Feng, Yu, Wang, Jinman, Bai, Zhongke, & Reading, Lucy
(2019)
Effects of surface coal mining and land reclamation on soil properties: A review.
Earth-Science Reviews, *191*, pp. 12-25.

https://doi.org/10.1016/j.earscirev.2019.02.015

Accepted Manuscript

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PII: S0012-8252(17)30592-5
DOI: https://doi.org/10.1016/j.earscirev.2019.02.015
Reference: EARTH 2798

To appear in: *Earth-Science Reviews*

Received date: 15 November 2017
Revised date: 6 February 2019
Accepted date: 12 February 2019

Please cite this article as: Y. Feng, J. Wang, Z. Bai, et al., Effects of surface coal mining and land reclamation on soil properties: A review, Earth-Science Reviews, https://doi.org/10.1016/j.earscirev.2019.02.015

Effects of Surface Coal Mining and Land Reclamation on Soil Properties: A Review

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Abstract:

Opencast coal mining has a series of consequences on land resources and places enormous pressure on the ecological environment. Stripping, excavation, transportation and dumping have different effects on soil physical, chemical and biological properties. Moreover, the reconstructed landscape produces increased small-scale spatial heterogeneity of mined soils. Currently, growing concerns for the negative consequences of mining have highlighted the importance of reclamation in minesoil studies. This review has examined the mechanisms of coal mining and reclamation that affect soil properties (physical, chemical, biological) and described soil development in reclamation, with an emphasis on the reclaimed minesoil (RMS) properties of reclamation sites. The major conclusions of this review were: (i) The randomness of soil dumping increased the heterogeneity of minesoil properties, which in turn increased the complexity of reclamation practice. (ii) The negative or positive consequences of mining and reclamation processes on RMS need to be recognized by scientific observations such as soil property multi-index analysis and soil chronosequences, on which the minesoil reconstruction practice are based. (iii) Five phases of reclamation (i.e., geomorphic reshaping, soil reconstruction, hydrological stability, vegetation restoration, and landscape rebuilding) should be considered as a comprehensive system for the reconstruction of minesoils. (iv) The application of new technologies (e.g., micro-terrain reshaping and soil non-destructive detection) and new studies (e.g., systematic study, rebuilding animal habitat, and biodiversity research) to minesoil recovery practice would enhance the new concepts of land reclamation and ecological restoration in mining areas.

Keywords: reclaimed mine soil (RMS); soil properties; surface coal mining; reclamation; five phases of reclamation

1. Introduction

Highly mechanized mining processes are widely used in surface mining because they generally provide an efficient approach for achieving high production (Shrestha and Lal, 2011). However, high production is also associated with large volumes of waste production (Ramani, 2012). During surface mining, the excavated materials from depths of 0-200 m are stripped off and they vary substantially in physical and chemical properties, such as soil bulk density, water holding capacity and water absorbing capacity (Šourková et al., 2005). Surface mining: (i) eliminates vegetation, (ii) changes landforms and landscapes, (iii) alters soil, and (iv) drastically disrupts hydrological regimes (Ahirwal and Maiti, 2016; Kumar et al., 2015). Although soil is highly sensitive to mining activities, it plays a crucial role in material cycling in the pedosphere through balancing soil nutrient, water and energy flows that ensure productivity and sustain biodiversity (Dominati et al., 2010). During excavation, transport and dumping, the original soil structure and properties are drastically altered. The rearranged soil is disturbed by mining operations and can be defined as minesoil or Technosols (Ahirwal and Maiti, 2018; Lehman, 2006; Zhang et al., 2014; Zipper et al., 2013), which develop from the mixture of fragmented rock and fine earthy material (Thomas et al., 2000). Thus, the quality and properties of minesoil vary among locations depending on local conditions (e.g. geology, climate, land-use) (Liu and Lal, 2013). As an important part of the mining and reclamation system, the minesoil system plays an important role in regulating different subsystems of the mining area, such as plant, water, and landscape subsystems. In fact, minesoil quality largely determines the future orientation of reclamation. Therefore, improved knowledge on the effects of mining and reclamation processes on changes in soil properties is needed.

The continuous mining process destroys vegetation/soil systems and reduces soil productivity and fertility, while the goal of reclamation involves returning the minesoil to its original state by restoring the nutritional properties of soil through a series of reclamation methods (Upadhyay et al., 2016). With engineering, chemical and biological measures, these reconstructed minesoils undergo a rapid maturation process and are utilized for the growth of grasses, trees and crops. Thus, high ecological and economic benefits can be obtained in a short period of time with proper management and protection (Bai and Zhao, 1995). However, the great heterogeneity and complexity of minesoils make their use for crops and vegetation, to redevelop productivity and ecosystem sustainability, an ongoing challenge.

Since the 1980s, many studies have investigated the undesirable effects of mechanized coal mining operations on the soil and vegetation systems as well as possible ways to minimize the damage. Several studies have assessed the effects of mining, the establishment of vegetation, and the development of reclaimed minesoil (RMS) (Ahirwal et al., 2017a; Akala and Lal, 2001; Bendfeldt et al., 2001; Carter and Ungar, 2002; Evanylo et al., 2005; Fettweis et al., 2005; Indorante et al., 1981; Juwarkar et al., 2010; Keskin and Makineci, 2009; Nyamadzawo et al., 2008; Shrestha and Lal, 2007; Shrestha and Lal, 2008; Shukla et al., 2005; Ussiri et al., 2006). These studies gave a basic understanding of minesoil properties and the ecosystem service of minesoil. Therefore, the aim of this review is to (i) give a brief overview on the interactions between minesoil systems and other systems throughout mining and reclamation processes, (ii) summarize the effects of coal mining and reclamation on minesoil properties, and (iii) suggest holistic reclamation approaches that can be applied for the restoration of minesoil.

2. Coal mining and reclamation process and minesoil

2.1. Mining and reclamation process

Surface mining techniques include strip mining, mountaintop removal mining, and open-pit mining. Although mining and reclamation operations are complex and regionally specific, the overall coal mining process consists of similar sequential stages (preparing the surface, drilling, blasting, overburden removal, loading the deposit, haulage of the mined deposit, and rehabilitation). The first step for a successful reclamation, following surface mining, is to salvage suitable topsoils and built a sustainable minesoil system. Yet, a sustainable mining and reclamation path calls for a holistic ecosystem reclamation approach (ERA) (Burger, 2011), the objective of which is to restore the ecosystem services provided by vegetation such as carbon sequestration, faunal habitat and floral productivity (Burger, 2011; Zipper et al., 2011). Thus, to ensure land productivity, mining and reclamation processes need to be considered as a whole when researching the impacts of coal mining on soil properties. The complexity of mining impacts on soil properties arises not only from the interactions of the mining subsystems and but also from other man-made systems, such as human communities and land-use types, and natural processes, such as the variations in climate and landscape (Ramani, 2012). Mining and reclamation involves changes in soil physical properties which can determine the influence of mining on soil chemical properties, soil fauna and plant growth (Nawaz et al., 2013). A simplified schematic of coal mining and reclamation processes are shown in Fig. 1.

2.2. Minesoil

Minesoils developed on anthropogenically altered landscapes that are affected by post-mining reclamation sessions become RMS (Shrestha and Lal, 2008). There are several ways in which mining and reclamation can influence soil properties (Fig. 2). Physical, chemical and biological properties of RMS form close connections. Any interference with the connection will lead to the degradation of the sound and healthy conditions of RMS. Over many centuries, soils have developed a sophisticated self-regulation capacity involving nutrient supply, chemical buffering, soil aggregate stabilization, porosity, aeration, water holding capacity, detoxification and self-regeneration (Vanbreemen, 1993). This self regulation capacity is driven by the five soil formation factors (i.e. climate, organisms, topography, parent material and time) that tie the soil and other systems together (Jenny, 1941). Therefore, minesoils can be reconstructed by enabling positive exchanges between the RMS system and other subsystems. Coal mining often causes drastic changes in the soil profile and the loss of soil organic carbon and nutrient pools (Indorante et al., 1981). As a direct result the soil system can suffer substantial and long-lasting damage, which negatively affects land productivity and ecosystem functionality (Hartmann et al., 2014). With the proper reclamation techniques and reclamation management practices, disturbed mined soils can be restored (Shrestha and Lal, 2010). However, without proper mining and reclamation procedures, RMS cannot easily recover to its original state. It is common to take 50 or 100 years for a satisfactory minesoil development, but full recovery does not always occur (Bradshaw, 1997; Bradshaw, 2000).

Physical, chemical and biological components of soil are not isolated; rather, these components are interconnected and play important roles in the development of a functioning soil system on severely disturbed lands (Rowland et al., 2009). The selection of minesoil indicators that reflect mining effects not only depends on the basic indicators associated with soil quality, fertility, and health, but also the factors that limit minesoil and plant productivity on mine sites (Bendfeldt et al., 2001). Coal mining results in structural and functional changes in minesoils, such as a high level of soil compaction, acidity, and toxicity; limitations in soil water holding capacity and the availability of nutrients; and the imbalance of soil microbial processes. Many indicators of minesoil properties showed anomalies in comparison with the undisturbed soils (Table 1). In addition to the influence of water, vegetation, landscape and other subsystems on the reclamation potential, minesoil reclamation practices involve complex and lengthy processes Thus, the study of minesoils should consider plants, water and landscape as a whole system. Connections and responses between RMS subsystem and other subsystems should be fully understood (Fig. 2).

2.3. The importance of minesoil property index selection and chronosequences

To provide a general overview of mining and reclamation effects on RMS, all of the physical, chemical and biological property changes should be included. Although the sources of RMS vary a lot, causing larger differences in the same parameters among different studies, the values of the same properties still present the same trends under the similar reclamation conditions. As time progresses, these parameters exhibit increasing or decreasing trends, which can be obvious references for the effects of reclamation and the possible reclamation methods (Table 1). Usually, the impact of mining and reclamation on minesoil cannot be assessed by individual soil parameters. An integrated analysis of soil physical, chemical and biological properties before and after reclamation will provide a meaningful assessment of the RMS status. There are many soil quality indices that have been proposed for minesoils by researchers (Mukhopadhyay et al., 2013; Mukhopadhyay et al., 2014; Sinha et al., 2009; Zhao et al., 2013; Muñoz-Rojas et al.,2016; Bendfeldt et al., 2001; Seybold et al., 2004; Rodrigue and Burger, 2004; Jones et al., 2005).

The analysis of ecosystem restoration after disturbance is challenging because it requires not only the above- and belowground ecosystem characteristics, but it also requires observations over long time periods. Soil chronosequences are an established approach to the challenge and have been used in many previous studies(Huggett, 1998; Jenny, 1946; Walker et al., 2010). The age chronosequence approach is important to understand the changes in soil physical, chemical and biological processes in a mineland ecosystem, especially because initial soil properties are often unknown (Shrestha and Lal, 2010). In mining areas, the restoration of disturbed systems is primarily a soil-driven process (Gleeson and Tilman, 1990; Wali, 1999), and the value of examining minesoil chronosequences in order to evaluate the effects of ecosystem restoration practices on soil processes has been recognized.

Indicators such as soil erosion and vegetation characteristics have been considered previously in determining reclamation success (Mummey et al., 2002; Wich, 2007). However, these aboveground indicators cannot reflect a holistic aspects of ecosystem structure and function (Dangi, 2012). Studies using soil chronosequences have shown that long-term soil development results in characteristic shifts in soil physical, chemical and biological properties (Akala and Lal, 2001; Avera et al., 2015; Carter and Ungar, 2002; Shrestha and Lal, 2008; Sun et al. 2017).

It is clear that reclamation is not a short-term investment. The recovery of large disturbances and the growth period of reclamation plants requires prolonged reclamation periods. However, there is still uncertainty surrounding the likely success of reclamation efforts. Over the short term, studies of soil and vegetation development during early succession on restored coal waste indicated some soil changes favoring the increase of plant community complexity (Alday et al., 2012). Although long-term effects (desirable or undesirable) are still unknown, all chronosequences tend to proceed toward a relatively stable equilibrium in the long term and they are likely to enhance rehabilitation/restoration ecology (Wali, 1999).

3. Minesoil physical properties

Surface materials such as native soils and rock spoils on the post-mining landscape can vary widely in their physical consistency and suitability for plant species (Zipper et al., 2013). These physical differences manifest in minesoil structural and functional changes. Physical properties, such as soil texture, bulk density, and aeration have a large influence on soil remediation by controlling soil hydraulic properties and hydrological stability. Therefore, these are selected as the main indices in the present study.

3.1. Minesoil horizon development

The soil dumping technology used determines the development of the reconstructed soil horizon. After mining disturbs soil horizons, RMS undergoes a self-restoring process. The younger minesoils develop through interactions between climate, living organisms, and the land surface, over time (Jenny, 1941; Sencindiver and Ammons, 2000). These soils and can show signs of pedogenesis after only 10 years and can develop weak B horizons. Minesoils have at least two horizons (Johnson and Skousen, 1995): a distinguishable surface horizon containing some organic matter and high percentage of fine earth material, and a lower horizon having poor structure and various sizes of rock fragments (Johnson and Skousen, 1995). In one minesoil study, the surface horizons were 2.5 to 10 cm thick when RMS ranged from 1 to 40 years (Haering et al., 1993). The thickness of the solum (A and B horizons) has previously been found to increase with age in minesoils (Thomas et al., 2000; Sencindiver and Ammons, 2000). A horizons of RMS can achieve a thickness of 13 cm in 5 years, and B horizons with silty-textured minesoils have developed in 12 to 19 years (Haering et al., 1993; Varela et al., 1992). Because of the complexity of minesoil properties, subsurface horizon formation has been reported in minesoils of various ages, ranging from several years to decades (Roberts et al, 1988b; Ciolkosz et al., 1980; Schafer et al., 1980). Moreover, young minesoils (1-7a) generally had massive structures, while old minesoils had developed cambic-like horizons, which were observed in 50-year-old minesoils with the shallow depths that barely to meet cambic criteria (Roberts et al, 1988a). Structural units and inherited properties from the materials used for the reconstruction of RMS were no longer visible as time progressed (Haering et al., 1993).

3.2. Minesoil textures

Minesoil textures vary from site to site. Many are similar to the textures of the surrounding undisturbed soils, but some differ because different textured overburden has been substituted for the native soil materials (Sencindiver and Ammons, 2000). Soil textural classification is based on particle-size analyses in most parts of the world (Nemes and Rawls, 2004). Particle size distribution (PSD) is used to characterize and describe soil texture and reflects soil changes during reclamation processes (Wang et al., 2015; Wood and Pettry, 1989). The minesoil PSD is affected by a variety of factors, such as rock/spoil material weatherability, reclamation time and weathering conditions (Haering et al., 1993; Wood and Pettry, 1989). The mean soil particle size of mined sites became finer than those of unmined sites under similar conditions (Wali, 1999). Generally, sandy loam and sandy clay loam textures are optimum for tree growth on minesoils (Burger and Zipper, 2002; Burger et al., 2005). Silty soils and soils with high clay content are more easily compacted and restrict soil aeration and drainage, which are chief causes of poor tree survival and growth (Jones et al., 2005). Moreover, large machinery compaction causes soil aggregation changes, which may decrease water and nutrient availability, aeration and plant production due to limitation in root growth (Abu-Hamdeh and Nidal, 2003; Kim et al., 2010). Soil pore structure development and aggregation formation are very long processes that involve the migration of clays, chemical elements, organic matter and various bonding mechanisms (Skousen et al., 1998). If the minesoils are compacted by large machinery, soil air and water exchanges are blocked, resulting in substantial, long-lasting and sometimes irreversible damage, which negatively affects soil productivity and ecosystem functionality (Cambi et al., 2015; Hartmann et al., 2014).

Many minesoils have a higher proportion of rock fragments and possess coarser texture (sandy, loamy sand and sandy loam) (Bussler et al., 1984; Zhen et al., 2015), which results in losses of water and nutrients from root zone via deep percolation and preferential flow (Asghari et al., 2011). The high coarse fragment content of many RMS affects rooting depth, water holding capacity and nutrient transport capacity (Asghari et al., 2011; Zipper et al., 2013). Smaller rock fragments are more prevalent in upper horizons than lower horizons because of the weathering. The texture of minesoils was found to be similar to the surrounding native soils, after 25 to 100 years, once rock fragments were sieved out (Johnson and Skousen, 1995; Turman and Sencindiver, 1986). A study of minesoil property changes conducted in the eastern USA showed that coarse fragment content decreased from 65% to 55% after 5-year reclamation and weathering processes. Similarly, in India, the coarse fragment content of RMS decreased by 20.4% compared to reference sites (Mukhopadhyay et al., 2016). Studies have also shown that the necessary coarse fragment content required for tree growth and restored productivity is below ~60% (Zipper et al., 2011).

3.3. Soil bulk density and aeration

Soil compaction is the physical form of soil degradation that changes soil structure and productivity (Mueller et al., 2010), and compaction poses a potential threat to sustainable development in mining and reclamation practices. In a mining area, the most frequently used parameter used to characterize minesoil compaction is bulk density (Panayiotopoulos et al., 1994). Due to the use of heavy machinery during mining and reclamation processes, RMS often have higher bulk densities (1.55 to 1.86 Mg m^{-3}) (Shrestha and Lal, 2008). As reclamation progresses, the bulk density of RMS decreases because more roots have penetrated the soil and porosity has increased (Wali, 1999). These soils need to be reclaimed with various methods and long time frames so that their properties can return to match those of the undisturbed soils (Wang et al., 2016). After 1 to 3 decades, soil bulk density can reach lower levels (~1.54~1.75 g cm^{-3}) that are more suitable for rooting and vegetation. Ten years of reclamation can cause RMS bulk density decrease from 1.35 to 1.53 g cm^{-3} at a dump site (Yang and Wang, 2013).

In compacted soils, the air and water exchange capacity is directly affected. Thus, for an accurate measurement of minesoil compaction, other properties, such as soil porosity, strength and moisture, are also needed (Lipiec and Hatano, 2003). High bulk density equates to low soil porosity. Air-filled porosity is most often used to evaluate soil aeration, and a critical value for plant growth would be < 10% (Lipiec and Hatano, 2003). It has been widely reported that soil porosity decreased after mechanical operations in compacted areas (Ball et al., 1994; Blackwell and Soane, 1981; Groenevelt et al., 1984; Munkholm et al., 2002; Nawaz et al., 2013), and it seems that transmission parameters, such as air permeability and oxygen diffusion rate (ORD), better reflect the aeration status of the physical changes of RMS. Reductions in soil aeration can be quantified by parameters such as the oxygen diffusion rate and air permeability (Cannell, 1977). Air permeability is related to soil structure, pore size and continuity (Lipiec and Hatano, 2003). Researchers found that air permeability was greater for coarse structures (4-8 mm peds) than for fine structure (<2 mm peds) at the same level of compactness (Lipiec and Hatano, 2003), while another study found that air permeability of sandy soils was higher than that of silt loam soil (Schjønning and Rasmussen, 2000). Regardless of soil texture, long time periods and deep plowing significantly increased air permeability (Ball et al., 1994; Bateman and Chanasyk, 2001), indicating that continued plowing and deep tillage are encouraged in RMS reclamation processes for agricultural utilization.

3.4. Hydrologic stability

Hydrologic restoration in minesites develops similar infiltration/runoff patterns to unmined landscapes with time (Ritter and Gardner, 1993), and that the rate of hydrologic change is affected by vegetation and soil types. Therefore, an effective restoration of uncompacted, deep soils and vegetation on reclaimed minesites is expected to ensure the hydrological stability at macroscales like landscape and watershed.

Hydrologic flow paths are restored by loosely placing minesoils that allow water infiltration, storage, drainage, and groundwater recharge (Burger, 2011). The relationship between precipitation and infiltration rate of RMS and groundwater conditions determines the amount of available soil water (Evans et al., 2015). Several factors affect water infiltration, including soil texture, coarse fragments and soil aggregation. Soil aggregation, in turn, was governed by soil organic matter and the activity of soil biota (Bronick and Lal, 2005). The poor condition of RMS, such as soil compaction and lack of vegetation, contributes to deficiencies in organic matter, leading to a vicious circle.

Researchers have found that RMS infiltration was influenced by high soil bulk densities and that infiltration rates can change over time. Surface soil compaction can lead to a slower infiltration rate shortly after mining and reclamation (Weiss and Razem, 1984). Therefore, soil surface hydrology is typically not in equilibrium on recently established mine sites. In central Pennsylvania, infiltration rates were found to be low during the initial stage of reclamation, but infiltration capacities increased over a 12-year reclamation effort (Ritter and Gardner, 1993).

Other researchers found that RMS infiltration was also highly influenced by the amount of vegetation (Zipper et al., 2011). Conversion of natural forest into other land uses due to mining was found to significantly reduce the nutrient contents and soil quality, and thus the infiltration rate in RMS was ten times lower than that in the reference forest (Ahirwal and Maiti, 2016). In reclaimed dumps, minesoil infiltration rate was a determining factor in the redistribution of rain or irrigation water (Larney and Angers, 2012). In short-term reclamation, water infiltration rates of RMS increased by stimulating microbiological activity; thus, the soil aggregate stability increased. With incremental additions of amendments, long-term increases in infiltration rates were achieved (Larney and Angers, 2012; Taylor et al., 2009). Improvements in soil hydraulic properties are expected to lead to improved revegetation success, which would help to ensure hydrologic stability of the reformed landscape.

Other vital hydraulic properties of RMS include water holding capacity and hydraulic conductivity (Table 1). The water holding capacity of degraded minesoils was lower than the water holding capacity of soils with proper amendments (Camberato et al., 2006; Fierro et al., 1999). Additionally, the field capacity increased and the wilting point decreased with reclamation age (Cejpek et al., 2013). Hydraulic conductivity was generally low in young sites. There was no clear evidence to support the idea that the spreading of topsoil leads to long-term improvements in soil hydrological properties (Cejpek et al., 2013).

4. Minesoil chemical properties

The effects of mining and reclamation on certain soil chemical properties have been investigated by several researchers (Johnson and Skousen, 1995; Shrestha and Lal, 2011; Varela et al., 1993; Zhen et al., 2015). One major environmental concern is the effect of weathering on minesoil functions. In some mining areas, it is an urgent issue to find the suitable topsoil substitutes to tackle the problem of soil scarcity and to create a viable rooting medium for good tree growth (Burger et al., 2007; Rodrigue and Burger, 2004; Zipper et al., 2011). Without timely and effective measures for the disposal of coal mining residues, these exposed materials are affected by several elements (temperature, precipitation, pressure, etc.) of the geosphere, hydrosphere and atmosphere. Heavy metal elements inside the mine residues and acid drainage travel into water and soil and become circulate among these spheres through weathering and dissolution processes (Larocque and Rasmussen, 1998), changing the minesoil chemical properties. Weathering processes remove soluble minerals from alkaline mine spoils, causing reductions of both electrical conductivity and pH, to ranges comparable to native forest soils (Burger et al., 2007). In most cases, weathered spoils and salvaged soils are often favorable for restoration (Zipper et al., 2011). Although further research on minesoil reconstruction materials' suitability for plant growth is needed, the adverse impact of weathering of reduced-sulfur minerals, pyrites and sulfides should be paid more attention (Zipper et al., 2013). For example, high-sulfur coal gangue oxidizes and acidifies when exposed to water and oxygen (Singer and Stumm, 1970), causing spontaneous combustion, air pollution, and the generation of acid mine drainage (Atkins and Pooley, 1982; Canovas et al., 2007; Herlihy et al., 1990; Zhao et al., 2007). The effect of acidity on minesoils is manifested by the leaching of Ca, Mg, and K from the soil profiles (Golez and Kyuma, 1997; Ross et al., 1985). The loss of base cations affects minesoil development, and the discharge of acid mine drainage are also a major threat to clean water resources.

4.1. Soil pH

Soil pH moderates the availability of plant nutrients during the process of RMS restoration (Shrestha and Lal, 2011). As one indispensable indicator of RMS chemical properties, soil pH varies widely among RMS and is easily affected by materials and environmental conditions. Sometimes, minesoil pH and other properties can be mutually influenced. Changes in RMS pH are generally caused by contamination of unweathered overburdened materials that contain carbonates (Shrestha and Lal, 2011). Fresh, unweathered non-pyritic sandstones and siltstones increase the pH (7.0-8.5) of constructed soils, which contrast to the moderately acidic pH (4.5-6.5) of the native soils (Emerson et al., 2009; Miller et al., 2012; Roberts et al., 1988b).

Reclamation activities also significantly change soil pH, and this can influence the growth of specific tree species (Zipper et al., 2013). For example, the growth rates of native tree species are often suppressed in alkaline minesoils (Emerson et al., 2009; Miller et al., 2012). Volunteer trees favor more acidic soils with a pH the range of ~4.5-6.5 (Zipper et al., 2013). Although pH preferences vary between tree species, 5.0 to 6.5 is often cited as being a generally favorable pH range for plants (Zipper et al., 2012). In addition, minesoil pH changes with reclamation time. After two years of reclamation, RMS constructed from unweathered siltstones declined from 7.1 to 6.4 (Roberts et al., 1988b). However, after 10 to 20 years of reclamation, rock spoils leached soluble salts and pH stabilized (above 6.5) (Zipper et al., 2013). Under this condition (i.e., RMS with a pH that is slightly acidic to the circumneutral range), native trees exhibit successful establishment and growth (Rodrigue and Burger, 2004).

4.2. Soil EC

As an integrated indicator of soil physical and chemical properties, soil EC is closely related to crop yield (Shrestha and Lal, 2011; Rodrigue and Burger, 2004). At lower depths of RMS, the EC was reported to be more than 200% greater than undisturbed soils (Shrestha and Lal, 2011). This may be attributed to soil contamination by spoil materials that contain a high amount of $CaCO_3$ (Shrestha and Lal, 2010). However, lower EC can be commonly found in weathered spoils as reclamation proceeds (Miller et al., 2012; Showalter et al., 2010). According to different studies, EC is determined by several factors, such as soil texture, depth, reclamation time, substrate and weathering conditions, but after a relatively long period of time (>20 years), the EC and other properties can sustain a favorable level for the growth of native species.

4.3. Soil C and N concentrations

Soil C and N are two major fractions of SOM pools. In mining areas, unsustainable management causes soil carbon and nitrogen loss, and these areas are likely to become net sources of greenhouse gas emissions (Shrestha and Lal, 2006). Study of minesoil C and N dynamics is critical to the understanding of C and N cycles and ecosystem functions (Shrestha and Lal, 2010).

SOC is the main component of soil organic matter (SOM), which is critical for the soil structure and fertility (Frouz et al., 2001; Ahirwal et al., 2017b). The loss of the C pool in disturbed soil usually occurs by mineralization, erosion and leaching (Izaurralde et al., 2000; Mukhopadhyay and Maiti, 2014). The concentration of soil organic carbon (SOC) in RMS has been found to decrease after mining and reclamation activities (Shrestha and Lal, 2011) (Table 1). Compared to undisturbed soils, the SOC content of RMS in 0-5 cm, 5-15 cm, and 15-30 cm decreased by 77%, 50% and 33%, respectively (Ganjegunte et al., 2010). The SOC pools in RMSs declined immediately after mining (Shrestha and Lal, 2011), and the surface layer of RMS had more SOC losses the deep layer of RMS since the surface layer was more active, dynamic and exposed to extreme weather conditions (Shrestha and Lal, 2011). Similar decreasing trends can be found in the concentrations of TN. A large loss in N after mining and reclamation has been confirmed previously, with the highest loss (>60%) of N occurring in the 0-15 cm layer (Ganjegunte et al., 2010). Previous studies have also shown that the depleted C and N pools can be restored through appropriate reclamation land use and soil management (Shrestha and Lal, 2007; Shrestha et al., 2009). A comparison of C: N ratios between undisturbed sites and RMS shows that in some cases there were decreases in this ratio but in one case, an increase was observed (Table 1). An obvious improvement in RMS quality, such as the increase in SOC and TN, required long-term reclamation practices lasting more than 20 years (Shrestha and Lal, 2010).

The depleted minesoil C and N pools can be restored through conversion to an appropriate land use and proper soil management (Lal, 2004a; Lal, 2004b; Shrestha and Lal, 2006). For example, the C and N loss in RMS can be minimized by proper handling of topsoil materials during removal, storage, and application, and also reclaiming as soon as possible. Soil and crop management practices such as application of manure, fertilizer, and the establishment of plants with high biomass production can also enhance mine soil fertility (Shrestha and Lal, 2011). The resulting improvements in minesoil quality can contribute to achieving food security and the

Sustainable Development Goals (SDGs) proposed by the United Nations (Bouma, 2014).

4.4. Toxic chemicals and metal concentrations

Compared to other parameters such as soil texture, pH and organic matter, micronutrients and heavy metals are not the dominant factors controlling the quality of minesoils in surface coal mining areas, however, a holistic assessment of soil quality should include the physical, chemical and biological properties as well as the presence of hazardous and potentially toxic chemicals (Mukhopadhyay et al., 2016). The seven essential micronutrients of plants (Fe, Mn, B, Zn, Cu, Mo, Cl) become toxic if the present concentrations greater than the threshold limits. Besides, heavy metals (As, Cd, Co, Cr, Hg, Ni, Pb, Se, etc.) are also added by anthropogenic activities during mining process (Maiti, 2013). Therefore, the environmental impact of metals released from coal mine waste remains a major issue in the reclamation practice. High concentrations of metals sometimes coincide with low pH values in the acid mine drainage (AMD), which has great impacts on the growth of vegetation (Askaer et al., 2008). Moreover, lower pH in RMS increases the bioavailabity of metals. To avoid these metals transferring to the ecological food-chain, some ameliorative measures, like liming at the minesoil surface to bring down the soil pH, are required (Maiti, 2007). The waste rocks removed during coal exploitation are low in coal content and contain high amounts of iron sulfide minerals that produce heat and acid when exposed to water and air (Askaer et al., 2008). Once the pH is lowered, metal elements, such as Ni, Al, and Zn, from sulfide oxidation as well as toxic chemicals, such as Cu, Pb and Cr, are leached (Larsen and Mann, 2005). Without the proper management of waste materials, which are very visible in piles and heaps around mining areas, large amounts of trace elements in AMD are easily channeled into nearby streams and rivers (Nganje et al., 2011). The predominant negative impacts of AMD such as soil acidity, toxic metal concentrations and vegetation damage, have been the focus of previous studies (Dang et al., 2002; Kumar and Maiti, 2015; Madejon et al., 2002). An integrated soil quality assessment containing metal elements was carried out on the reclaimed coalmine overburden in India. Concentrations of metal elements (K, Ca and Mg) were higher in the reclaimed sites than in the mine spoil reference sites, whereas the content of micronutrients (Fe, Cu, Zn, and Mn) decreased significantly in the reclaimed sites (Mukhopadhyay et al., 2016). This decrease can be attributed to the uptake effect of plants.

5. Minesoil biological properties

Soil biota govern processes related to nutrient, energy and organic matter cycling. The biodiversity of soil fauna reflects the ecosystem metabolism; therefore, it is often used as an indicator of soil quality to evaluate the recovery conditions in mining areas. For this reason, the identification of RMS biodiversity in reclamation systems and the objective of increasing RMS biodiversity introduces two major issues to reclamation practices. The abundance of soil fauna is significantly related to microhabitat conditions, which reflect of the distribution of organic matter as an important factor that affects microclimate (Frouz et al., 2011). In order to keep a self-sustaining soil-plant system in reclamation sites, the microorganisms play an important role in the decomposition of litter, mineralization process, nutrient cycling, and accumulation of organic matter and formation of humus (Maiti, 2013d). Soil microbial biomass and activity are commonly used as the indicators of the group of microbes, such as bacteria, fungi and actinomycetes (Maiti, 2013c). Microbial biomass provides information about the overall amount of microflora in soil and is a good indicator of the overall growth of the microbial community during succession. To estimate minesoil microbial activity, microbial respiration, cellulose decomposition and soil enzyme are commonly measured (Helingerova et al., 2010). Many studies have been conducted in mining and reclamation, mainly focusing on the changes in biomass of microfauna and mesofauna and the activity of soil enzymes. These studies contain not only the changes in biological properties but also the spatial variation of biota caused by dumping and overburdened topography. Moreover, the diversity and dynamic complexity of animals, plants and micro-organism communities constitutes the ecosystem. Under the impact of mining, post-restoration diversity is a result of site-level factors and various historical contingencies (Maiti, 2013b). The main purpose of biodiversity conservation is to increase the ecosystem services of microorganisms, animal and plants, such as soil microfauna and large fauna.

The removal of topsoil during surface coal mining instantly reduces the pool of soil organic matter (Larney and Angers, 2012); additionally, the habitat of soil organisms is greatly altered. As the soil profiles are basically turned upside down, and those substrate materials may contain fossil carbon that are sensitive to erosion, unsuitable water regimes and nutrient deficiency (Frouz et al., 2006; Scullion and

Malinovszky, 2010). In the coal mine dump, the reconstructed soils therefore upset the equilibrium of biological activity, and the processes required to regain a dynamic equilibrium state require a long time period. The soil hosts a complex system of organisms that are involved in many biological processes, such as nitrogen and carbon cycling, which also affect the soils physical and chemical properties, and ultimately the ecosystem of mined lands (Frouz et al., 2006). For example, aeration and pH affect the activity of many microorganisms, which in turn, change the relevant processes involved in nutrient cycling. The activity of soil organisms provides useful information when monitoring the quality of minesoil produced from severe coal mining disturbances, and microbial properties have increasingly been used in the evaluation of soil recovery efforts (Li et al., 2015). As the microbial community is sensitive to the soil environment and is related to diverse soil processes, including decomposition of organic residues, nutrient cycling, and degradation of toxic compounds and pollutants (Kaschuk et al., 2010), it has been used as an ecological indicator in severely disturbed mine sites by many researchers (Claassens et al., 2012; Filcheva et al., 2000; Frouz et al., 2006; Helingerova et al., 2010).

5.1. Soil microfauna

At post-mining sites, microfauna include small animals and unicellular organisms that are visible only under a microscope. The microbial community is responsible for nutrient cycling and soil organic matter accumulation (Bradshaw, 1984; Frouz et al., 2007) and provides the base for the reclamation plant growth. A field study of microbial properties was conducted in heaps of coal mining materials and lasted for

41 years; the study showed that the organic matter accumulation and the development of the soil microbial community were closely related; additionally, most soil microbial parameters measured at 30- to 40-year-old reclamation sites were of comparable magnitude to those at undisturbed sites (Frouz and Novakova, 2005).

5.2. Soil enzymes

The importance of soil enzymes has been widely recognized. They regulate the function of the ecosystem, and play key biochemical functions in the overall process of organic matter transformation and nutrient cycling in soil system. Various intracellular and extracellular enzymes that originate from microorganisms, plants and animals constitute the overall enzyme activity in soil. Enzymatic activity can be easily influenced by the disturbance of minesoils. Researchers have found that different enzymes can be used as suitable indices for monitoring RMS quality and reclamation progress in surface coal mines (Ciarkowska et al., 2014; Finkenbein et al., 2013). Therefore, suitably chosen enzyme activities have been used to study the effectiveness of reclaimed treatments on soil quality under normal conditions (Finkenbein et al., 2013; Li et al., 2012; Schimann et al., 2012; Maiti, 2013a). As reclamation succession age increased, most enzyme activities improved, and the enzyme contents of reclamation sites were higher than those of the control groups, despite the different vegetation treatments of reclamation sites (Baldrian et al., 2008; Li et al., 2015). Other studies also had similar results (Table 1).

5.3. Larger soil fauna

Organisms such as mesofauna and macrofauna (e.g., microarthropods, macroarthropods, enchytraeids and earthworms) are only a minor fraction of the total living biomass in soil (Beare, 1997), but the appropriate amount of these organisms also reflects the condition of RMS. Larger animals are called mesofauna and include organisms such as earthworms, arthropods, and large nematodes; macrofauna also include burrowing mammals, such as moles and rabbits, which can be indicators of soil condition at reclamation sites. Soil fauna play an important role in the decomposition and incorporation of organic matter in the soil (Dunger et al., 2001; Petersen and Luxton, 1982). The effect of large soil fauna may be affected by many factors, among which the vegetation cover is the most important (Frouz et al., 2006). Vegetation supplies a large quantity of easily decomposable litter for mesofauna in post-mining sites. The non-reclaimed sites had poorly developed mesofauna communities, while the reclaimed sites were occupied by abundant mesofauna and well-developed earthworm communities (Frouz, 2002; Frouz et al., 2001). Studies also showed that the spatial heterogeneity of soil fauna caused by heaping may help soil fauna locate suitable conditions during different times of the year and help organisms address temporal fluctuations in environmental factors, which indicated the strong connection between soil recovery and abiotic processes (Frouz et al., 2011).

6. Soil amendment measures in surface coal mining areas

Physical, chemical and biological techniques provide powerful support and ensure the implementation of reclamation. During reclamation, mechanical schemes for soil reconstruction and other artificial methods can effectively shorten the recovery period, while the roles of natural regeneration and time should be given more attention. In addition, reconstruction of a mine soil system depends on the vegetation for improving the soil physical, chemical and biological condition of disturbed sites. Such mine soil medium of sufficient quality may benefit from addition of organic amendments that will accelerate nutrient cycling, overcome chemical and physical limitations, and provide receptive environment for plant growth (Bendfeldt et al., 2001). Based on the cost minimization principle, the ideal recovery method should focus on providing the best conditions where soils can self-create, and these conditions should be achieved in a fairly short time span (Filcheva et al., 2000).

6.1. Physical amendment

Physical amendment is the basis of reclamation, since it is the core of soil reconstruction and has a huge influence on the development of the landscape and topography. The physical amendments of RMS can be implemented along with the other essential aspects of soil: structure, water, fertilizer, air and heat. Techniques such as crushing, ripping, grading, and drainage are employed to improve physical conditions of minesoils (Wong, 2003). However, problems with minesoil structure are virtually inescapable. Overcoming physical and nutritional problems are topics commonly emphasized in the research.

In surface coal mine areas, one major output that occupies large land resources is the dump. The stability of dumping depends on topsoil dumping techniques or geomorphic landform design (Topp et al., 2010; Burger, 2011). In reclamation succession, soil dumping techniques not only determine the soil spatial heterogeneity but also the vegetation schemes and microtopography, which have great impacts on

RMS properties (Topp et al., 2010). Without proper measures, landslides, soil erosion and other geological hazards will definitely increase the costs of reclamation, and most importantly, the safety of the local environment and society will be threatened. By a series of engineering measures, the goal of landscape reshaping for an approximate original contour (AOC) can be achieved (Burger, 2011). In addition, soil dumping schemes should be carefully planned before exploitation.

Another consequence of soil dumping is severe compaction by large machinery, which producing ground pressure greater than 5 kg cm^{-3} (Bradshaw, 1997). One effective way to solve this problem is to loosen compacted soils and establish vegetation immediately. No further attention should be required because the root growth, organic matter accumulation, and microbial community will prevent the return of compaction. However, a soil bulk density greater than 1.8 g cm^{-3} normally inhibits root growth completely (Bradshaw, 1997). Mechanical schemes for compaction are encouraged to sustain desirable plant life, and these schemes can be applied in the compaction area (Fulton et al., 2002).

During reclamation, soil moisture distribution can be easily affected by the landform change and soil compaction. Either excess or lack of water will cause minesoil problems. As one of the environmental impacts of mining, the water disequilibrium calls for a holistic ecosystem reclamation approach (ERA) (Burger, 2011). The ERA in the mountainous area like the Appalachian coalfields includes geomorphic landform design, topsoil replacement, stream reconstruction and reforestation. Because of the requirements for water in different coal mine areas, the reconstruction of water equilibrium depends on the pre-mining hydrologic patterns, and addresses both terrestrial and aquatic impacts. In mountainous areas, the geomorphic landform design deals with soil erosion control and achieves AOC. The vegetation recovery needs to be established not only on the basis of AOC, but also on the reliance on humid system. In some areas, the vegetation establishes during the wet period and seedlings of non-competitive species may also be applied (Bradshaw, 1997). In a general way, the appropriate selection of species, such as hydrophilous or drought-tolerant plants determines the long-term survival and effectiveness of reclamation.

6.2. Chemical amendment

The purpose of chemical amendments is to change the imbalanced state of minesoil. Common soil chemical remediation includes elution and the application of extractants that are reductant-oxidant. Some treatments, such as soil washing and flushing, have demonstrated potential effectiveness in removing heavy metals from soils (Liu and Lal, 2013). However, these methods are not the best choice for the remediation of minesoils due to the high costs. Therefore, lower-cost soil liming and fertilization are more suitable for minesoil restoration (Macdonald et al 2015). These methods are used to overcome some of the problems associated with acidic and barren conditions. Organic wastes such as sewage sludge and refuse or manure compost can be used as minesoil chemical amendment, as they are a slow release nutrient source. Inorganic wastes such as pulverized refuse, pulverized fuel ash are also suitable amendments.

As soil chemical properties also significantly influence re-vegetation success, it is important to actively establish site-specific vegetation, which can fulfill the objectives of stabilization, pollution control, visual improvement and removal of threats to human beings (Wong, 2003). If the minesoils have high levels of heavy metals, metal-tolerant plant species are better suited for such sites (Wong, 2003). Similarly, minesoils with saline or sodic materials require the selection of salt tolerant species (Purdy et al., 2005).

6.3. Biological amendment and plants

Plants are efficient bioaccumulators that can add organic material to the soil, and they are associated with a relatively large number and diversity of soil organisms (Zhao et al., 2013). Therefore, reforestation is often conducted on disturbed coal mine lands where the pre-mining land use type is forest. Biological reclamation of minesoils also depends on the selection of appropriate tree species and their ameliorative effects (Dutta and Agrawal, 2002; Mukhopadhyay et al., 2013; Sinha et al., 2009). The reestablishment of essential soil properties is necessary for forest restoration (Zipper et al., 2011), and planted trees can act as catalysts of natural succession (Parrotta et al., 1997b). Based on the theory of plant remediation of RMS and decades of research, the Forestry Reclamation Approach (FRA) was developed. According to the "five steps" of the FRA, rooting and formation of non-compacted soil medium are essential. Using less competitive ground cover for two types of trees and proper planting techniques would be helpful for the early stages of vegetation reclamation; thus, they can be good for the recovery of RMS (Zipper et al., 2011).

Once the plants get established, the plant-soil interactions promote ecosystem restoration Among several interactions in reclamation systems, the plant-soil interaction is one of the most important components. The mechanism of RMS formation and the role of vegetation in reclamation processes need to be recognized. Since soil is a fundamental component of the ecosystem, changes in soil properties are likely to affect future vegetation development (Frouz et al., 2008; Jangid et al., 2011). Soil systems also provide an important pool of many biogenic elements, such as C, N and P (Frouz et al., 2013), but poorly developed soils in mining areas result in the loss of soil nutrients. Thus, understanding the interactions of RMS and vegetation is particularly important because of the potential to mitigate the adverse impact of mining processes (Ahirwal et al., 2017b; Lal, 2004b; Schimel et al., 1994).

The interactions between vegetation growth and soil development during the processes of mining and reclamation have usually been widely studied (Skousen et al., 1994; Johnson and Skousen, 1995; Rodrigue and Burger, 2004). At reclaimed sites, vegetation composition affects soil organic matter content and quality, which in turn, affects the microbial communities and the soil functions (Frouz et al., 2009; Macdonald et al., 2015; Mummey et al., 2002; Sorenson et al., 2011). On the one hand, vegetation, has both direct and indirect effects on soils, is an efficient biomass generator and is a dominant factor in reclaimed ecosystems (Frouz et al., 2013). For better soil recovery effects, plants selection, species diversity and richness are important factors that determines the potential of reclamation (Wali, 1999). On the other hand, soil attributes, such as ample rooting media, proper aeration, and adequate moisture and nutrient supply are important for the growth of the vegetation (Rodrigue and Burger, 2004). Although there is no uniform standard to reflect the plant growth and minesoil property relationship, land productivity can be used as a clear indicator to assess the effect of soil-plant interaction, and the comparison of it between the mined sites and non-mined sites and the non-forestland are necessary.

6.4. Land use options

The recovery effect of minesoils determines the land use potential. The establishment of various land-use types, including grassland, forest, cropland, rangeland, wildlife habitat and recreational land, is encouraged in RMS (Shrestha and Lal, 2006). Although the final use of reclaimed land depends on the local needs, the success of reclamation depends on the prevailing ecological conditions (Wali, 1999). The artificial effect plays a greater role than the natural effect in agricultural systems. However, when comparing forest systems with agriculture systems, the situation is the opposite. Based on the target of cultivation practices, different operations should be applied. For agricultural use, crop rotations and tillage cannot be neglected. One successful rotation is 1 year of sweet clover and grass, 1 year of winter rye, and 4 years of alfalfa and grass. Soil tillage operations should be minimized to avoid compaction and structural homogenization (Krummelbein et al., 2012). Deep plowing at the beginning of reclamation and after 3 years of reclamation is recommended (Krummelbein et al., 2012). For forest reclamation, proper ameliorations such as deep loosing and fertilizer application are necessary, as well as the measurement of tree species and density of forests. However, compared to agricultural cultivation, forest sites can only be ameliorated during site construction and before or when the trees are planted (Krummelbein et al., 2012).

The design of the post-mining landscape is part of regional land-use planning. The integration of trees with agricultural crops and/or livestock either simultaneously or sequentially can be beneficial, and agroforestry is a sustainable and environmentally friendly land-use system that improves socio-economic and cultural welfare without competing with traditional agriculture or forestry (Krummelbein et al., 2012).

7. Conceptual model of five phases of reclamation and future studies

7.1. Five phases of reclamation on minesoils

The reclamation practice of minesoil can be divided into five phases: geomorphic reshaping, soil reconstruction, hydrological stability, vegetation restoration, and landscape rebuilding, among which soil reconstruction is the core phase. The five phases of reclamation should be viewed not as a simple combination of separated steps, but as a systematic process.

(i) *Geomorphic reshaping.* In reclamation practices, geomorphic reshaping is a critical step of high-quality reclamation, as it is the foundation for all following reclamation phases (Macdonald et al., 2015; Toy and Chuse 2005). At microsite scale, not only will the RMS properties influence early topographic development, butthe suitable soil textures, placement and arrangements, will also help improve the stability of reshaped landform. Moreover, the creation of undulating or hilly surfaces will influence early ecosystem development as well as future trajectories (Macdonald et al.,

2015) (#1 in Fig. 3).

(ii) *Soil reconstruction.* The process of soil reconstruction focuses on decreasing negative effects by limiting factors such as compaction, acidity, soil carbon loss, therefore, both natural regeneration and artificial amendments will benefit this process. One major target of soil reconstruction is to restore RMS quality and productivity, thus the use of organic amendments is favorable for RMS re-establish nutrient cycling and development processes. Salvaging topsoil, litter layers, seed pools and coarse woody debris and placing these materials on the surface of reclaimed mined sites are encouraged to restore soil organic matter and nutrient pools, and discourage exotic, invasive plants (Burger, 2011) (#2 in Fig. 3).

(iii) *Hydrological stability.* Due to the close relationships between and among soil, water and vegetation, the hydrological stability also links soil reconstruction and vegetation restoration together. Vegetation removal causes hydrologic effects such as sediment transport (causing erosion), downstream water yields and flooding peaks, and soil compaction caused by traditional reclamation techniques need to be paid more attention (DeFries and Eshleman, 2004; Zipper et al., 2011). For the maintenance of hydrological stability, loosely placing RMS restores hydrologic flow paths, allowing water infiltration, storage, drainage, and groundwater recharge (Burger, 2011). Appropriately designed reshaped landforms and landscapes redistribute moisture, readjust water movement and maintains hydrological equilibrium (Macdonald et al., 2015). Moreover, established vegetation promotes the development of infiltration/runoff patterns, and prevents on-site effect like surface runoff and off-site effect like stream erosion (Toy and Chuse 2005). Thus, an integrated management of topography, RMS, water, vegetation and landscape is required to achieve effective control of erosion and sedimentation in reclaimed mining areas and their surroundings (Zapico et al., 2018) (#3 in Fig. 3).

(iv) *Vegetation restoration.* The importance of vegetation has been verified by reclamation practices (Frouz et al., 2013; Macdonald et al., 2015; Zipper et al., 2011; Zipper et al., 2013). Complete plants community will be a function of landform development, RMS condition, hydrological restoration and landscape design. The restoring of RMS capabilities and plants productivity also helps to provide broader ecosystem services. The plant-soil interaction initiates nutrient cycling and the development of soil biota, and improves infiltration and soil water-holding capacity. Further, as soil conditions on reclamation sites are often highly variable, planting a mixture of tree species is often advisable, and allows the developing forest to build resistance and resilience to pests and other stressors (Macdonald et al., 2015). Plant species composition also provides of a variety of potential habitats and allows the developing forest to build resistance and resilience to pests and other stressors (Parrotta et al. 1997a; Macdonald et al., 2015). In addition, the establishment of vegetation might be slow, but it improves surface conditions by the interactions between soil and plants (#4 in Fig. 3).

(v) *Landscape rebuilding*. Geomorphic reshaping and landscape rebuilding are discussed at microsite scale and landscape scale respectively (Macdonald et al., 2015). Rebuilt landscapes can be sustained through effects of changes in topography (e.g.

land consolidation), hydrological stability (e.g. water movement and erosion risk), soil properties (e.g. physical, chemical and biological properties), and vegetation establishment (e.g. richness and diversity). Furthermore, through gardening and aesthetic methods, landscape rebuilding greatly improve minesoil properties and provide multiple ecosystem services (#5 in Fig. 3).

7.2. Future studies

RMS, the main subject of this review, is considered as the core element in the mining system that is easily affected by mining and reclamation processes. Traditional research on RMS produced better benefits from reclamation practices. Studies of the physical, chemical and biological properties of RMS provide specific suggestions on soil amendments. However, the thorough application of new technologies at reclamation sites is inadequate, and a full acquisition of knowledge in terms of RMS is still constrained by the lack of thorough studies on the minesoil system and other systems in mining areas. Increasingly, five phases of reclamation have been well established and authenticated in a 30-year reclamation practice in China. With the application of new technologies and the five identified phases, further research needs related to RMS arise (Fig. 3). These include:

(1) *Attach importance to the systematic analyses of soil-water-vegetations-landscape interactions:* Ecosystem services in minelands are based on the analysis of minesoil subsystems and other subsystems such as water, vegetation, and landscape. Not only do the mechanisms of component interactions need to be understood but also value of ecosystems need to be taken seriously.

(2) *Improve the RMS monitoring technology:* The application of non-destructive detection technology such as computed tomography (CT) for RMS monitoring at micro- and meso-scale provide solutions for the disturbed soil reconstruction. Further, the application of remote sensing (RS), unmanned aerial vehicle (UAV) and ground-penetrating radar (GPR) can be used to meet the monitoring of minelands needs at macro-scale.

(3) *Enhance the aesthetics of reclamation:* The combination of ecosystem and landscape is inadequate to further management and development, the aesthetics of reclamation that assist with landscape rebuilding and management are encouraged.

(4) *Expand the RMS research on macro-scale*: Traditional RMS researches paid more attention on the micro- and meso-scale. With the further advance in mineland ecosystem service research, the RMS macro-scale studies become a trending. Thus, such expand on research scale can bring broader topics of RMS studies at multi-scale.

(5) *Embrace the SDGs:* The UN SDGs allows soil science to demonstrate its relevance for realizing a sustainable society by 2030. Soils are at the heart of the SDGs and the unique role of soils in influencing use of other resources validates the efforts of the scientific community towards integrated resource management. Facing all challenges with new solutions, minesoil studies will contribute and extend the scope of soil science.

8. Conclusions

Minesoil recovery is a worldwide topic that has attracted the attention of scientists' for decades. The processes of surface coal mining inevitably cause the degradation of minesoils. Factors such as soil compaction, contamination, weathering and bioturbation result in drastic changes in the soil horizon, texture, hydraulic properties, and productivity. Inappropriate mining and reclamation measures may aggravate the minesoil functional deterioration. Previous studies on minesoils emphasized the specific aspects of soil properties that provide useful information for soil reclamation. The complexity and vulnerability of mining areas make the study and practice of reclamation difficult; therefore, more comprehensive studies are needed. In most mining sites, the goal of RMS recovery is to generate a forestry or agricultural system. The RMS system, natural system, and anthropogenic system are interrelated. This combination of different management systems provides many benefits, especially in severely damaged mining areas. Both economic yield and environmental protection are encouraged in modern reclamation practices. In addition, more attention should be paid to the natural and artificial effects on the comprehensive process of mining and reclamation.

Experimental studies have shown that mining results in increased soil bulk density, decreased soil aeration, available water, organic matter and biomass, and variations in soil pH. The causes of minesoil property changes are artificial (heavy machinery compaction, contamination, etc.) and natural (weathering). Although reclamation helps RMS regain equilibrium, the processes occur over long timescales and do not ensure the system will recover to its original state. In spite of an increasing number of articles on the effects of mining and reclamation, there is an urgent need to apply new concepts and multiple measures in reclamation studies and practices. The five phases of reclamation provide a powerful tool and guidance for understanding soil reclamation. Scientifically sound papers on (i) new concepts and methods to assess mining-induced soil degradation, (ii) new strategies for reducing soil degradation and (iii) systematic studies on RMS are particularly necessary for the near future.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (41271528), Beijing Higher Education Young Elite Teacher Project (YETP0638), and the Fundamental Research Funds for the Central Universities of China (2652017002).

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Table 1 Effects of mining and amendment process on soil properties.

erties	Soil depth (cm)	Undisturbed soil (US)/ Control group (CG)	Reclaimed soil	Mining effects	Amendment effects	Years after reclamation	Land use/Plant	Refer
	0-45	2.2 (US)	52.4	Increase		19	Forest–shrub–grass	Wang et al., 201
nt (%)	0-12	9.4 (US)	40.5	Increase		25	Nonagricultural land use	Turman and Ser
	0-15	1.17 (US)	1.29-1.42	Increase	Decrease	28	Pasture, hay, forest	Shrestha and La
	0-20	1.65 (CG)	1.35-1.50		Decrease	15	Shrub	Fu et al., 2010
cm^{-3})	0-10	1.52 (CG)	1.53		Decrease	37	Crop	Kolodziej et al.,
	0-15	1.29 (CG)	1.46		Increase	>22	Crop	Rahe et al., 201
	0-15	1.41 (US)	1.69	Increase		<1	Grassland	Shrestha and La
	0-40	38.35-40.11 (CG)	40.92-50.19		Increase	15	Shrub	Fu et al., 2010
	0-40	51 (CG)	62		Increase	25-30	Shrub	Cejpek et al., 20
	0-10	30.38 (CG)	34.95		Increase	Untold	Crop	Sen and Kumar,
capacity (%)	0-20	33.2	35.1		Increase	16	Forest	Ahirwal and Ma
	0-40	63 (CG)	55		Decrease	25-30	Shrub	Cejpek et al., 20
%)^{e}	0-40	29 (CG)	39		Increase	25-30	Shrub	Cejpek et al., 20
	0-10	6.55 (CG)	25.23		Increase	>22	Crop	Rahe et al., 201
	0-10	5.2 (US)	9.4		Increase	26	Pasture	Shukla et al., 20
rate (cm h^{-1})	50	10.4 (CG)	16.5		Increase	13	Forest	Clark and Zippe
	0-15	1-2	8		Increased	4	Untold	Guebert and Ga
	0-20	2.96 (US)	0.28	Decrease		10	Forest	Ahirwal and Ma
hydraulic	0-10	4.0 (CG)	4.5		Increase	37	Crop	Kolodziej et al.,
(m d^{-1})	15-79	3.2 (CG)	0.3		Decrease	4	Crop	Krummelbein et

erties	Soil depth (cm)	Undisturbed soil (US)/ Control group (CG)	Reclaimed soil	Mining effects	Amendment effects	Years after reclamation	Land use/Plant	Refer
	0-15	4.6-7.0 (US)	4.9-8.1	Increase		<1	Grassland	Shrestha and La
	0-5	7.7 (CG)	8.3		Increase	8	Plantation	Helingerova et a
	0-10	7.47 (CG)	7.33		Decrease	18	Forest	Li et al., 2015
	0-20	7.4 (US)	8.3		Increase	14	Shrub	Yang and Wang,
	0-15	6-8 (US)	8.1		Increase	10	Forest	Shrestha and La
uctivity (dS m^{-1})	0-15	0.04-0.30 (CG)	0.23-0.53		Increase	24-58	Crop/Grassland	Lorenz and Lal Kumar, 2016; 2004
	0-15	0.04-0.15 (US)	0.12-0.35	Increase		1-19	Forest–shrub–grass	Shrestha and La al., 2015
	0-20	0.19 (CG)	0.46		Increase	15	Shrub	Fu et al., 2010
(g kg^{-1})	0-10	1.79 (CG)	1.54		Increase	>22	Crop	Rahe et al., 201
	0-15	1.77-2.96 (US)	0.54-1.10	Decrease		<1	Grassland	Shrestha and La
	0-45	2.6 (US)	6.5	Increase		19	Forest–shrub–grass	Wang et al., 201
arbon (TOC)	0-10	21.97 (CG)	17.27		Increase	>22	Crop	Rahe et al., 201
	0-40	1.41-1.47 (CG)	5.22-5.73		Increase	15	Shrub	Fu et al., 2010
	0-15	35.3-65.5 (US)	10.9-29.2	Decrease		<1	Grassland	Shrestha and La
	0-10	11.80 (CG)	10.99		Decrease	>22	Crop	Rahe et al., 201
	0-15	11.3-15.2 (US)	8.4-12.0	Decrease		<1	Grassland	Shrestha and La
	0-15	4.4 (CG)	11.9		Increase	58	Grassland	Lorenz and Lal,
	0-20	3.11 (CG)	9.23		Increase	15	Shrub	Fu et al., 2010
	0-10	2.93 (CG)	2.55		Increase	Untold	Crop	Sen and Kumar,
	0-15	11.4 (US)	24.2	Increase			Crop	Kumar and Mai
	0-10	8.76 (CG)	8.39		Decrease	Untold	Crop	Sen and Kumar,
	0-10	15.58 (CG)	14.79		Decrease	Untold	Crop	Sen and Kumar,

erties	Soil depth (cm)	Undisturbed soil (US)/ Control group (CG)	Reclaimed soil	Mining effects	Amendment effects	Years after reclamation	Land use/Plant	Refer
	0-15	101.2 (US)	43.49	Decrease			Crop	Kumar and Mai
	0-10	2.78 (CG)	2.52		Decrease	Untold	Crop	Sen and Kumar,
	0-15	30.5 (US)	7.03	Decrease			Crop	Kumar and Mai
	0-15	168 (US)	1112.33	Increase			Crop	Kumar and Mai
	0-10	0.06 (CG)	0.03		Decrease	Untold	Crop	Sen and Kumar,
	0-15	0.25 (US)	0.51	Increase			Crop	Kumar and Mai
	0-10	0.85 (CG)	0.63		Decrease	Untold	Crop	Sen and Kumar,
	0-15	45.33 (US)	1195	Increase			Crop	Kumar and Mai
atter (%)	0-20	0.78 (CG)	1.35		Increase	0.6	Forest	Li et al., 2012
tivity[a]								
g^{-1})	0-20	0.27 (CG)	0.10		Decrease	0.6	Forest	Li et al., 2012
^{1})	0-20	1.39 (CG)	1.77		Increase	0.6	Forest	Li et al., 2012
g^{-1})	0-20	1.63 (CG)	1.51		Increase	0.6	Forest	Li et al., 2012
U cm^{-2})	0-5	351 (CG)	1090		Increase	45	Forest	Baldrian et al., 2
se (µg INF g^{-1} 2	0-10	334.6-499.1 (US)	24.3-339.5	Decrease		Untold	Grassland	Claassens et al.,
mass (µg Cmic	0-15	175 (CG)	237		Increase	22-32	Forest	Frouz et al., 201
(µg cm^{-2})	0-5	0 (CG)	2.5		Increase	45	Forest	Baldrian et al., 2
A (µg cm^{-2})	0-5	0.9 (CG)	14.7		Increase	45	Forest	Baldrian et al., 2
ial PLFA	0-10	0.04-0.22 (US)	0.02-0.32	Unclear		Untold	Grassland	Claassens et al.,
	0-30	0.12 (CG)	0.09		Decrease	22-32	Forest	Frouz et al., 201
(%)	0-10	31.00-48.65 (US)	20.46-49.22	Decrease		Untold	Grassland	Claassens et al.,

erties	Soil depth (cm)	Undisturbed soil (US)/ Control group (CG)	Reclaimed soil	Mining effects	Amendment effects	Years after reclamation	Land use/Plant	Refer
g cm^{-2})	0-5	0.15 (CG)	13.35		Increase	45	Forest	Baldrian et al., 2
ora (g)	0-10	2.93 (CG)	2.02		Decrease	25	Forest	Filcheva et al., 2
	0-10	0.75 (CG)	0.39		Decrease	25	Forest	Filcheva et al., 2
g^{-1})	0-5	4.3-12.8(CG)	3.3-6.2		Decrease	15-25	Shrub	Frouz and Nova
cast[b] % of soil	0-15	26.7 (CG)	23.1		Increase	22-32	Forest	Frouz and Nova

[a] Soil enzyme activity can be characterized by the amount of catalase, urease, and invertase.

[b] According to Frouz et al., 2009.

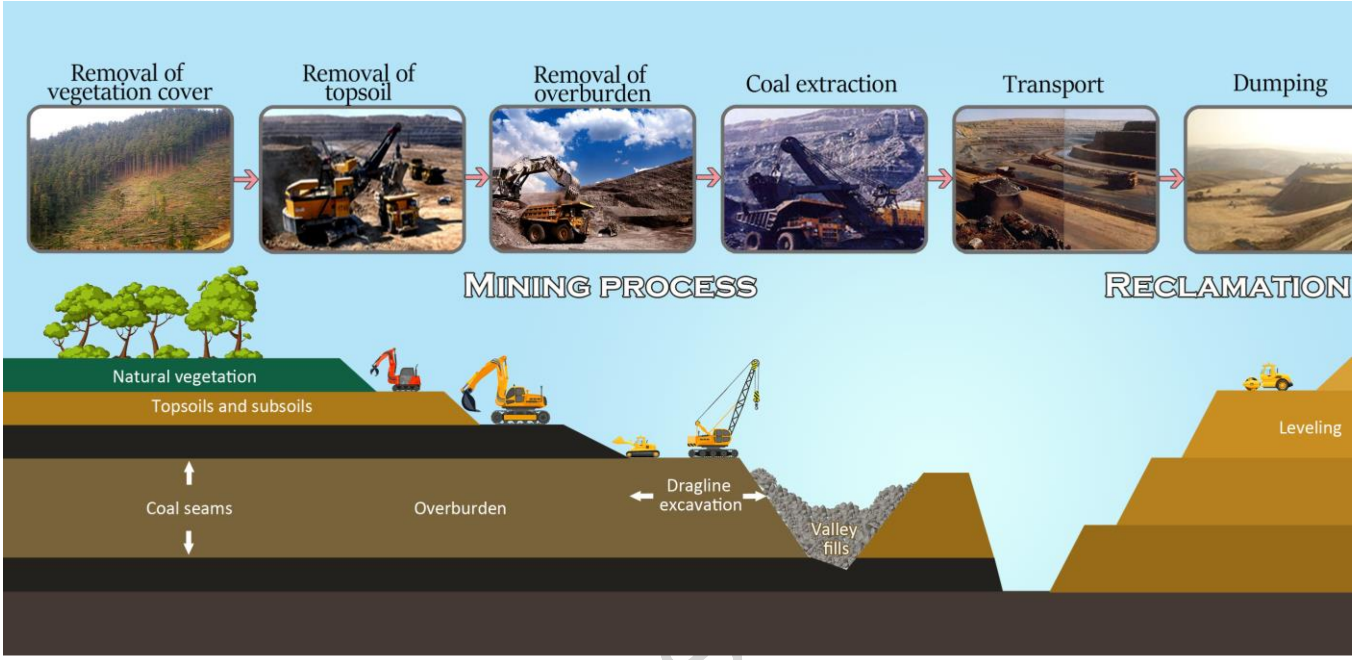

Figure 1 Coal mining and reclamation processes.

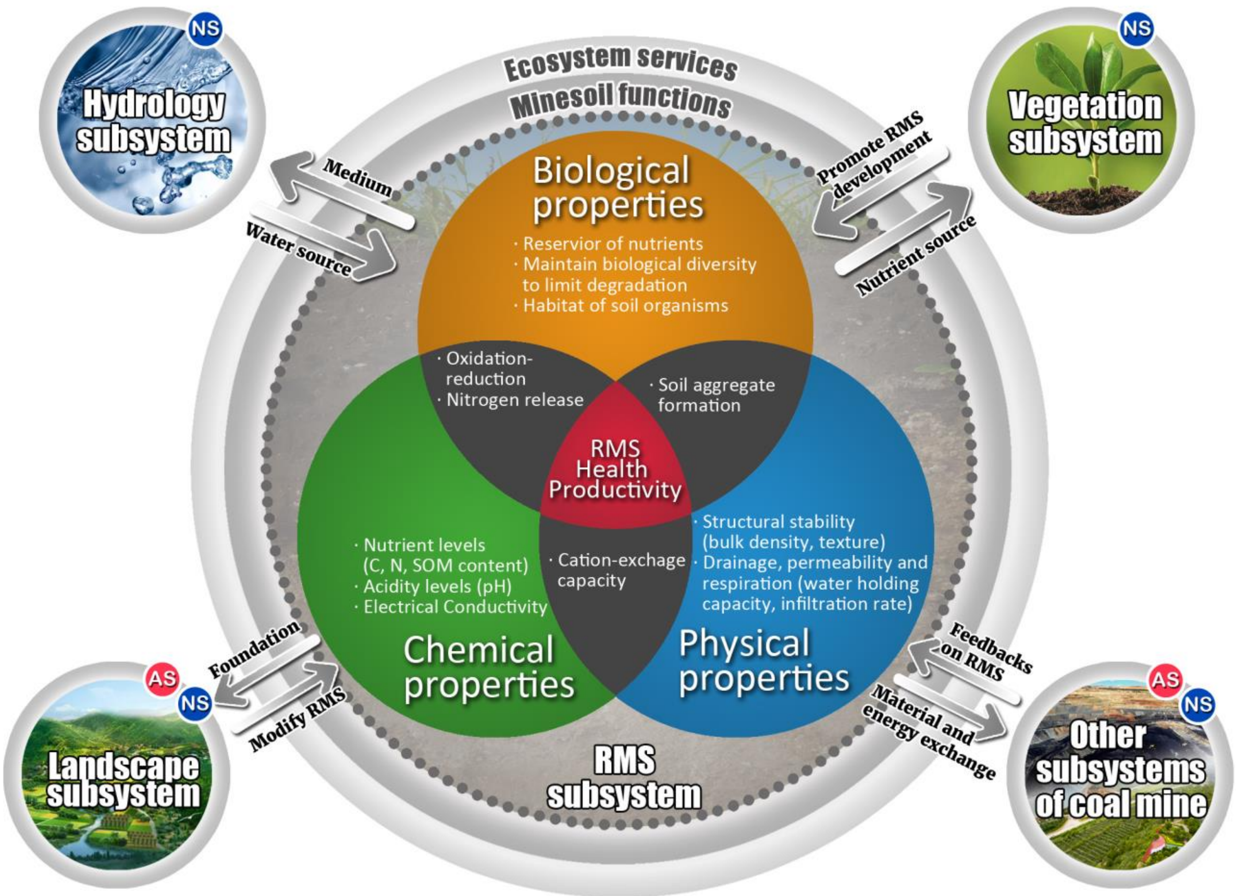

Figure 2 Inter-linkages between RMS subsystem and other subsystems. AS and NS represent artificial system and natural system respectively, and the marks on the edge of every subsystem

show which part of the big systems it belonged to.

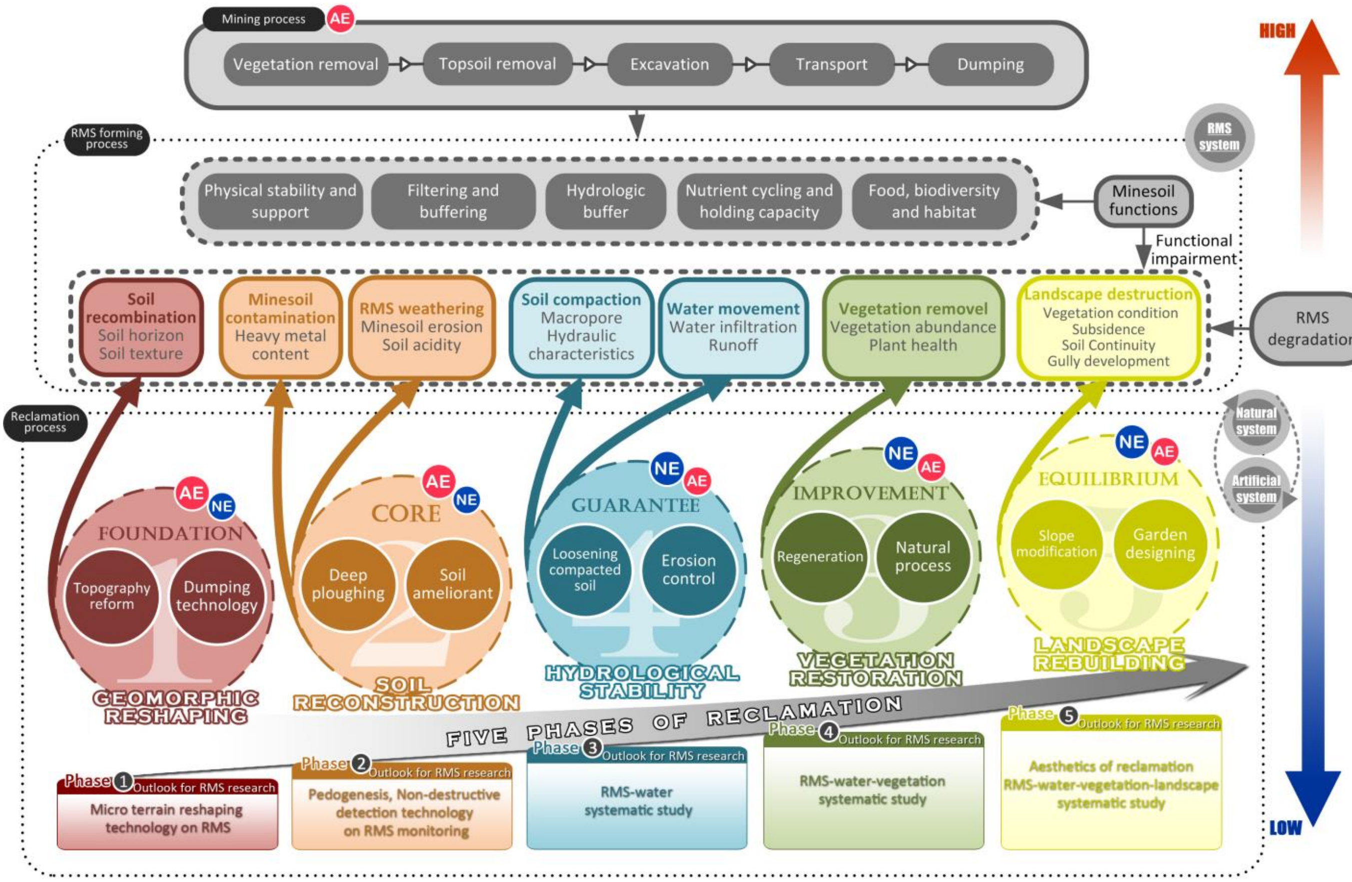

Figure 3 Effects of mining and reclamation processes on soils and interactions among natural, artificial and reclaimed mine soils (RMS) systems. The five phases of reclamation indicate the five most important amendment factors on RMS. Soil reconstruction is the core of the five phases, and all phase are closely connected. AE is artificial effects; NE is natural effects; and the imbalance size imbalance on the figure indicates the different contributions. RMS degradation rate will decrease as mining processes decrease and reclamation accelerates.