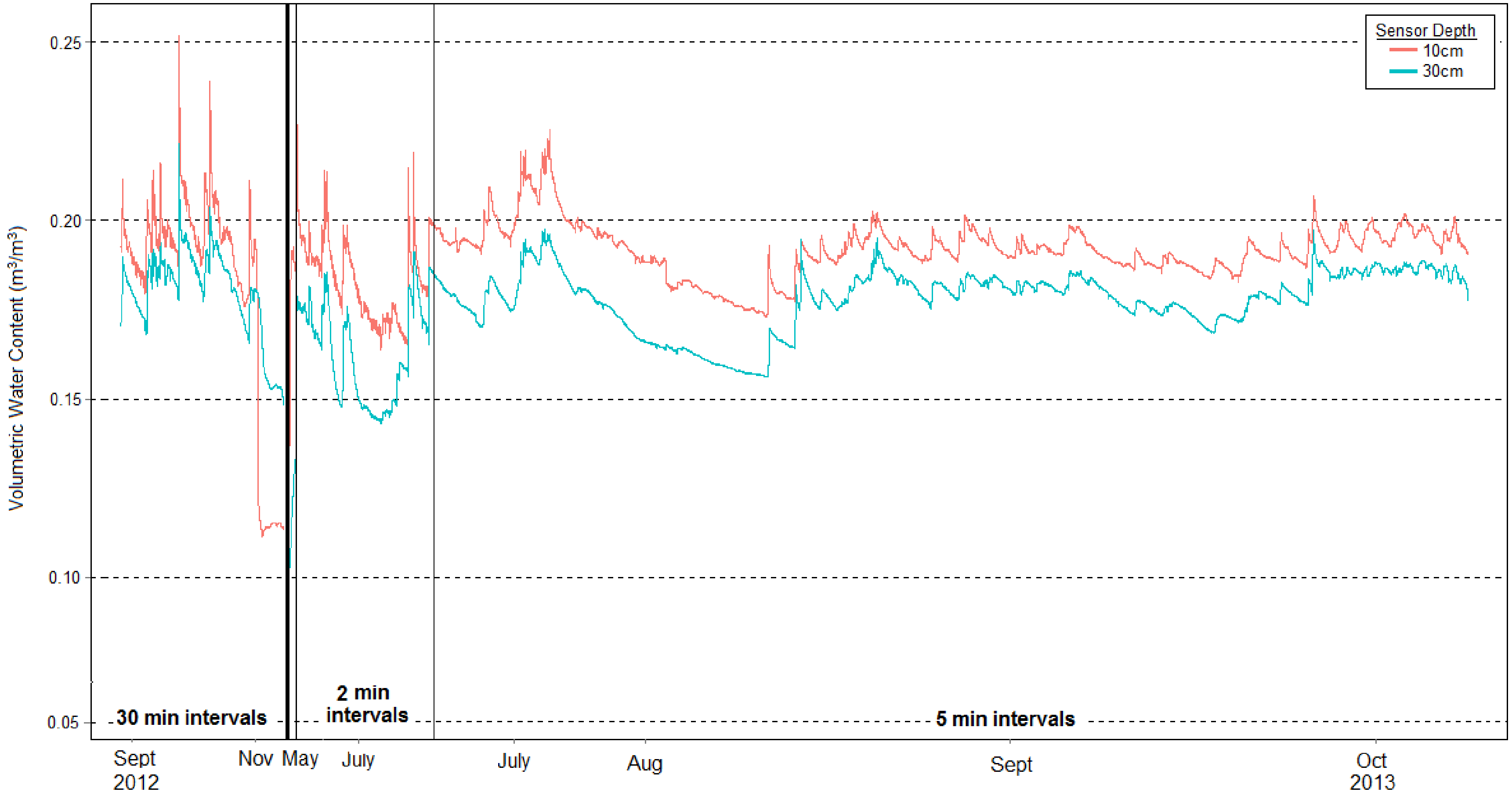


Figure 37. Soil moisture regime of reclamation plots of 80% organic Technosols of 30 cm depth. Measurement intervals are indicated. Soil moisture readings between December and April 2013 are not shown, as sensors cannot read 'moisture' when water is in solid phase. n =3.

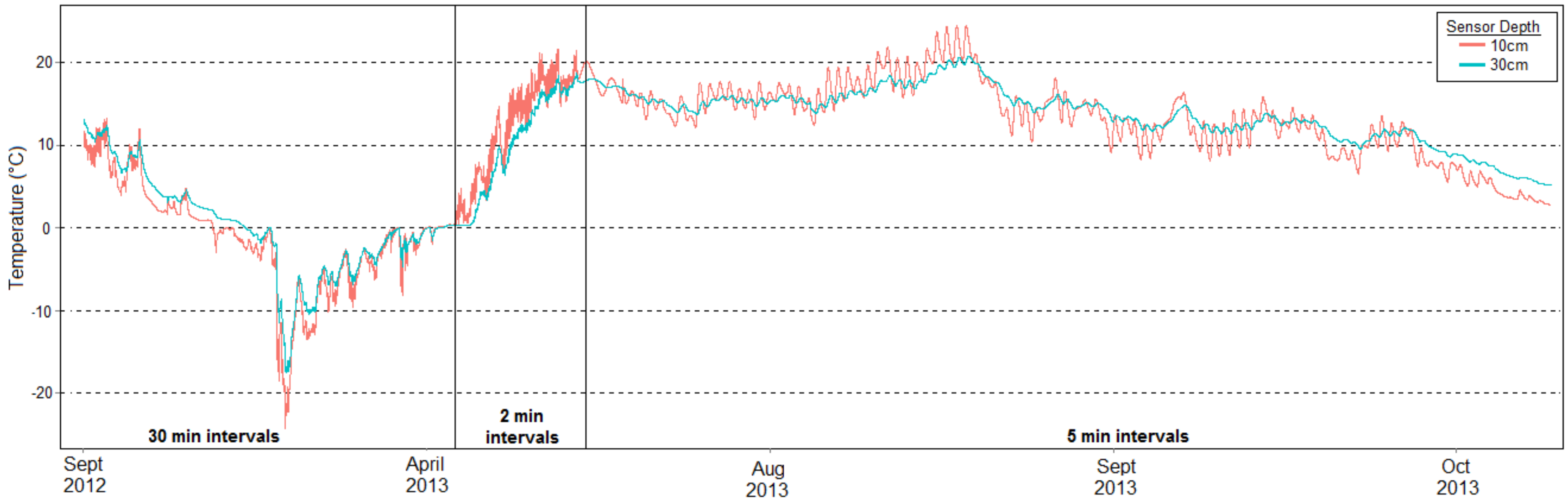


Figure 38. Soil temperature regime of reclamation plots of 80% organic Technosols of 30 cm depth. Measurement intervals are indicated. n =3.

Plot 3 Soil Moisture (40% organic Technosol of 60 cm depth; Figure 39). Soil moisture trends at 10 and 30 cm depths were similar to those at similar depths of Plot 1. Soil moisture ranged from approximately 0.110 – 0.140 m^3/m^3 at all depths. Patterns in wetting and drying at a 30cm depth mirrored those that occurred at a 10 cm depth with a slight lag in response time to precipitation events and less extreme fluctuations. Soil moisture at a 10 cm depth was consistently higher than soil moisture at a 30 cm depth. However during dry weather periods, soil moisture at a 30 cm depth did exceed soil moisture levels at a 10 cm depth. Soil moisture at a 60 cm depth was consistently higher than soil moisture at 10 and 30 cm depths, ranging from approximately 0.13 - 0.155 m^3/m^3. Responses to wetting and drying events at a 60 cm depth were quite muted in comparison to 10 and 30 cm depths having an associated long lag period associated with those responses. Soil moisture remained consistently above the permanent wilting point (0.04 m^3/m^3) at 10, 30 and 60 cm depths.

Plot 3 Soil Temperature (40% organic Technosol of 60 cm depth; Figure 40). Soil temperature followed a diurnal pattern at both 10 and 30 cm depths, but did not at a 60 cm depth. Temperatures at all depths increased steadily into the middle of August, and continued to decrease steadily into the late fall. Soil temperatures at a 10 cm depth ranged from approximately 5 – 25°C during the growing season. Peak soil temperatures were less than 1°C below air temperatures recorded for the same time periods. Soil temperatures at a 30 cm depth ranged from approximately 12 – 22°C. Maximum temperatures were reached approximately 6 hours later at a 30 cm depth than at a 10 cm depth. Soil temperatures at a 60 cm depth ranged from approximately 13 – 20°C during the growing season. The responses observed to changes in air temperature were less as depth increased. During the growing season soil temperatures at a 10cm depth were consistently higher than temperatures at a 30 cm depth during the day, with the reverse being monitored during the night. Soil temperatures at a 60 cm depth remained lower than temperature at 10 and 30 cm depths while soil temperature was increasing, and remained warmer than temperatures at 10 and 30 cm depths while temperatures were decreasing. During the late fall, soil temperatures stayed elevated longer as depth increased. Soil temperatures reached below freezing at 10 and 30 cm depths in the middle of November 2012, and fell below 0°C at a 60 cm depth in the middle of January 2013, when soil temperatures began to decrease quite dramatically. Soil temperatures dropped as low as -25°C at a 10 cm depth, -18°C at a 30 cm depth, and -12°C at a 60 cm depth. Soil temperatures began to thaw in March 2013, and with temperatures above 0°C by the end of April 2013.

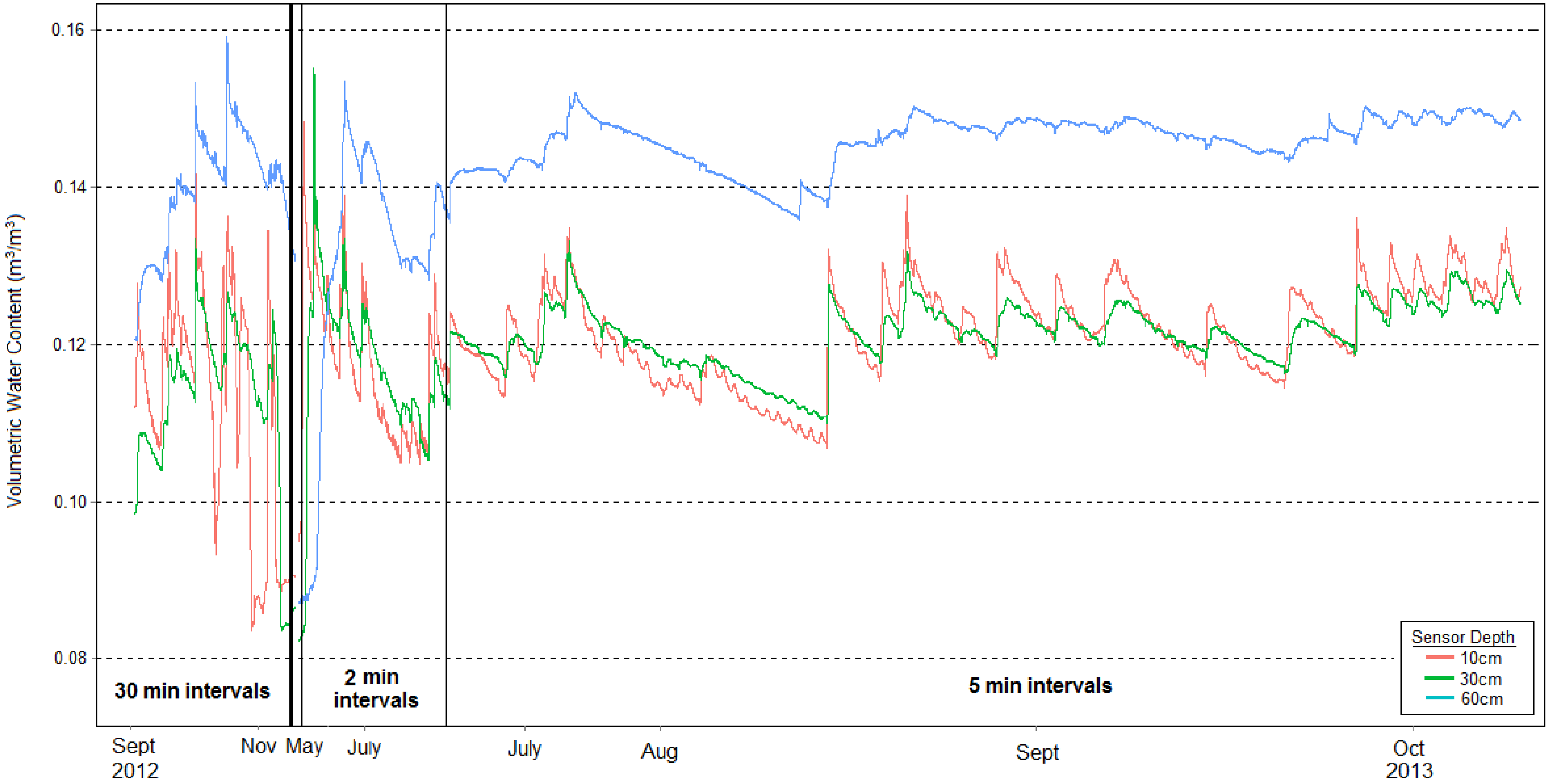


Figure 39. Soil moisture regime of reclamation plots of 40% organic Technosols of 60 cm depth. Measurement intervals are indicated. Soil moisture readings between December and April 2013 are not shown, as sensors cannot read 'moisture' when water is in solid phase. n =3.

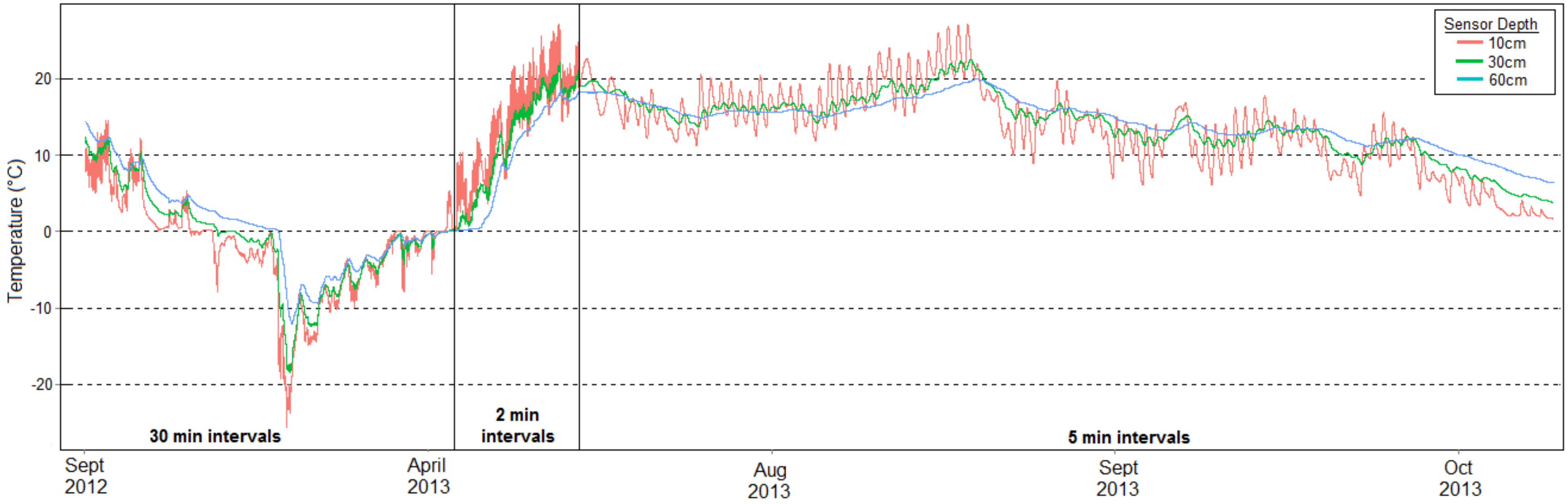


Figure 40. Soil temperature regime of reclamation plots of 40% organic Technosols of 60 cm depth. Measurement intervals are indicated. n =3.

Plot 4 Soil Moisture (80% organic Technosol of 60 cm depth; Figure 41). Soil moisture patterns at 10 and 30 cm depths were similar to those at similar depths of Plot 2, although soil moisture was consistently higher at a 10 cm depth in Plot 2 than at a 10 cm depth in Plot 4. Soil moisture ranged from approximately 0.130 – 0.200 m^3/m^3 at a 10 cm depth, and from approximately 0.140 – 0.170 m^3/m^3 at a 30cm depth. Patterns in wetting and drying at a 30 cm depth mirrored those that occurred at a 10 cm depth with a slight lag in response time to precipitation events. Soil moisture at a 30 cm depth was consistently lower than soil moisture content at a 10 cm depth and soil moisture at a 60 cm depth was consistently higher than soil moisture at 10 and 30 cm depths, ranging from approximately 0.17 - 0.220 m^3/m^3. Responses to wetting and drying events at a 60 cm depth were quite muted in comparison to 10 and 30 cm depths, with a long response time lag period. Soil moisture remained consistently above the permanent wilting point (0.10 m^3/m^3) at 10, 30 and 60 cm depths.

Plot 4 Soil Temperature (80% organic Technosol of 60 cm depth; Figure 42). Soil temperature followed a diurnal pattern at both 10 and 30 cm depths, but did not at a 60 cm depth. Temperatures in all depths increased steadily into the middle of August, and continued to decrease steadily into the late fall. Soil temperatures at a 10 cm depth ranged from approximately 8 – 25°C in the growing season. Peak temperatures were about than 3°C below air temperatures recorded for the same time periods. Soil temperatures at a 30cm depth fluctuated approximately between 14 – 22°C approximately. Temperatures reached peak values approximately 10 hours later at a 30 cm depth than at a 10 cm depth. Soil temperatures at a 60 cm depth ranged from approximately 14 – 18°C in the growing season. Responses to changes in air temperature were less as depth increased. During the growing season soil temperatures at a 10 cm depth were consistently higher than temperatures at a 30 cm depth during the day, with the opposite trend being monitored during the night. Soil temperatures at a 60 cm depth remained lower than temperatures at 10 and 30 cm depths as soil temperature was increasing, and remained warmer than temperatures at 10 and 30 cm depths as temperatures were decreasing. During the late fall, soil temperatures remained elevated longer as depth increased. Soil temperatures dropped below freezing in the middle of November 2012 at a 10 cm depth, at the end of December 2012 at a 30 cm depth, and at a 60 cm depth in the middle of January 2013, with soil temperatures further decreasing quite rapidly. Soil temperatures were as low as -22°C at depth of 10 cm, -13°C at depth of 30 cm, and -5°C at depth of 60 cm. Soil temperatures began to increase rapidly in March 2013, and rose above 0°C by the end of April 2013.

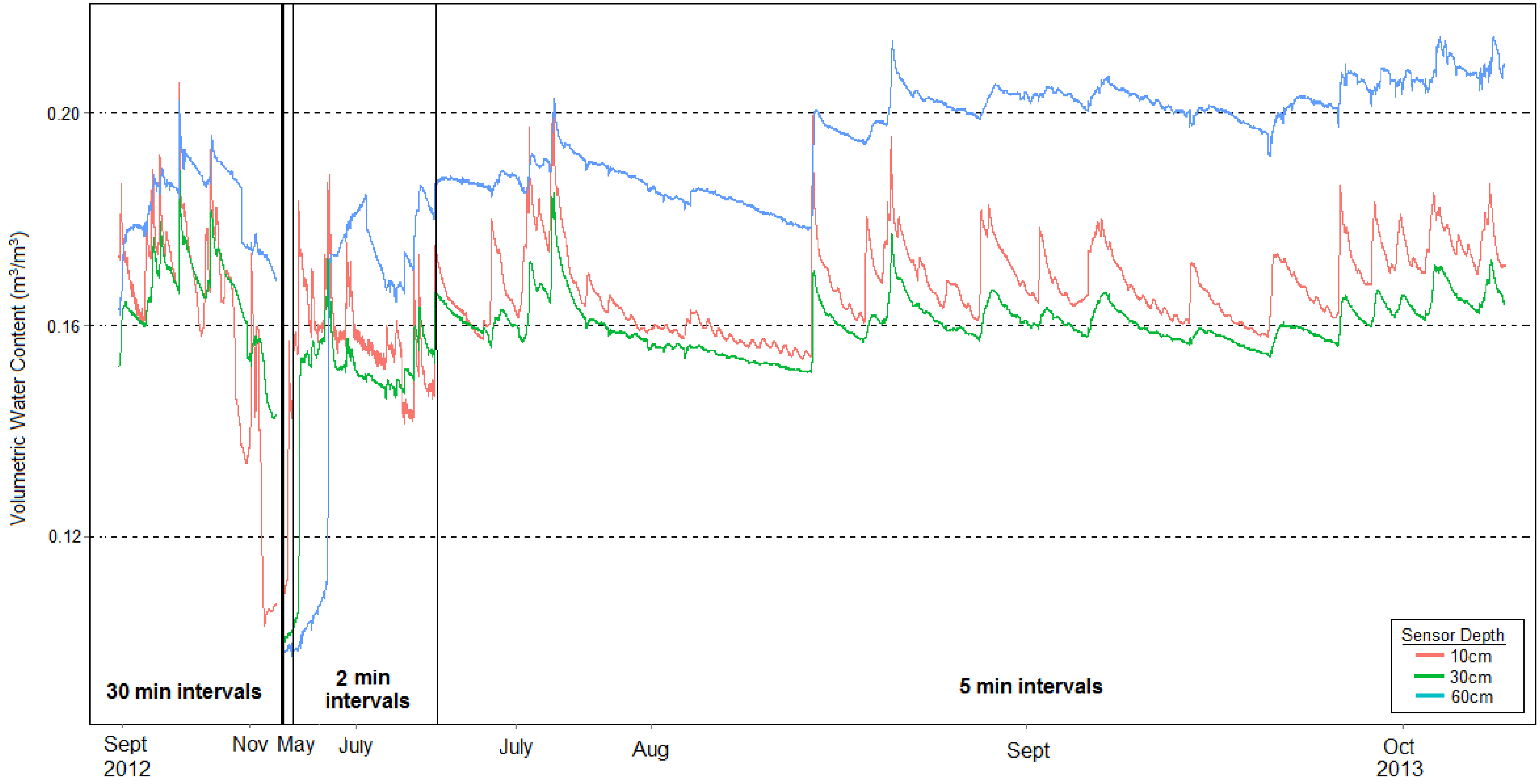


Figure 41. Soil moisture regime of reclamation plots of 80% organic Technosols of 60 cm depth. Measurement intervals are indicated. Soil moisture readings between December and April 2013 are not shown, as sensors cannot read 'moisture' when water is in solid phase. n =3.

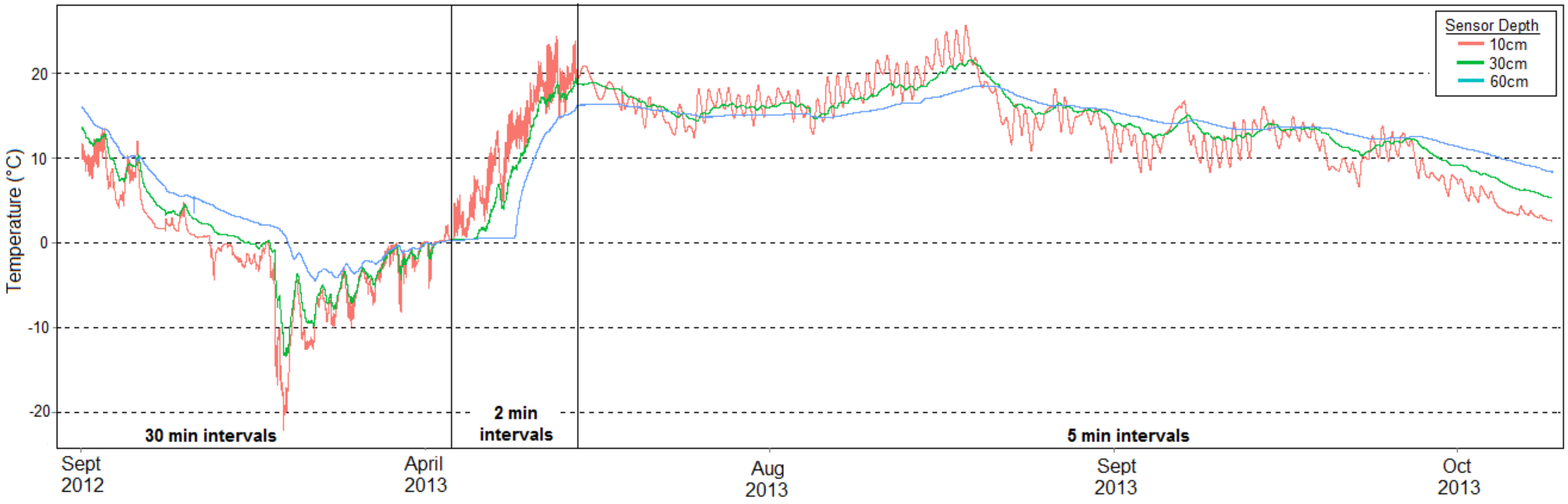


Figure 42. Soil temperature regime of reclamation plots of 80% organic Technosols of 60 cm depth. Measurement intervals are indicated. n =3.

Wetting and Drying after Precipitation Events of Varying Intensity and Duration

June 10 – June 21, 2013. Plots received 1.8mm of precipitation starting in the late evening on June 10, 2013, lasting for a 12 hour duration. Following this event, there was no subsequent precipitation until the early afternoon of June 21, excluding a small amount (0.2mm) of precipitation fell on June 12 and on June 16. Plots had not received precipitation before the June 10 event since June 2, 2013. Soil moisture did not noticeably increase at any depth in Plot 1, Plot 2, or Plot 3; instead soil moisture continued to steadily decrease (Figure 43). Soil moisture increased dramatically at a 10cm depth in Plot 4, with a lagging and less dramatic increase in soil moisture at a 30 cm depth. Soil moisture also increased at a 60 cm depth, peaking later than soil moisture increases at 10 and 30 cm depths, and maintaining elevated levels for a longer period of time. Water potential increased slightly in Plots 1, 2 and 4, but did not increase in Plot 3 (Figure 44). Lag time in reaching peak water potential was greatest in Plot 4, which was of 60 cm depth, as opposed to 30 cm depth (Plot 1 and 2).

Figure 43. Soil moisture changes in two Technosols of 30 and 60 cm depths, after a low intensity, short duration precipitation event on June 10, 2013. Plots are ordered from 1 (top left), Plot 2 (top right), Plot 3 (bottom left) and Plot 4 (bottom right). n =3 for each sensor depth.

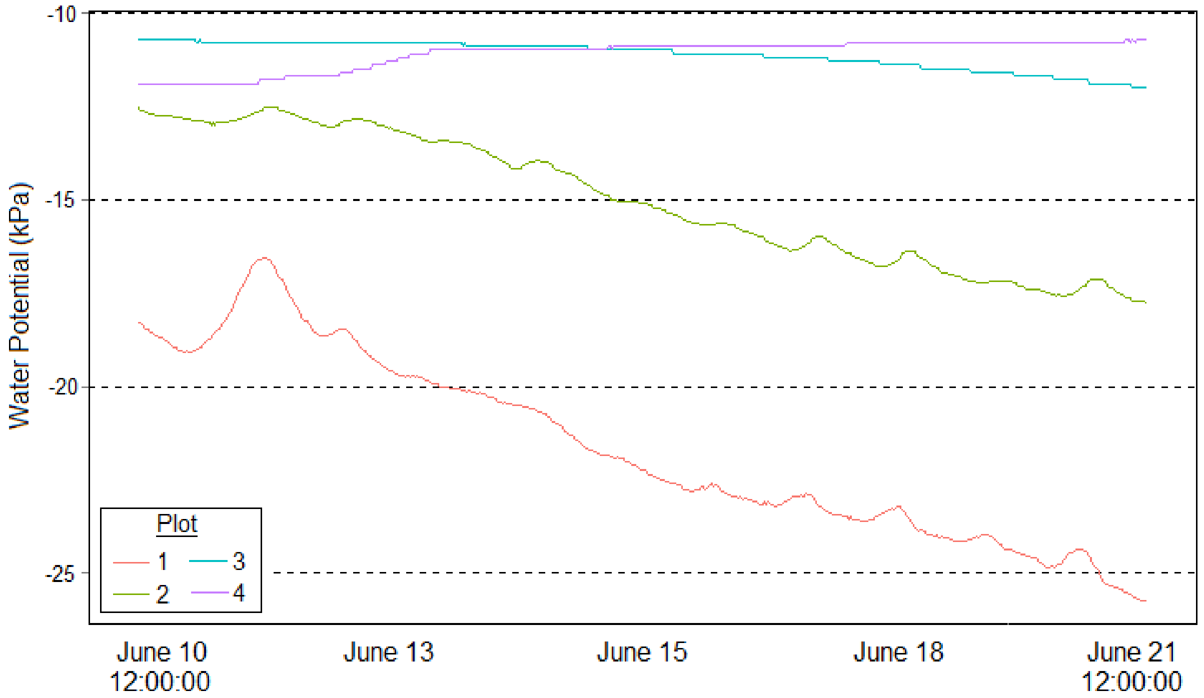


Figure 44. Water potential changes in two Technosols of 30 and 60 cm depths after a low intensity, short duration precipitation event on June 10, 2013. n =3 for each sensor depth.

June 26 – July 6, 2013. Plots received 8.8mm of precipitation starting in the early morning of June 26, 2013, lasting for a 34 hour duration. Following this event, there was no subsequent precipitation until the early afternoon of July 6, 2013. Plots had not received precipitation before the June 26 event since June 24, 2013. Soil moisture noticeably increased in all plots at 10 and 30 cm depths after the precipitation event (Figure 45). In all plots, moisture increased the most rapidly at a 10 cm depth, but maintained increased moisture levels over the shortest amount of time. Plot 2 maintained moisture at a 10 cm depth three times as long as Plot 1. Plot 3 and Plot 4 retained soil moisture at a 10 cm depth for a similar amount of time as Plot 1. Drying occurred more quickly at a 10 cm depth in all plots than at a depth of 30 cm, resulting in higher soil moisture at a 30 cm depth than at a 10 cm depth in Plots 1 and 4. Soil moisture at a 60 cm depth did not increase noticeably after the low intensity precipitation event. There was a sharp increase in soil moisture at a 60 cm depth in Plot 4 (corresponding to increases in soil moisture at varying depths in other plots) on July 2, possibly a result of an unrecorded precipitation event. Water potential increased noticeably in Plots 1 and 2, but did not seem to increase significantly in Plots 3 and 4 (Figure 46). Water potential remained elevated in Plot 1 for only a short duration of time; four days after the precipitation event, water potential levels began to decrease rapidly. Plot 2 was able to maintain elevated water potential levels for almost a week after the precipitation event. Although water potential did not increase in Plot 4, water potential was highest in this plot and only continued to increase even after a week without precipitation.

Figure 45. Soil moisture changes in two Technosols of 30 and 60 cm depths, after a low intensity, long duration precipitation event on June 26, 2013. Plots are ordered from 1 (top left), Plot 2 (top right), Plot 3 (bottom left) and Plot 4 (bottom right). n =3 for each sensor depth.

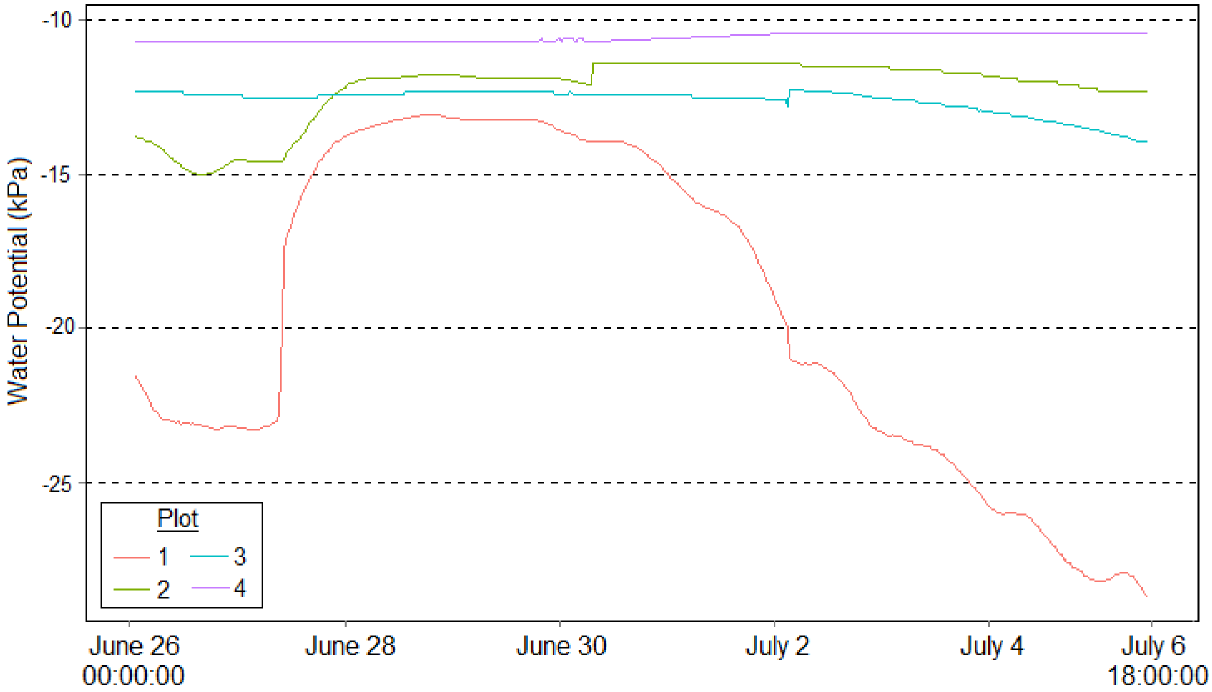


Figure 46. Water potential changes in two Technosols of 30 and 60 cm depths, after a low intensity, long duration precipitation event on June 26, 2013. n =3 for each sensor depth.

July 6 – July 14, 2013. Plots received 10.4mm of precipitation starting in the early morning of July 6, 2013, lasting for a 13 hour duration. Following this event, there was no subsequent precipitation until late in the evening of July 9, 2013 at which time plots received 14.8mm of precipitation over a 13 hour duration. Plots had not received precipitation before the July 6 event since June 27, 2013. Soil moisture noticeably increased at all depths in all Plots after the first and second rain events on July 6 and 9 (Figure 47). In plots that contained the same amount organic component (Plot1 and Plot3, Plot 2 and Plot 4) soil moisture at 10 and 30 cm depths was higher after precipitation events in plots that were 30 cm deep (Plot 1 and 2) compared to plots that were 60 cm deep (Plot 3 and 4). Soil moisture increased at a 10 cm depth, by about 0.04 m^3/m^3 in Plot 2, and by approximately 0.02 m^3/m^3 in Plots 1, 3, and 4. At a 30 cm depth, moisture increased by approximately 0.02 m^3/m^3 in the shallow plots, and by approximately 0.01

m^3/m^3 after the first precipitation event, and by approximately 0.005 m^3/m^3 after the second precipitation event in the 60 cm deep plots. Soil moisture at a 60 cm depth increased by approximately 0.005 m^3/m^3 after each rain event in Plot 3, and by approximately 0.015 m^3/m^3 in Plot 4 after the first event, and by approximately 0.005 m^3/m^3 after the second event. Soil moisture peaked almost a day after the rain event, in the middle afternoon of July 7, at a 10 cm depth in all Plots. Soil moisture peaked 5 hours later at a 30 cm depth, and approximately 10 hours later at a 60 cm depth. Soil moisture levels remained elevated longer as depth increased – with soil moisture at a 10 cm depth decreasing at about twice the rate as moisture at a 30 cm depth. There was only a slight decrease in soil moisture at a 60 cm depth, even after three days of drying. Immediately following the first precipitation event, on July 6, water potential sharply increased in Plot 1, rising from approximately -30 to -12.5 kPa (Figure 48). Water potential increased slightly in Plots 2 and 3, and did not noticeably increase in Plot 4 which maintained water potential levels at approximately -10.5 kPa throughout. After the second precipitation event, on July 9, water potential in all plots ranged between -10.5 kPa and approximately -12 kPa.

Figure 47. Soil moisture changes in two Technosols of 30 and 60 cm depths, after two moderate intensity, short duration precipitation events on July 6 and July 9 2013. Plots are ordered from 1 (top left), Plot 2 (top right), Plot 3 (bottom left) and Plot 4 (bottom right). n =3 for each sensor depth.

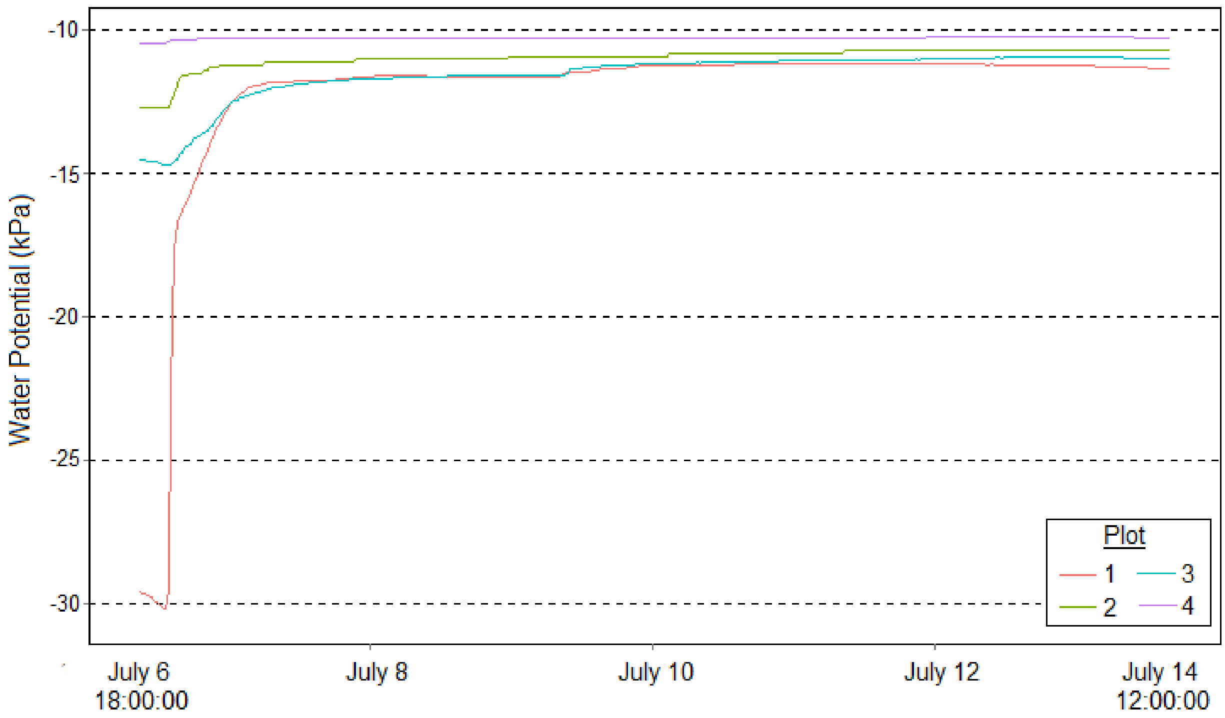


Figure 48. Water potential changes in two Technosols of to 30 and 60 cm depths, after two moderate intensity, short duration precipitation events on July 6 and July 9 2013. n =3 for each sensor depth.

July 19 – July 21, 2013. Plots received 19.4mm of precipitation starting in the late afternoon of July 18, 2013, lasting for a 35 hour duration. Following this event, there was no subsequent precipitation until the late morning of July 22, 2013. Plots received moderate precipitation on July 15 and July 17 before the July 18 event. Soil moisture had started to decrease noticeably at 10 and 30 cm depth in all plots, only a few hours after precipitation ended (Figure 49). In Plots 1, 3 and 4 which contain 40% organics, soil moisture at a10 cm depth decreased more rapidly after precipitation than soil moisture at a 30 cm depth. Soil moisture in Plot 2, which contained 80% organics, decreased equally as fast at 10 and 30 cm depths. This rate of decrease was similar to soil moisture decreases at a 30 cm depth in Plot 4, but much faster than soil moisture decreases in Plots 1 and 3. Even though soil moisture decreased more quickly at 10 and 30 cm depths in Plots 2 and 4, absolute soil moisture remained approximately 0.05 - 0.06 m^3/m^3 higher than in Plots 1 and 3. Soil moisture at a 60 cm depth in Plot 3 and 4 was still increasing as soil moisture at 10 and 30 cm depths was decreasing, and peaked late on July 19, about a day after precipitation started. There was no noticeable decrease in soil moisture at a 60 cm depth after two days of drying; Soil moisture at 60 cm depths in Plot 3 and 4 remained at approximately 0.1425 m^3/m^3 and 0.1875 m^3/m^3. Water potential continued to increase slightly in all plots after the initial rain event on July 18, after two days without precipitation (Figure 50). Water potential of all plots ranged between -10.2 and -11.4 kPa.

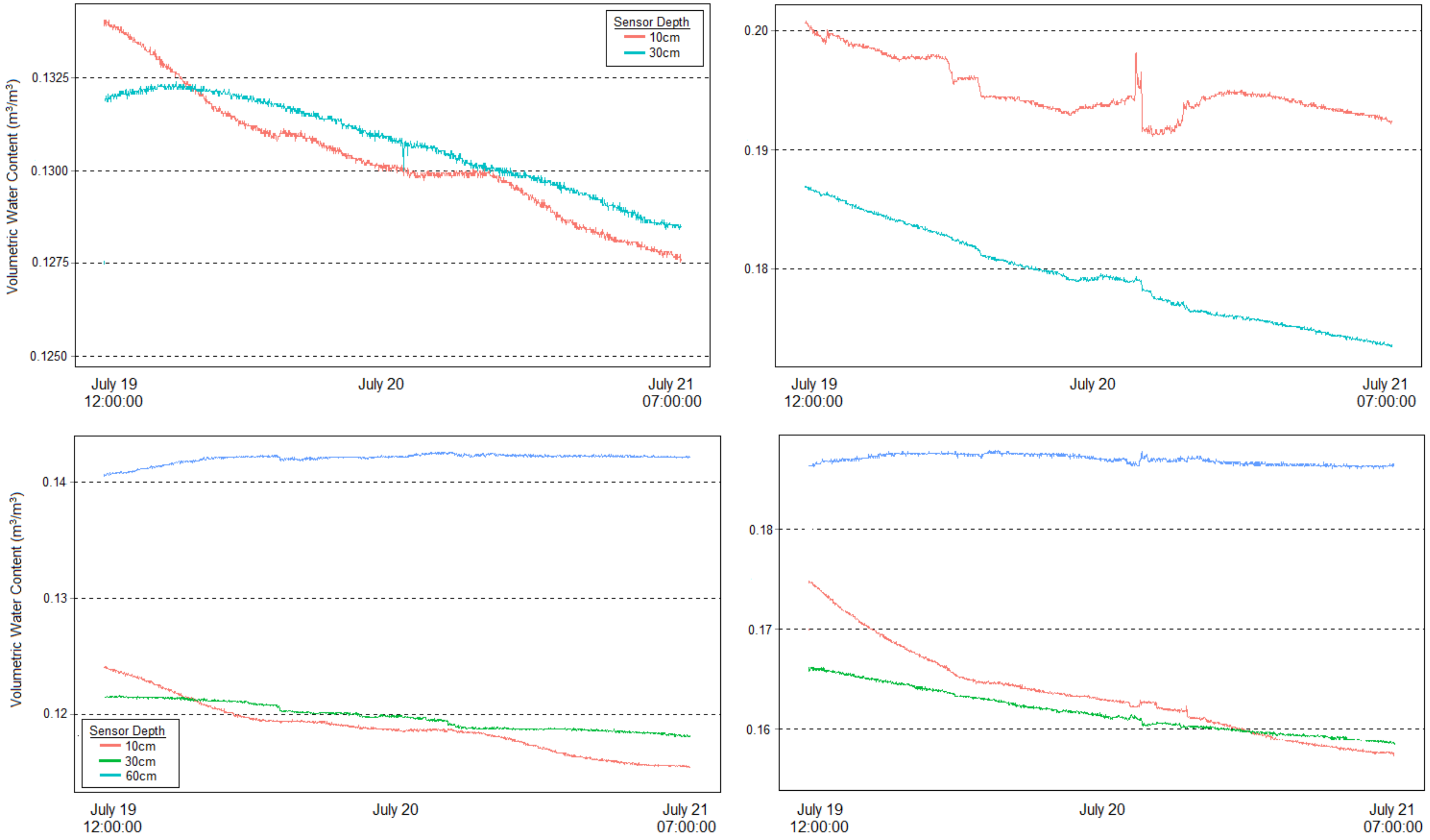


Figure 49. Soil moisture changes in two Technosols of 30 and 60 cm depths, after a moderate intensity, long duration precipitation event on July 18, 2013. Plots are ordered from 1 (top left), Plot 2 (top right), Plot 3 (bottom left) and Plot 4 (bottom right). n =3 for each sensor depth.

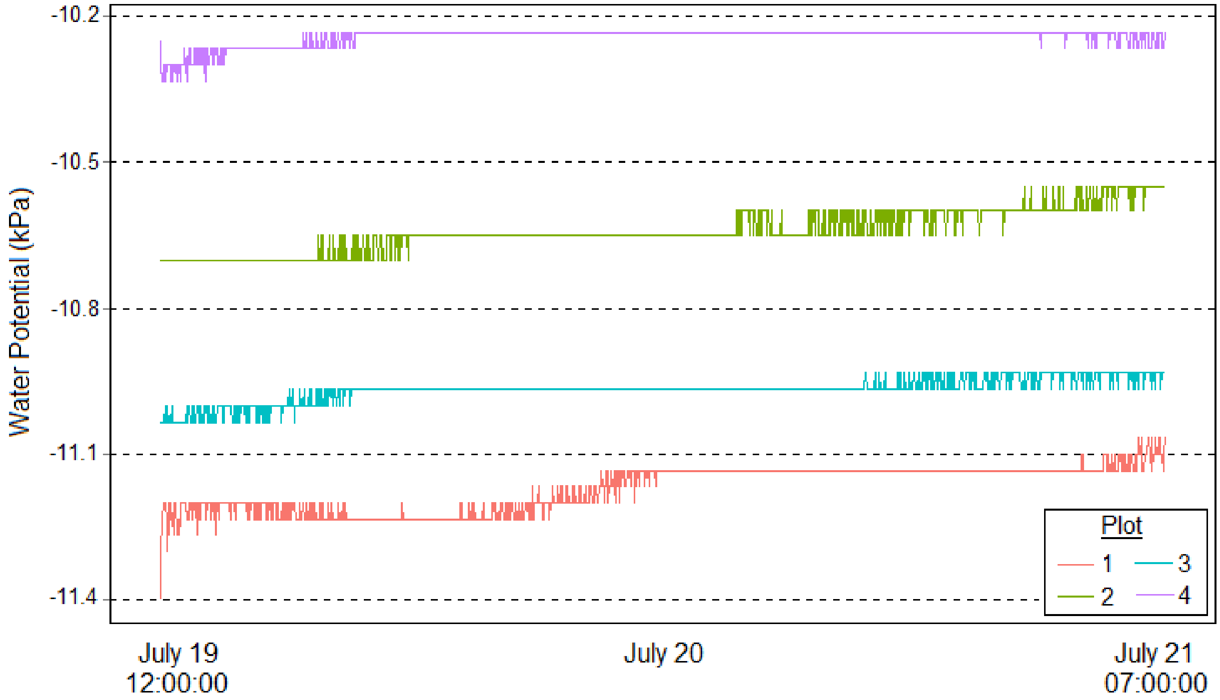


Figure 50. Water potential changes in two Technosols of 30 and 60 cm depths, after a moderate intensity, long duration precipitation event on July 18, 2013. n =3 for each sensor depth.

August 25 – August 29, 2013. Plots received 49.8mm of precipitation starting in the afternoon of August 25, 2013, lasting for a 9 hour duration. Following this event, there was no subsequent precipitation until the late evening of August 29, 2013. Plots had not received precipitation before the August 25 event since August 13, 2013. There was a noticeable increase in soil moisture at all depth of all plots (Figure 51). There was a sharp increase in soil moisture at a 10 cm depth in all plots; soil moisture in Plot 1 increased by approximately 0.035 m^3/m^3, Plot 2 by approximately 0.015 m^3/m^3 during the precipitation event, and then by another 0.01 m^3/m^3 approximately 12 and 48 hours later, Plot 3 by approximately 0.02 m^3/m^3 and Plot 4 by approximately 0.045 m^3/m^3. Changes in soil moisture at a 30 cm depth followed patterns of soil moisture changes at a 10 cm depth, however there was a slight lag time in reaching peak soil moisture in Plots 1, 3 and 4. Plot 2 had rapid responses to precipitation at a 30 cm depth that were greater in magnitude than changes in soil moisture at a 10 cm depth. In Plots 1 and 3, soil moisture at a 30 cm depth increased by about two thirds as much as the soil moisture at a 10 cm depth, and by one half in Plot 4. Soil moisture at a 60 cm depth reached its peak about half a day after the precipitation event in Plot 3 and a few hours after the precipitation event in Plot 4. Soil moisture remained elevated at 60 cm depth – without noticeably decreasing in Plot 3, and only decreasing by about 0.05 m^3/m^3 in Plot 4 after 4 days of drying. Even after heavy precipitation, soil moisture at a 60 cm depth in Plot 3 (0.145 m^3/m^3), was not as high as soil moisture at a 10 cm depth in Plot 4 (0.1575 m^3/m^3), even after dying for four days. Immediately following the first precipitation event, on August 25, water potential sharply increased in Plot 1 and 2, rising from approximately -24 to -12.5 kPa in Plot 1, and from approximately -14.5 to -11.5 in Plot 2 (Figure 52). Water potential increased slightly in Plots 3, but did not noticeably increase in Plot 4 which maintained water potential levels at approximately -10.5 kPa throughout.

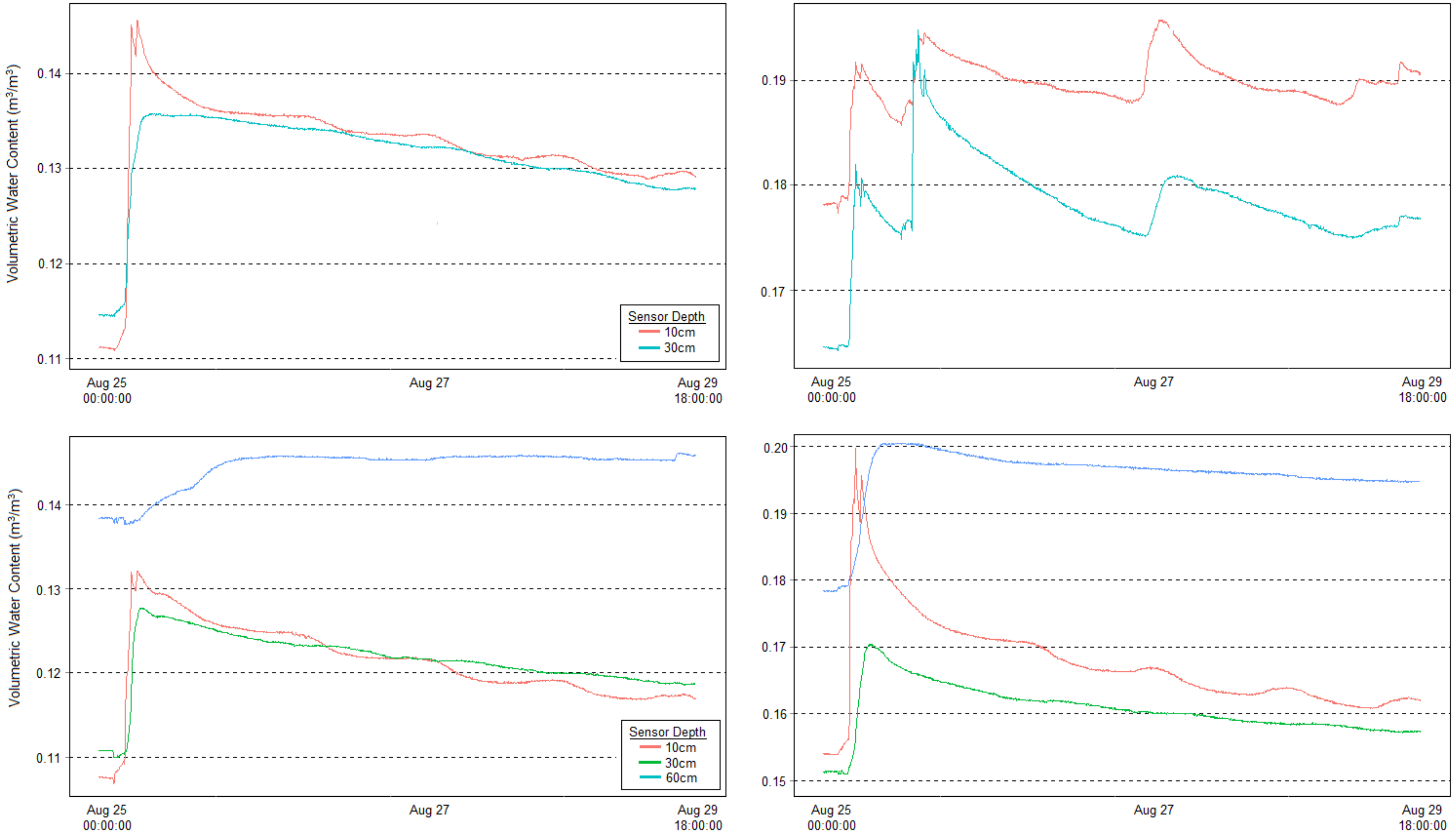


Figure 51. Soil moisture changes in two Technosols of 30 and 60 cm depths, after a high intensity, short duration precipitation event on August 25, 2013. Plots are ordered from 1 (top left), Plot 2 (top right), Plot 3 (bottom left) and Plot 4 (bottom right). n =3 for each sensor depth.

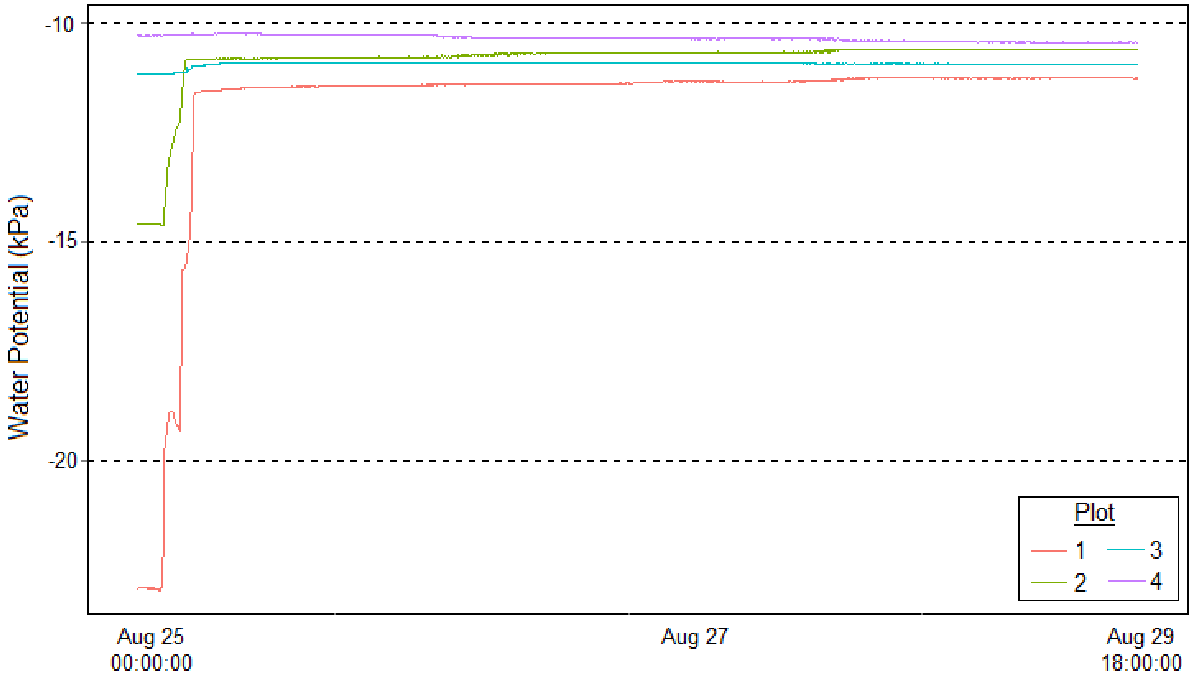


Figure 52. Water potential changes in two Technosols of 30 and 60 cm depths, after a high intensity, short duration precipitation event on August 25, 2013. n =3 for each sensor depth.

4.23 – Soil & Soil Pore Water Chemistry

Soil samples sampled from the Technosols had significantly different amounts of total soil nitrogen (N) and calcium (Ca) (Table 11) and significantly different amounts of bioavailable soil potassium (K), magnesium (Mg), boron (B), iron (Fe) and molybdenum (Mo) (Table 12) ($p<0.05$). Plots 1 & 3 had higher total Ca and bioavailable Mo than Plot 2; Plots 1 & 3 had lower total N and higher bioavailable Mn than Plots 2 & 4; bioavailable K was higher in Plot 2 than Plots 1 & 3 and higher in Plot 4 than Plot3; Plot 2 had higher amounts of bioavailable B than Plot 1; and bioavailable Fe was higher in Plot 4 than Plots 1 & 3, and higher in Plot 2 than Plot 1 ($p<0.05$).

Table 11. Total plant nutrients in two Technosols of 30 and 60 cm depths (1: 40% at 30 cm; 2: 80% at 30 cm; 3: 40% at 60 cm; 80% at 60 cm). Averages are shown, with standard error in italics. n = 3 for each plot. Letters indicate significant differences between plots ($p<0.1$).

	Macronutrients						**Micronutrients**						
Plot	**Ca** %	**K** %	**Mg** %	**P** %	**N** %	**S** %	**B** ppm	**Cu** ppm	**Fe** %	**Mn** ppm	**Mo** ppm	**Ni** ppm	**Zn** ppm
1	^{a}3.41	1.64	1.31	0.05	^{a}0.06	0.38	23.100	29.100	2.15	403.667	61.567	22.600	104.333
	0.21	*0.04*	*0.08*	*0.004*	*0.01*	*0.09*	*1.877*	*1.704*	*0.22*	*29.447*	*11.328*	*2.250*	*2.186*
2	^{ab}3.05	1.58	1.23	0.05	^{b}0.18	0.50	32.500	28.867	2.15	410.000	47.300	17.700	127.333
	0.04	*0.05*	*0.05*	*0.002*	*0.02*	*0.10*	*5.839*	*8.505*	*0.22*	*14.000*	*1.762*	*0.833*	*18.478*
3	^{a}3.35	1.69	1.21	0.05	^{a}0.05	0.38	27.367	23.333	2.13	411.333	51.300	22.467	105.067
	0.09	*0.02*	*0.04*	*0.001*	*0.01*	*0.09*	*2.446*	*2.008*	*0.09*	*17.295*	*3.156*	*1.932*	*3.984*
4	^{b}2.74	1.55	1.07	0.04	^{b}0.15	0.44	20.500	20.267	1.76	374.333	47.167	17.367	102.000
	0.03	*0.05*	*0.02*	*0.000*	*0.02*	*0.05*	*0.702*	*0.968*	*0.08*	*16.895*	*9.251*	*1.027*	*2.082*

Table 12. Bioavailable plant nutrients in two Technosols of 30 and 60 cm depths (1: 40% at 30 cm; 2: 80% at 30 cm; 3: 40% at 60 cm; 80% at 60 cm). Averages are shown, with standard error in italics. n = 3 for each plot. Letters indicate significant differences between plots (p<0.1).

	Macronutrients				**Micronutrients**						
Plot	**Ca ppm**	**K ppm**	**Mg ppm**	**P ppm**	**B ppm**	**Cu ppm**	**Fe ppm**	**Mn ppm**	**Mo ppm**	**Ni ppm**	**Zn ppm**
1	0.002	^{b}18.83	^{b}0.76	<0.002	^{a}0.23	0.36	^{a}45.80	^{a}0.18	^{a}14.28	0.29	<0.001
	-	*1.34*	-	-	*0.01*	*0.18*	*1.80*	*0.01*	*3.05*	*0.09*	-
2	<0.009	^{bc}26.23	^{a}1.61	<0.002	^{b}0.31	0.28	^{bc}57.20	^{b}0.08	^{ab}9.28	1.21	<0.001
	-	*1.59*	*0.14*	-	*0.02*	*0.12*	*0.92*	*0.01*	*1.28*	*0.43*	-
3	0	^{a}16.63	^{b}0.51	<0.002	^{ab}0.29	0.40	^{ab}51.43	^{a}0.21	^{a}14.07	0.29	<0.001
	-	*1.39*	*0.10*	-	*0.02*	*0.05*	*0.07*	*0.03*	*0.55*	*0.02*	-
4	<0.009	^{c}28.07	<0.0008	<0.002	^{ab}0.28	0.24	^{c}60.00	^{b}0.07	^{b}6.78	1.44	<0.001
	-	*3.48*	-	-	*0.02*	*0.10*	*2.68*	*0.02*	*0.10*	*0.23*	-

Soil pore water sampled from Plots 1 and 3, which were composed of 40% organics had consistently higher levels of dissolved Ca, K, Mg, SO_4^{2-} (S), Cl, Fe, Mn, Mo, and Ni than soil pore water sample from Plots 2 and 4, which were composed of 80% organic. However, only Mo and SO_4^{2-} were considered present at significantly different amounts when pore water samples from all plots were compared for a specific sampling date ($p<0.05$) (Table 13). Pore water sampled on July 21, 2013 contained significantly higher amounts of dissolved Mo in Plot 3 than in Plots 2 and 4 ($p<0.05$), and significantly higher amounts of SO_4^{2-} in Plot 1 than Plots 2 and 4 ($p<0.1$); on August 9, 2013 pore water samples from Plots 1 and 3 contained significantly higher amounts of SO_4^{2-} than Plots 2 and 4 ($p<0.1$); on August 13, 2013, pore water samples from Plots 1 and 3 contained significantly higher amounts of Mo than Plots 2 and 4 ($p<0.05$); on October 28, 2013 pore water samples from Plot 1 contained significantly higher amounts of Mo than Plots 2, 3, and 4 ($p<0.1$), Plot 1 had significantly higher amounts of SO_4^{2-} than Plots 2 and 4 ($p<0.1$) and Plot 3 also had significantly higher amounts of SO_4^{2-} than Plot 2 ($p<0.1$).

Table 13. Plant macro and micronutrients contained in pore water in two Technosols of 30 and 60 cm depths (1: 40% at 30 cm; 2: 80% at 30 cm; 3: 40% at 60 cm; 80% at 60 cm). Averages are shown, with standard error in italics. n = 3 for each plot. Letters indicate significant differences between plots ($p<0.1$).

	Macronutrients					**Micronutrients**							
Plot	**Ca**	**K**	**Mg**	**P**	**SO_4**	**B**	**Cl**	**Cu**	**Fe**	**Mn**	**Mo**	**Ni**	**Zn**
	μg/L	**μg/L**	**μg/L**	**μg/L**	**mg/L**	**μg/L**	**mg/L**	**μg/L**	**μg/L**	**μg/L**	**μg/L**	**μg/L**	**μg/L**
July 21													
1	105933	50200.0	19033	17.00	^{ab}297.3	3813.33	8.83	9.20	5280	1.4	^{a}75.67	13.90	9.4
	23275	*7257.0*	*5149*	*6.86*	*108.3*	*1708.94*	*6.86*	*0.99*	*1187*	*0.4*	*6.42*	*2.35*	*3.2*
2	57700	30266.7	8380	36.70	^{b}25.6	2693.33	0.62	7.80	2920	1.1	^{b}9.55	8.49	9.0
	1021	*1560.3*	*281*	*5.22*	*1.5*	*354.51*	*0.05*	*2.37*	*55*	*0.3*	*0.33*	*0.51*	*0.5*
3	71500	38706.7	11983	25.27	^{a}337.0	1460.00	2.93	8.49	3570	1.5	^{ab}36.41	9.80	8.2
	24878	*17984.2*	*4457*	*7.10*	*120.8*	*653.41*	*1.56*	*4.15*	*1238*	*0.4*	*16.84*	*3.74*	*2.3*
4	33667	21480.0	4550	38.13	^{b}20.4	733.67	1.71	3.80	1743	0.6	^{b}8.81	5.05	8.6
	16009	*10331.3*	*2180*	*9.90*	*8.6*	*172.12*	*1.41*	*1.23*	*833*	*0.0*	*1.06*	*1.78*	*2.1*
August 9													
1	53230	27236.7	9353	38.03	^{a}182.8	2667.00	17.13	5.70	3340	0.9	42.40	8.03	45.4
	24572	*12186.9*	*4249*	*13.25*	*61.3*	*1312.51*	*14.38*	*2.54*	*1532*	*0.3*	*19.15*	*3.81*	*32.0*
2	53733	28366.7	7633	62.60	^{b}23.5	2227.00	1.80	14.37	3433	3.9	5.56	10.97	27.1
	504	*1010.5*	*596*	*48.50*	*2.5*	*647.99*	*0.92*	*7.78*	*249*	*3.3*	*0.15*	*3.17*	*11.1*
3	76100	47500.0	13900	<0.45	^{a}152.1	1082.73	1.48	6.11	2901	0.8	39.30	6.95	6.1
	12819	*11104.4*	*2041*	-	*57.9*	*566.29*	*0.29*	*3.29*	*1550*	*0.1*	*6.94*	*3.83*	*3.3*
4	52633	31700.0	7900	10.70	^{b}17.0	2032.67	0.72	5.24	3077	0.4	5.98	6.80	19.9
	2916	*1305.1*	*505*	-	*3.2*	*1208.68*	*0.17*	*1.31*	*185*	*0.2*	*1.26*	*0.26*	*8.3*

Table 13. Plant macro and micronutrients contained in pore water in two Technosols of 30 and 60 cm depths (1: 40% at 30 cm; 2: 80% at 30 cm; 3: 40% at 60 cm; 80% at 60 cm). Averages are shown, with standard error in italics. n = 3 for each plot. Letters indicate significant differences between plots (p<0.1).

	Macronutrients					**Micronutrients**							
Plot	**Ca** **μg/L**	**K** **μg/L**	**Mg** **μg/L**	**P** **μg/L**	**SO$_4$** **mg/L**	**B** **μg/L**	**Cl** **mg/L**	**Cu** **μg/L**	**Fe** **μg/L**	**Mn** **μg/L**	**Mo** **μg/L**	**Ni** **μg/L**	**Zn** **μg/L**
August 13													
1	60500	41833.3	13070	<0.45	160.9	4663.33	1.06	7.95	3503	0.8	^{a}79.40	8.30	7.3
	15847	*6838.7*	*3179*	-	*58.9*	*500.71*	*0.03*	*0.99*	*916*	*0.1*	*11.89*	*1.52*	*3.1*
2	48900	24766.7	7293	<0.45	20.4	3766.67	1.17	8.39	2850	0.7	^{b}8.76	7.65	22.4
	1914	*1894.1*	*312*	-	*1.2*	*558.40*	*0.64*	*2.84*	*146*	*0.2*	*0.50*	*0.17*	*10.2*
3	64867	52200.0	13873	1.11	150.2	3066.67	0.23	7.67	3157	1.0	^{a} 53.97	7.44	1.2
	10161	*12182.9*	*2970*	-	*55.5*	*1020.36*	*0.10*	*1.42*	*490*	*0.3*	*7.49*	*1.38*	*0.1*
4	37033	24433.3	5190	8.05	18.0	2106.67	0.79	13.84	1817	0.3	^{b}16.00	5.71	21.3
	9569	*7194.8*	*1219*	-	*4.2*	*678.39*	*0.55*	*8.69*	*459*	*0.1*	*7.83*	*0.53*	*12.5*
October 24													
1	55333	33300.0	9403	<0.45	^{a}87.0	1686.67	0.61	6.04	2733	0.6	^{a}71.93	6.66	9.8
	7504	*4782.3*	*1454*	-	*29.8*	*337.85*	*0.13*	*0.40*	*379*	*0.1*	*16.53*	*1.03*	*8.8*
2	39533	19800.0	5803	<0.45	^{b}11.9	1476.67	0.36	4.61	1957	0.8	^{c}5.20	4.78	4.0
	2806	*1401.2*	*478*	-	*2.0*	*170.23*	*0.05*	*1.24*	*143*	*0.1*	*0.42*	*0.33*	*1.6*
3	62033	35800.0	9973	<0.45	^{b}19.7	1052.33	0.27	5.36	3003	1.0	^{ab}59.53	6.66	8.9
	8911	*8016.4*	*1938*	-	*6.9*	*159.36*	*0.11*	*0.78*	*478*	*0.3*	*17.37*	*1.10*	*0.4*
4	29310	16533.3	3853	<0.45	^{b}15.4	927.10	0.50	5.52	1509	0.7	^{bc}11.25	3.78	8.4
	13702	*7714.1*	*1779*	-	*8.0*	*502.93*	*0.14*	*3.40*	*722*	*0.4*	*3.80*	*1.62*	*3.3*

4.24 – Vegetation Survival

Tickle grass (*Agrostis scabra)* did not establish well on any of the reclamation plots. Upon returning to the field site in the fall of 2013, two months after seeding, emerging stems of tickle grass were evident, but were quite short and thinly dispersed on the plot. Tickle grass seemed to establish more easily in small hollows on the top of the reclamation plots, as indicated by thicker growth in those areas. In the spring of 2014, no tickle grass seeds were present on any plot. Green alder (*Alnus viridis)* had a low survival rate; the highest being 8 of 16 transplants surviving, and 1 as the lowest (Table 14).

Table 14. Green alder survival assessed spring 2014, of 16 individuals transplanted on to reclamation plots in the fall of 2013.

Plot	**Surviving Green Alder**	
1A	31.25%	(5)
2A	-	
3A	-	
4A	12.5%	(2)
1B	-	
2B	50.0%	(8)
3B	6.25%	(1)
4B	-	
1C	37.5%	(6)
2C	37.5%	(6)
3C	18.75%	(3)
4C	18.75%	(3)
Control	31.25%	(5)

4.3 – Discussion

4.31 – Soil Moisture and Temperature

During the growing season (May – October), soil moisture and water potential measurements remained above the permanent wilting point of each Technosol at all soil depths monitored. Although this observation suggests the presence plant available water in the plots during the growing season, the absolute amount of water present may not be adequate to sustain plant productivity as successional revegeation occurs, since species composition and age have been shown to affect overall transpiration rates of boreal forest stands (Ewers et al. 2005). Specifically, as trees grow in size, their water requirement increases. Dawson (1996) measured transpiration rates in sugar maples of varying size and found that larger trees (9 -14 m tall) had significantly higher transpiration rates than smaller trees (3-5 m tall). The transpiration rate of the larger trees was more than four times greater than transpiration rate of the smaller trees. The smaller trees however, sourced water exclusively from soil water, with the larger trees also sourcing water from the groundwater reservoirs. Water loss through evaporation should also be considered as more, and larger, plants are established on the reclamation plots. Vegetation will protect the soil surface from sunlight and wind, which in turn may reduce air temperatures at the soil surface, and loss of water through evaporation from the soil surface. Including measurements of plant transpiration rates and soil evaporation rates would complement the study as it progresses, giving a greater understanding of changes in the water balance as vegetation establishes on the newly formed Technosols, an important factor as the Technosols are further tailored to enhance plant productivity. Gwenzi et al. (2012) monitored transpiration and plant physiological responses to environmental conditions of plants grown on vegetated engineered covers which allowed the authors to identify improvements in the design of their engineered covers. Gwenziet al. (2012) suggested amending engineered covers with more fine textured materials to improve water storage and encourage deep rooting of vegetation. Future tailoring of the Technosols used in this study could explore the effects of material size on soil water storage, with subsequent effects on plant productivity.

Plot 4, which contained an 80% organic soil of 60 cm depth, maintained the highest soil moisture (at a 60 cm depth) throughout the year and most effectively maintained elevated moisture after precipitation events than any other plot. Plot 2, which contained 40% organic soil of 30 cm depth, maintained the highest soil moisture within 30 cm from the soil surface throughout the year. This moisture retention capability most likely a consequence of both increased organic matter in the Technosol and increased plot depth, which provided protection from surface evaporation. There was a noticeable difference in soil moisture between plots that had similar depths and different organic content. On average, plots that had higher organic content maintained soil moisture levels that were 0.05 - 0.07 m^3/m^3 higher than plots of lower organic content but equal depth.

Hudson (1994) found that as organic matter increased from 1% to 3% (in volume) in soils of varying textures, the available water capacity approximately doubled. This was due to a greater increase in the volume of water held at field capacity than that held at permanent wilting point. Increasing the amount of organic matter in a soil can increase the soil’s water holding capacity for a several reasons: smaller particle size and preferential aggregation improve capillary water holding capacity and resistance to compaction while reducing bulk density which, in turn, increases pore space in the soil (Francou *et al.* 2008; Paradelo & Barral 2013; Soane 1990). In the case of our Technosols, plant available water was approximately equal, with the amount of water held at field capacity and permanent wilting point increasing equally as the amount of organic material doubled in the Technosols.

Organic matter also aids in reducing surface crusting and increasing water infiltration into the soil. Lado et al. (2003) found that increasing soil organic matter of a sandy loam increased aggregate stability and limited crust formation while increasing infiltration rate. Reduced infiltration resulting from crusting and reduced aggregate stability may be the cause of sharp increases in soil moisture after precipitation events in plots that had 80% organic Technosols (Plots 2 and 4); whereas plots that had 40% organic Technosols (Plots 1 and 3) did not show such sharp increases in soil moisture. After a rain event of moderate intensity on July 6, (Figure 47) soil moisture at a 10 cm depth of 80% Technosols increased by 0.035 and 0.025 m^3/m^3 (Plot 2 and 4), whereas soil moisture at a 10 cm depth in 40% Technosols increased by approximately 0.015 m^3/m^3 only. Increasing the depth of a plot did seem to increase soil moisture at a 30 cm depth, but did not consistently increase soil moisture at a 10 cm depth, while soil moisture at a 60 cm depth was always consistently higher than soil moisture at 30 and 10 cm depths in the same plot. Water from light precipitation may not infiltrate far into the reclamation plot (Figure 43), preventing increases in soil moisture at a 30 cm depth. However, when precipitation can infiltrate to a 30 cm depth, moisture is lost just as quickly or more rapidly as moisture at the 10 cm depth in plots that are 30 cm deep (Plots 1 & 2) (Figure 47, 49 & 51), while drying is slower at a 30 cm depth than at a 10 cm depth in plots that are 60 cm deep (Plots 3 & 4). These results may have been due to water draining into the underlying rock layer at the rock/soil interface in the 30 cm deep reclamation plots, while soil moisture is maintained at an elevated level at a 30 cm depth in the 60 cm reclamation plots because underlying soil layers are already moist. Moisture will be lost from surface soil as it evaporates, and as it moves into the underlying soil layers. Results from this study indicate that plots should contain a high amount of organic material to improve water retention in the soil (and possibly infiltration rate). Plots that were 30 cm deep had higher moisture within 30 cm of the soil surface than plots that were 60 cm deep (when plots of similar organic content were compared). This will be critical for successful vegetation establishment, as most plants root within 30 cm of the soil surface. However, expecting to lose up to 30% of material as organics are decomposed and loss of depth as the Technosols settle, Technosols could be applied at a depth of approximately 60 cm to provide adequate rooting depth and moisture as Technosols age. If Technosols Increased organic content seems to be more beneficial to increased depth of a plot, with regards to water retention and maintaining a reservoir of available water, although at a depth below the rooting zone of most plants). Plot 2 (80% organics at 30cm depth) had higher soil moisture measurements at a 30cm depth than Plot 3 (40% organics at 60 cm depth) did at a 60 cm depth. .

Temperature regimes of the reclamation plots indicate that increasing organic content and depth of a Technosol will increase the insulating effect of that soil, which could protect plant roots from over winter damage. No combination of varying depth and organic material content of Technosols prevented soils at a 30 or even 60 cm depth from reaching below freezing temperatures on the exposed plots, and all surface soils froze, and thawed, at approximately the same time annually in all reclamation plots.

4.32 – Soil Nutrients and Pore Water

Higher total nutrient concentrations of Ca in 40% organic Technosols and N in 80% organic Technosols was not reflected in increased bioavailable nutrient concentrations of the soil or in soil pore water samples. Pore water samples from 40% Technosols had higher concentrations of plant macronutrients than pore water samples of 80% organic Technosols, which indicates that most nutrients in the pore water were contributed to the Technosol from the finely crushed mine rock. However 80% organic Technosols had higher concentrations of bioavailable nutrients which over time will be released as organic material decomposes (Table 12). At present increased nutrients in 40% organic Technosols could increase vegetation survival, but nutrients held in the abundant organic material of the 80% organic Technosol could contribute to increased vegetation survival long term. At sampling time, because plots were without vegetation, nutrient concentrations in pore water samples may not correspond with bioavailable nutrient concentrations from soil samples because laboratory extraction methods are not representative of processes occurring in the plots. $LiNO_3$ extraction should yield results that are representative of what root exudates will extract from a soil – not just water alone. As vegetation is transplanted on to the reclamation plots, soil pore water samples should be taken at regular intervals throughout the growing season to better understand how root development and vegetation establishment may influence nutrient availability as the Technosols develop and organic material decomposes.

4.33 – Vegetation Survival

Tickle grass establishment was most likely hindered by increased temperature and inadequate amounts of soil moisture at the time of seeding. August had the highest recorded temperatures, and lowest soil moisture measurements. If seeding occurred during the fall or spring, periods of increased moisture availability with lower potential for seed desiccation, there may have been a higher survival rate of tickle grass. As the study progresses, soil moisture should be monitored in the critical soil surface zone for seedling establishment as additions of mulch or other amendments are used to increase soil moisture in the surface soils to promote seedling establishment and growth. The low survival rate of green alder transplants can most likely be attributed to transplant method and time of transplanting. As much soil as could gently be removed was shaken from each green alder before being planted on the reclamation plots. Although this afforded an ideal opportunity to inspect the root systems of the green alders for nodules and damage from uprooting, this may have hindered their establishment on the reclamation plots at the time of transplanting (August 2013). Acquiring adequate water would have been critical at this time of the season – if roots did not have good connectivity with the surrounding soil after being transplanted acquiring enough water for successful establishment would have been difficult. The Sudbury Regreening Program conducts spring and fall tree planting on barren sites that had been historically affected by the mining industry; survival rate of green alder one year after transplants was 97% (VETAC 2013). Transplant survival rate could be improved if planting occurred in the spring or fall when more moisture is available. Although meaningful statistical analysis could not be performed effectively on such a small sample size, Plot 2 had the highest average survival rate of green alder (43%), which could be attributed to the fact that this plot consistently had the highest soil moisture levels at a 10 cm depth (the depth at which most roots were found). Plot 3, which had the lowest soil moisture levels at a 10cm depth, had the lowest survival rate (13%). Plot 1 and 4 had similar soil moisture levels in the surface 30 cm of Technosol plots, and the second and third highest green alder survival rates (34 % and 16%) which could be attributed to increased macronutrient concentrations in the pore water of 40% organic Technosols.

4.34 – Conclusions, Implications and Recommendations

Plots constructed with Technosols having high organic content (80%) had a greater water retention than plots constructed with Technosols having low organic content (40%), and subsequently consistently higher soil moisture levels at any given time and depth when plots of similar depth were compared. Plots constructed with Technosols of 60 cm depth were able to maintain a reservoir of plant available water at depth that did not show significant decreases in soil moisture throughout the growing season. However this reservoir is below the rooting zone of most vegetation. Increased organic content of a soil did seem to be more beneficial to soil moisture levels than increased depth of a soil. Poor green alder and tickle grass survival may have been negatively affected by increased temperatures and limited water availability at the time of, and immediately following transplanting. However, elevated soil moisture within the rooting zone of shallow plots and plots with increased organic material, and higher concentrations of plant nutrients in 40% organic Technosols did seem to contribute to differences in green alder survival. Temperature data from the plots indicate that soils at the 10 cm depth remain consistently above freezing by the end of April, which could be a more appropriate time to transplant vegetation to the plots in future.

Technosols composed of 80% organics applied to a 30 cm depth were the most suitable Technosol treatment for use in reclamation, based on soil moisture levels, bioavailable plant nutrient concentrations of the soil and vegetation transplant survival rates. However, it is recommended that 80% organic Technosols be applied to 60 cm depth, so that adequate material is maintained for plant rooting as the organic material in the Technosols decomposes and settling occurs. Since increasing depth of the Technosol decreases moisture levels in the rooting zone, future research should focus on the use of mulches or other surface treatments to increase soil moisture. This will be critical for seedling establishment if deeper plots are selected for use. Mackenzie and Naeth (2010) have demonstrate that surface applications of LFH layers from forest floors also provide a source of propagules and improved nutrient availability for plants.

Additional soil moisture sensors could be installed at a shallower depth to monitor changes in soil moisture throughout the growing season to help identify ideal times for transplanting and to determine which soil amendment or surface treatment increases soil moisture most effectively. Gwenziet al. (2012) suggested amending their engineered cover with more fine textured materials to improve water storage and deep rooting of vegetation. Until nitrogen becomes available as woody residuals begin to decompose and nutrient cycling is restored, small applications of fertilizer may be required to increase nitrogen levels in the soil. The pH of the Technosols is not ideal for boreal forest vegetation and should be lowered through amendment application. The use of elemental sulphur could provide this limiting nutrient and help lower soil pH, which could help promote natural vegetation establishment on the plots. Future tailoring of the Technosols used in this study could explore the effects of material size on soil water storage and its subsequent effects on plant productivity. As the project continues, measurements of infiltration rate, crust formation and bulk density will be critical to understanding the processes that may be affecting soil moisture levels in the reclamation plots. As vegetation is transplanted or establishes on the reclamation plots measurements of evaporation and transpiration should be monitored for a better understanding of changes in the water balance as vegetation establishes on the newly formed Technosols, which will become an important factor as soils are further tailored to enhance plant productivity.

Chapter 5

5 Summary, Conclusions & Recommendations

5.1 - Summary

Constructing a soil out of locally sourced, industrial by-products for use as cover soils in the reclamation of damaged lands could help improve land reclamation methods by reducing environmental impacts, and allows mining companies to tailor soil properties to specific site or use requirements. Barrick Gold’s Hemlo Operations is supporting research in manufacturing a cover soil that will be suitable to create ‘cover islands’ of native boreal vegetation for reclamation of large mine rock piles generated through their open-pit mining activities. Woody residuals, sourced from the former Domtar, White River Sawmill (White River, ON), primary paper sludge sourced from Terrace Bay Pulp Inc. (Terrace Bay, ON) and finely crushed intermediate volcanic and metasedimentary mine rock, sourced from the open-pit mine at Barrick-Hemlo (Hemlo, ON) were used to manufacture multiple Technosols that were assessed as growth media in a 10 week growth study using annual ryegrass (*Lolium multiflorum*).

Woody residuals and a mixture of the two subtypes of finely crushed mine rock were identified as viable materials to manufacture a growth medium. Technosols that contained an organic constituent yielded lower root:shoot ratios than Technosols that did not contain an organic constituent; specifically a strong negative correlation existed between the amount of woody residuals used in Technosol production and root:shoot ratio. There was no significant difference in biomass production or allocation between Technosols manufactured with equal amounts of paper sludge or woody residuals when adequate water was available; however when plants were subjected to ‘drought conditions’ ryegrass grown in Technosols constructed with woody residuals were able to produce significantly greater above ground biomass than ryegrass grown in Technosols containing paper sludge. Greater biomass yield from Technosols constructed with woody residuals most likely resulted from optimal pH range for ryegrass growth, and elevated levels of bioavailable plant macronutrients and water holding capacity.

As research progressed into a field study, two new Technosols were constructed using woody residuals and mixed mine rock. A Technosol consisting of 40% organics (and 60% mine rock) by volume and a Technosol consisting of 80% organics (and 20% mine rock) by volume were constructed to simulate ‘vegetated islands’ on site at Barrick-Hemlo. Monitoring soil microclimate data throughout the soil profiles of each plot provided a base line of annual soil moisture and temperature dynamics on plots void of vegetation. Increasing the amount organic material and depth of the Technosol increased soil moisture in the reclamation plots. Technosols with higher organic content also had significantly higher concentrations of bioavailable plant nutrients, although this was not reflected in pore water samples. In the second summer of the study, select plots were seeded with Tickle Grass (*Agrostis scabra*) and sixteen individual Green Alder saplings (*Alnus viridis*) were transplanted to each of the selected plots. Although, soil moisture remained consistently above estimated permanent wilting points of each Technosol there were low survival rates of Tickle Grass and Green Alder after over wintering on the reclamation plots – the low survival rate can most likely be attributed to seeding and transplanting occurring during the middle of summer when environmental conditions were not ideal for vegetation establishment.

5.2 – Conclusions

Woody residuals can be used as the organic constituent to manufacture a Technosol that provides adequate water holding capacity and bioavailable plant nutrients to consider it a successful growth medium. Technosols manufactured with primary paper sludge as the organic constituent are not suitable for use as a growth media for boreal forest vegetation.

Technosols manufactured with 40 and 80% woody residuals and mixed, finely crushed mine rock can sustain soil moisture levels above permanent wilting point. Technosols of 60cm depth maintained a stable reservoir soil moisture at depth. Technosols containing 80% woody residuals and of 30 cm depth maintained the highest soil moisture levels at a 10cm depth which most likely contributed to increased survival of Green Alder saplings grown on these Technosols.

5.3 – Recommendations

Technosols constructed with primary paper sludge as the organic constituent should not be used in reclamation activities in the boreal forest ecosystem, unless amendments are used with the Technosol to decrease pH levels and increase bioavailability of plant nutrients. Technosols constructed with woody residuals can be used, with an 80% by volume of organics preferred to maintain adequate soil moisture and plant nutrients over the long term. Depositing Technosols to a 60 cm depth is recommended so that adequate material is maintained for plant rooting, as the organic material in the Technosols decomposes, and settling occurs. To increase soil moisture in the top 10 cm of the Technosol, which in turn may increase seedling and transplant survival, surface amendments or mulches should be investigated and used in conjunction with Technosols of high organic composition and deposited to a depth of 60 cm.

Studies focusing on decomposition and incorporation rate of woody residuals in the Technosols, with focus on functional microbial processes would enhance comprehension of changes in nutrient cycling and soil aggregation as Technosols age. The use of fertilizer to increase soil nitrogen may be necessary until woody residuals start to decompose. Soil pH may also need to be adjusted using soil amendments such as elemental sulphur to promote native boreal forest vegetation establishment. As vegetation establishes on the reclamation plots measurements of infiltration rate, crust formation, bulk density evaporation and transpiration should be monitored for a complete understanding of changes in the water balance as vegetation establishes on the newly formed Technosols, which will be important as soils are further tailored to enhance plant productivity.

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Appendices

Table A1. Average total concentrations of essential plant macro- and micronutrients in the soils composed of woody residuals or primary paper pulp and metasedimentary or intermediate volcanic finely crushed mine rock.

	Macronutrients							**Micronutrients**			
	Ca (%)	**Mg (%)**	**Ca:Mg Ratio**	**K (%)**	**P (ppm)**	**N (%)**	**S (%)**	**Cu (ppm)**	**Fe (%)**	**Mn (ppm)**	**Zn (ppm)**
Metasediments											
+Woody Residuals											
0%	2.27	0.64	3.55	1.75	411.7	0.01	0.13	22.8	1.80	265.7	59.2
25%	2.21	0.62	3.56	1.68	423.7	0.05	0.16	18.5	1.73	266.3	61.4
50%	2.18	0.61	3.57	1.58	401.7	0.12	0.11	17.8	1.63	277.3	63.7
75%	2.23	0.55	4.05	1.34	400.7	0.21	0.08	15.4	1.36	291.3	77.7
+ Paper Sludge											
25%	2.35	0.62	3.79	1.66	399.4	0.01	0.05	22.9	1.76	261.0	55.3
50%	3.65	0.59	6.19	1.47	394.4	0.02	0.06	22.7	1.59	261.0	48.6
75%	4.04	0.57	7.09	1.48	398.4	0.03	0.06	21.8	1.57	260.7	52.1
Intermediate Volcanics											
+Woody Residuals											
0%	3.41	0.84	4.06	2.17	485.0	0.01	0.30	18.0	1.67	323.0	68.2
25%	3.38	0.78	4.33	2.03	503.0	0.05	0.60	19.7	1.62	336.7	67.1
50%	3.26	0.86	3.79	2.03	493.0	0.08	0.74	22.2	1.63	336.0	74.4
75%	2.74	0.69		1.48	425.7	0.31	0.71	25.1	1.16	331.3	101.8
+ Paper Sludge											
25%	2.92	0.58	5.03	2.26	466.0	0.01	0.47	17.9	1.48	273.3	57.8
50%	3.59	0.56	6.41	2.01	547.7	0.02	0.43	19.2	1.40	290.0	61.4
75%	5.87	0.80	7.34	1.72	518.0	0.02	0.53	21.6	1.68	352.3	67.6

Table A2. Average bioavailable concentrations of essential plant macro- and micronutrients in the soils composed of woody residuals or primary paper pulp and metasedimentary or intermediate volcanic finely crushed mine rock.

	Macronutrients					**Micronutrients**			
	Ca (ppm)	**Mg (ppm)**	**Ca:Mg Ratio**	**K (ppm)**	**P (ppm)**	**Cu (ppm)**	**Fe (ppm)**	**Mn (ppm)**	**Zn (ppm)**
Metasediments									
+Woody Residuals									
0%	62.50	5.96	10.49	37.20	0.02	0.02	<DL	<0.0004	<0.001
25%	135.07	10.63	12.71	36.57	0.41	0.06	0.03	<0.0004	<0.001
50%	202.00	14.27	14.16	37.40	0.34	0.05	0.08	<0.0004	<0.001
75%	280.33	21.13	13.27	38.93	3.44	0.06	0.20	<0.0004	<0.001
+ Paper Sludge									
25%	56.50	12.27	4.60	27.47	0.18	0.03	1.34	0.02	<0.001
50%	65.83	48.10	1.37	47.97	0.45	0.10	5.86	0.09	<0.001
75%	70.33	48.43	1.45	41.47	0.48	0.10	5.87	0.13	<0.001
Intermediate Volcanics									
+Woody Residuals									
0%	96.93	10.93	8.87	59.20	<0.002	0.02	0.07	<0.0004	<0.001
25%	147.33	13.77	10.70	45.90	0.72	0.05	0.14	0.14	<0.001
50%	181.67	15.13	12.00	44.80	1.57	0.03	0.07	<0.0004	<0.001
75%	339.67	23.47	14.47	62.43	4.84	0.04	0.21	0.05	0.06
+ Paper Sludge									
25%	52.13	12.13	4.30	27.93	0.17	0.02	0.36	<0.0004	<0.001
50%	68.93	27.13	2.54	37.53	0.36	0.17	2.00	0.09	0.10
75%	61.70	40.73	1.51	35.97	0.46	0.07	1.37	0.05	<0.001

Table A3. Average soil moisture values at matric potentials from -0.333 MPa to -15 MPa for soils made with metasedimentary (1 &2) and intermediate volcanic (3 & 4) mine rock, woody residuals (1 & 3) and primary paper sludge (2 &4). Percentages indicate the amount of organic matter in each Technosol. n = 3 for each Technosol.

Soil Type	**Gravimetric Water Content (%)**						
	0.1 MPa	**0.333 MPa**	**1 MPa**	**2 MPa**	**4 MPa**	**8 MPa**	**15 MPa**
1-0%	11.50	10.34	3.39	3.13	5.65	1.00	1.04
1-25%	16.78	9.86	5.72	4.43	3.12	2.36	2.57
1-50%	23.54	22.74	9.80	9.51	11.15	4.64	5.18
1-75%	44.36	35.09	19.23	18.30	12.47	11.51	9.34
2-25%	14.57	14.66	5.90	4.95	2.68	2.32	0.95
2-50%	26.09	12.42	10.62	5.64	4.12	-	1.94
2-75%	61.50	26.51	15.48	7.91	10.25	8.24	5.26
3-0%	10.85	10.73	2.35	2.49	4.45	0.55	0.63
3-25%	17.03	9.47	4.75	4.58	2.50	1.90	2.30
3-50%	26.09	22.70	9.72	8.87	5.87	5.66	5.17
3-75%	40.43	30.70	17.35	15.68	11.46	11.46	11.10
4-25%	14.81	5.31	1.87	3.39	1.55	1.13	0.81
4-50%	27.76	11.24	5.91	4.82	4.65	3.29	4.04
4-75%	93.59	28.41	21.98	12.44	14.10	17.01	10.69

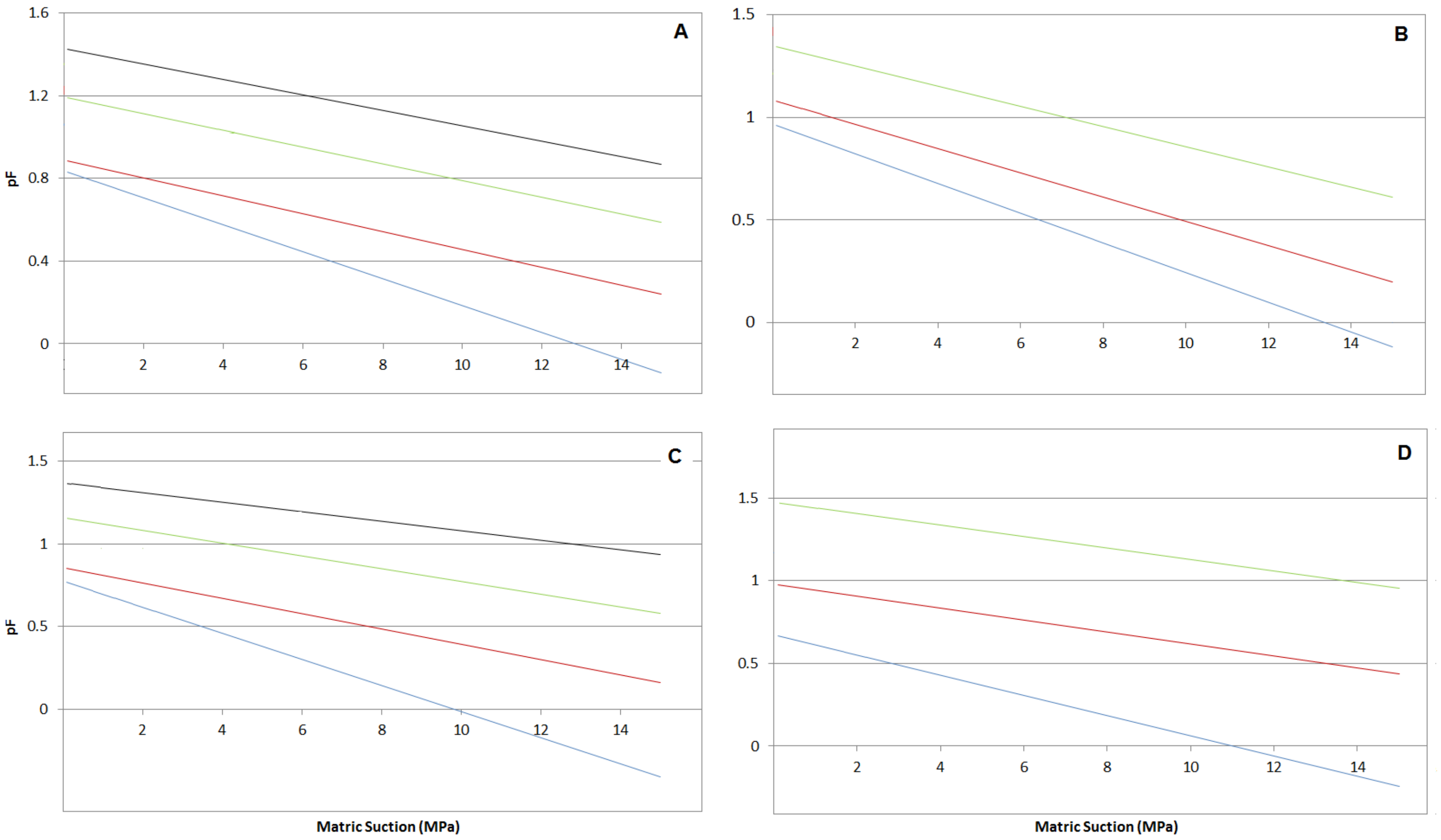

Figure A1. Soil moisture characteristic curves showing pF values, for Technosol composed of metasedimentary mine rock and woody residuals (A), metasedimentary mine rock and paper sludge (B), intermediate volcanic mine rock and woody residuals (C) and intermediateve volcanic mine rock and paper sludge (D). Soils containing 0% organics (black), 25% organics (green), 50% organics (red) and 75% organics (blue) are shown. n = 3 for each Technosol.

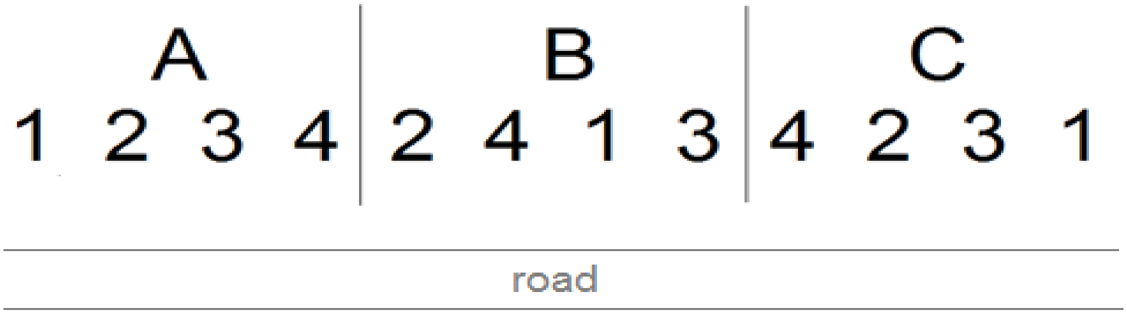

Figure A2. Barrick reclamation plot layout diagram. Treatments are indicated by numbers (1: 40% organic, 30cm depth; 2: 80% organic, 30cm depth; 3: 40% organic, 60cm depth; 4: 80% organic, 60cm depth) and randomly distributed within a replication block (A, B or C).

Table A4. Soil microclimate sensor identification and location in Barrick reclamation plots.

Logger	Port	Plot	Sensor	Depth (cm)
EM21901	1	1C	5TM-1	10
	2	1C	5TM-2	30
	3	1C	MPS-920	30
	4	3C	5TM-3	10
	5	3C	5TM-4	30
EM21902	1	3C	MPS-922	60
	2	3C	5TM-5	60
	3	2C	5TM-6	10
	4	2C	MPS-919	30
	5	2C	5TM-7	30
EM21903	1	4C	MPS-921	60
	2	4C	5TM-8	10
	3	4C	5TM-9	30
	4	4C	5TM-11	60
	5	3B	MPS-924	60
EM21904	1	3B	5TM-11	10
	2	3B	5TM-12	30
	3	3B	5TM-13	60
	4	1B	5TM-14	10
	5	1B	5TM-15	30
EM21905	1	1B	MPS-917	30
	2	4B	5TM-17	30
	3	4B	5TM-18	60
	4	4B	MPS-928	60
	5	4B	5TM-19	10
EM20808	1	2B	MPS-926	30
	2	2B	5TM-20	10
	3	2B	5TM-21	30
	4	4A	MPS-927	60
	5	4A	5TM-22	10
EM21907	1	4A	5TM-23	30
	2	4A	5TM-24	60
	3	3A	MPS-923	60
	4	3A	5TM-25	10
	5	3A	5TM-26	30
EM21914	1	3A	5TM-27	60
	2	2A	MPS-916	30
	3	2A	5TM-28	10
	4	2A	5TM-29	30
EM21913	1	1A	MPS-929	30
	2	1A	5TM-30	10
	3	1A	5TM-31	30

Table A5. Plot dimensions measured in the field to determine seeding rate (gm^{-2}).

Plot	Dimensions (m x m)	Surface Area (m^2)	Seed weight (g)
1A	4.1 x 4.0	16.4	32.8
1B	4.2 x 4.6	19.32	-
1C	4.8 x 4.5	21.6	43.2
2A	4.35 x 4.1	17.84	-
2B	5.0 x 4.6	23	46.0
2C	4.5 x 4.7	21.15	42.3
3A	3.7 x 3.7	13.69	-
3B	3.7 x 3.5	12.95	25.9
3C	3.7 x 3.6	13.32	26.6
4A	3.8 x 4.0	15.2	30.4
4B	3.9 x 4.3	16.77	-
4C	4.0 x 4.25	17	34.0

Table A6. Heights of individual green alder as measured by the tallest stems. Tree number corresponds to coordinates on plot as shown in Figure 35.

Plot	**Tree Height (cm)**																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**Av**	**SE**
1A	20	22	22	12	10	10	14	29	38	26	18	10	9	16	6	27	18.1	2.21
1C	15	15	11	30	16	25	19	14	19	15	15	18	27	22	6	10	17.3	1.58
2B	18	20	20	19	9	7	7	15	11	22	11	13	15	7	31	12	14.8	1.65
2C	17	13	9	35	9	28	6	33	17	16	11	20	11	24	8	21	17.4	2.23
3B	17	16	14	11	38	31	10	19	15	18	10	10	52	37	18	9	20.3	3.13
3C	22	29	7	26	13	9	4	16	23	17	17	13	10	12	19	25	16.4	1.81
4A	26	9	20	36	19	9	20	11	18	12	7	7	19	13	10	46	17.6	2.71
4C	31	13	10	20	25	4	3	14	19	20	15	29	8	10	6	26	15.8	2.22
Hwy17	11	8	8	38	8	7	10	11	17	6	9	15	10	30	21	32	15.1	2.49

Table A7. Soil fertility parameters of two Technosols and their parent materials.

Sample	Organic Matter	Phosphorus P ppm		Percent Base Saturations				K/Mg Ratio	pH	CEC
		Bicarb	Bray-P1	%P	%K	%Mg	%Ca		pH	meq/100g
Mine Rock	0.2	139	340	27	5.6	6.4	81.3	0.87	6.9	19.6
Woody Residuals	46.3	28	46	4	2.7	14.6	73.9	0.18	6.5	14.3
80% Organic Technosol	14.7	4	4	-	1.2	7.8	85.5	0.15	7.2	20.8
40% Organic Technosol	3.2	137	395	33	4.5	5.8	75.9	0.78	7	28

Table A8. Soil fertility values of bioavailable plant nutrients in two Technosols and their parent materials

Sample	Potassium	Magnesium	Calcium	Sulfur	Zinc	Manganese	Iron	Copper	Boron
	K ppm	Mg ppm	Ca ppm	S ppm	Zn ppm	Mn ppm	Fe ppm	Cu ppm	B ppm
Mine Rock	432	150	3190	75	12.8	30	105	2.3	0.2
Woody Residuals	151	250	2110	8	16.1	34	52	0.5	0.4
80% Organic Technosol	100	195	3550	50	10.2	36	70	0.9	0.4
40% Organic Technosol	488	195	4250	140	9.1	35	79	1.6	0.3