Post-mining ecosystem reconstruction

Article

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Terrestrial Minesite Rehabilitation

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Summary

The global decade of restoration brings into sharp focus the need to rehabilitate lands that have been damaged by mining, to provide safe, stable, and productive landscapes. For the majority of mines, the required final land use is some form of natural, semi-natural or managed ecosystem, such as agriculture, aquaculture or forestry. Mining activities lead to three post-mining landscape types that require rehabilitation (i) waste rock dumps, (ii) tailing storage facilities and (iii) the mined land itself. The repair of damaged ecosystems is described by many terms including restoration, rehabilitation, revegetation, ecological restoration, and reclamation. These are overlapping in meaning, have regional biases and all fall short of what is really required: ecosystem reconstruction. This requires a highly multidisciplinary approach drawing on geotechnical engineering, social science, soil science, law, hydrology, botany, geology, pollination biology, financial planning, alongside ecologists. Ideally mine rehabilitation should be progressive and start early in the life of the mine and employ a strict regime of characterising and tracking waste materials for use in creating safe and stable post-mining landscapes. This will limit risks and optimise outcomes, especially when wastes contain toxic metals or severe acidity, alkalinity or salinity. Some mine sites are appropriate for the restoration of native ecosystems that existed pre-mining but many, including landscape features created from waste materials, are not. Criteria for successful land rehabilitation are complex, multivariate, and highly contingent on the agreed final land use. Future advances in mine rehabilitation include the use of geomorphic landscape design and emerging thinking on cradle-to-cradle mining.

Mining and humanity

Humanity needs to mine. If we are to address the current challenges of sustainable development and climate change mining is essential. The UN recognises that ending poverty, and other deprivations, must go together with economic development while tackling climate change. Historically, humanity has only two sources of materials: things we grow and things we mine. While the circular economy offers new opportunities for resource reuse, it has its limitations and is not a panacea. To rapidly facilitate the equitable sustainable development required to alleviate poverty and mitigate climate change, resources will have to come out of the ground. The question is, how? Will we continue to mine in such a way as to leave terrible legacies, scars on the landscape and polluted ecosystems or are we now able to restore sustainable ecosystems and provide socially equitable land uses? The answer is yes, and while mining has a poor reputation environmentally, this need not be so in the future.

Mining is often completely destructive to the landscapes in which it is practiced. It is an essential human endeavour but can be the most damaging anthropogenic activity on land, essentially comparable to glacial scouring or meteor strikes. The completion of mine extraction results in an ecosystem in its most degraded state. From this point, practices have been developed to repair the landscape and make post-mining terrains safe, environmentally benign and even productive. Yet due to poor planning, material management, closure design and a lack of understanding of biology and ecosystems by engineers, this all too often can lead to polluting wastes, with various structures such as open voids, rock dumps and tailings dams, that fail chemically, leading to pollution, or physically, leading to complete collapse of dams in the worst cases. The objective of rehabilitation is to provide a safe and stable landscape to allow some form of productive, or at least non-harmful land use, that might include revegetation with crops for food or fibre or some form of rehabilitated self-sustaining ecosystem. Levels of success have been highly variable, with most post-mining landscapes providing some undesirable outcomes for local communities, ecosystems and consequent biodiversity.

Globally, economies continue to have a voracious need from mined metals and minerals, and even developed economies such as the EU fail to come close to recycling targets within a circular economy model. In 2022 recycled material accounted for 11.5% of material used in the EU, an increase of less than 1% since 2010. Therefore, mineral extraction from land is not only inevitable but necessarily going to continue, and this land needs to be treated with care, as a temporary land use, not as a terminal land use.

To understand mine site rehabilitation a rudimentary awareness of mining practices is required. Most modern mining is opencast (opencut) and this leads to mine footprints (the total mine lease area) that are ever larger to capture all the belowground resources and, as is typical, store mined and process wastes on the surface. For most metalliferous mines, such as gold and copper mines, a deep pit is excavated to access the ore body. These may be exceptionally large with, the largest, Bingham Canyon Mine in Utah USA being 1.2 km deep and 4km wide. The fate of these remnant voids (the hole in the ground) is often to become a permanent feature of the post mining landscape and these voids very often fill with water to form pit lakes. Of the materials excavated, much is often overburden and inter-burden, and is essentially waste rock, this material may contain other minerals, not of current commercial interest, and are collected as *waste rock dumps* (WRD, industry standard term). The ore is usually processed on-site, extracting the mineral rich phase (often with chemicals such as sulfuric acid and cyanide) and discarding the residue or *gangue* (the valueless fraction). The residue created is known as tailings, usually a suspended slurry and this is stored in earthen dams. These *tailings storage facilities* (TSF, industry standard term) contain quantities of non-target metals such as copper, mercury, cadmium and zinc, and may include radioactive uranium, thorium, radium and their daughter isotopes. Some mines are surficial and do not generate deep pits, these strip-mining operations tend to be no more than 10-15 metre in depth but may cover many tens of miles in land surface disturbed and are typical for bauxite and mineral sand mining.

Mining activities lead to three primary landscape types (excluding underground mines) that require rehabilitation (i) the waste rock dumps, (ii) the tailing storage facilities and (iii) the mined land itself. The mined land may consist of the void and disturbed surrounds or extensive strips of surficially disturbed landscape. In many mines geological strata contain pyritic materials that can generate acidity when moved to the surface and exposed to oxygen and water. Consequently, wastes are classified into potentially acid forming (PAF) and not acid forming materials (NAF) and must be handled differently in the rehabilitation process.

Rehabilitation and mining

Minesite rehabilitation is a complex process, a key component of the multifaceted practise of mine closure. When mining processes are relatively benign, such as surface strip-mining for non-toxic metals, the land may be restored to previous uses with reasonable success. Examples range from industrial landscapes to native biodiverse ecosystems. However, in most cases this does not hold true, and WRD and TSF often contain metalliferous waste materials that have physical and chemical attributes quite different from any materials from which soil formation (pedogenesis) might occur on human timeframes. These materials may not only be toxic *in situ* but may also contaminate local receiver environments (land, rivers, lakes and sea) through aeolian and water movement processes. These can have long-term negative impacts on ecosystems and human health. To avoid this outcome, suitable rehabilitation of the post-mining landscapes is necessary.

The rehabilitation of mine sites if often thought of as the domain of restoration ecologist and biologist, as these disciplines have expertise is restoration. As mining is so completely destructive the original landscape, it requires complete *ecosystem reconstruction*. Therefore, mine site rehabilitation requires a highly multidisciplinary approach and the co-ordination of expertise including geotechnical engineers, social scientists, soil scientists, lawyers, hydrologists, botanists, geologists, pollination biologists, financial planners, alongside ecologists. As many post-mining structures (WRD, TSF) are inherently unsafe in the long-term, reconstructing a safe and stable ecosystem is often a priority over the purest approach of restoration ecology to retore precisely what was there before. Planning for mine closure, and consequently mine rehabilitation, must start before mining commences. While this approach is now more common, most active mines across the globe do not start planning their rehabilitation until close to the end of the mine life.

Conventional restoration ecology describes a process known as *ecological restoration* commonly defined as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” however in post-mining landscapes “assistance” is often insufficient as a complete ecosystem needs to be reconstructed, often with hostile and unstable materials that need specific handling and management. Consequently, the term “restoration” (endeavours aimed at a full recovery of an ecosystem to its pre-disturbance structure and function) does not apply in most cases. This is why other terms are commonly used in industry such as *revegetation*, *reclamation*, and *rehabilitation*. None of these fully capture the scope and scale required for complete ecosystem reconstruction after mining. *Revegetation* is simply the establishment of plants and is the ecological equivalent of gardening. It offers no long-term solutions, does not require native species and this approach often leads to failure without constant management. *Reclamation* essentially converts unusable disturbed land into some form of functional land use. This may be biologically productive, recreational, urban, or industrial and rarely uses historical or indigenous ecosystems as a target. *Rehabilitation* intends to reestablish some form of ecosystem functioning on degraded sites, where the goal is renewed and enduring provision of ecosystem services which may not be related to the pre-mining ecosystem. Rehabilitation and reclamation intend to create a safe and stable functioning landscape. In practice these terms are used interchangeably and have regional divergences. In the southern hemisphere, rehabilitation is more commonly used and in the north reclamation tends to be favoured.

Rehabilitation after mining

The starting points for rehabilitation should be intimately interlinked with pre-mining activities, local communities, financial viability, and ecosystem assessment. Before any mining commences prospective ore grades need to be assessed and this is done by drilling probe (bore) holes and extracting cylindrical cores of rock. These samples are subject to a number of tests, not just concerning ore grade, but also minerology, porosity, permeability, particle size and pH. The samples contain valuable information for rehabilitation and can foreshadow viable pathways to reconstruct ecosystems. If mining is feasible, the next key step is to identify the desirable end land use. This must be done in consultation with local communities and other stakeholders. Many decisions about materials handling and placement will be contingent of the final target land use, that must be a desirable one for the local community. This may be anything from a racetrack to a restored biodiverse (semi)natural ecosystem. The intention here is that the mining company is "borrowing" the land and returning it to a useful, safe and functional land use. Whatever the land use, the exiting ecosystem and the post-mining ecosystem need to be understood. Mining may be prevented for reasons as diverse as the presence of rare stygofauna, aboriginal rock art, hydrological risks of flooding or the generation of unmanageable acidity. All of these issues need to be considered within the financial envelope ascribed to the project. Underestimates of cost to rehabilitate a given mine and lead to premature mine closure and abandonment of sites leaving a long-term negative legacy for the local natural and human ecology. Financial instruments are often employed to ensure such outcomes do not occur but generally bonds taken as indemnity fall far short of even the most basic remedial requirements, which might explain the negative light in which mining is currently viewed.

Once mining begins it is essential that the native soils are stripped and preserved. In this conventional model of soil handling, soil storage is a major issue as it takes up space in the mine lease footprint, yet preferential storage techniques require shallow stockpiles, this is compounded by the fact that the biological and chemical fertility of the soils is lost over time, where periods of storage over 20 years is not uncommon. In reality, all too many mines misplace their topsoil due to poor records and material management, a general issue that underpins many difficulties in rehabilitation. In such circumstances other waste materials are used to form cover systems in the hope they will be stable and soil forming. In an optimal model soil is not stored but returned directly to a part of the mine already exploited and prepared to be rehabilitated and receive newly harvested soil. This can be improved upon still further by stripping topsoil and subsoil separately and returning them to the mine pit in reverse order (see Figure 1). The optimal process of stripping and returning soils in this manner is called double-stripping and direct-return soil management (Figure 2). Variations on this model of soil management that underpin ecosystem reconstruction are known as progressive rehabilitation, where mining and rehabilitation occur in concert, with many advantages (Figure 3). Progressive rehabilitation encourages the mining operation to track its materials, minimise the need for stockpiling, allows the closure team to learn and adapt practices and requires rehabilitation costs to be incrementally allocated, reducing the end of mine life liability. Progressive rehabilitation is not always possible due to the nature of the mining activity and the footprint of the mine. It is most commonly practiced in surface mines including iron ore, coal, bauxite and mineral sands mines.

For the majority of mines globally the required final land use is some form of natural, semi-natural or managed ecosystem, such as agriculture, aquaculture or forestry. To achieve this successfully, one needs to start from below the ground up. After site clearance and detailed material characterisation of all wastes, the first steps require the proper handling of materials, isolating PAF and highly erosive materials within any TSF, WRD and any other planned landscape. Once the new landscape structures are developed, ideally using geomorphic landscape design and benign wastes, they need to be deep ripped (subsoiled) to remediate compaction caused by the trafficking of machinery. At this stage potentially soil forming wastes and subsoil and topsoil can be applied, followed by the sowing of seed (or planting of seedlings) and judicious application of fertiliser. The above description is highly generic and contingent on the target ecosystem.

Pedogenesis underpins the long-term sustainability of rehabilitation. To simplify the complexity of soil formation, which consists of many interacting processes that proceed simultaneously at different rates, climate, topography and the biota all interact over time (Figure 4). In cases where post mining materials are characterised by extreme pH, salinity, or metal toxicity pedogenesis may be inhibited. Where mining wastes are relatively benign these may contrast positively with native parent materials primarily because mine soils are comparatively very young mixtures of finely crushed tailings or fragmented rock. It is the smaller particle sizes, and chemistry of the minerals, that determine the rates at which mined minerals are changed to secondary minerals creating new soil. Waste mineralogy also determines the potential fertility of these incipient soils and hence the biological activity and plant growth potential. For example, weathered basaltic wastes can form highly fertile soil forming material.

Much consideration has been given to the restoration of native plant communities, especially where these contain high levels of biodiversity and/or endemism. This is an excellent ambition for appropriate surface strip-mining where, mining can leave large tracts of benign mine floor where deep ripping and direct return soil handling can be employed, the most notable example being bauxite mining in Australia. However, this option does not extend to the wastes, where bauxite tailings are highly caustic (circa pH 11), and extremely difficult to rehabilitate.

Several important aspects of the plants used in rehabilitation need to be considered for native rehabilitation success. Seed provenance, especially in the context of climate change, is increasingly important for long term success. Keystone species in *de novo* ecosystems may have different responses to nutrients added in fertilisers, and knowing the nutritional requirements and tolerances of plants is important when considering appropriate fertilisation for restoring native ecosystems. When not understood, floristic communities may develop in ecological trajectories not desired and ambitions to match target ecologies are lost. In some cases of ancient highly weathered soils no fertiliser addition to restored biodiverse forests can have better outcomes for floristic diversity and growth than standard fertiliser practices. The water relations of plants also need to be known, particularly if they are to survive dry summers or wet winters in their early years of establishment. Many plants will also require microbial symbionts such as nitrogen fixers (rhizobia or Frankia) and/or mycorrhizas in order to establish and thrive. Finally, susceptibility of the vegetation to pathogens needs to be understood. Sowing species which may quickly succumb to pests, whose populations may be unpredictable in a new ecosystem, needs consideration.

Success criteria

There have been many attempts to stipulate criteria for assessment of success in post-mining landscapes, with varying degrees of effectiveness. These are typically developed by regulators and mining companies, and ideally should include local communities and other stakeholders. Measurement criteria for rehabilitation completion need to be holistic and establish whether the rehabilitation is going to be sustainable. This needs to address economic and social targets as well as environmental targets. Nonetheless, for natural ecosystem rehabilitation the success is defined primarily on ecological grounds and has all too often relied on simple observations of the presence or absence of particular flora and fauna. Success criteria are now being developed that move beyond these simplistic measures and should be based on definitive and implied measures of ecosystem functions that are complex and multivariate.

Enduring monitoring programmes should assess performance through time against clear objectives. Ongoing monitoring enables continuous improvement in progressive rehabilitation settings by providing information to guide future modifications to monitoring and environmental management. Where possible they should include aspect of ecosystem trajectory and understanding of belowground as well as aboveground components.

Ecosystem based criteria should include a wide range of assessments including: geotechnical stability, nutrient cycling, colonisation of invertebrates, microbial ecology, surface erosion, drainage chemistry and volume, plant performance and communities structure, plant-microbe symbionts, colonisation of pollinators, and soil organic matter development as minimal requirements. The concept should be to build a complete picture of the development and functioning of the new ecosystem, with a view to predict its future trajectory, potentially benchmarked against existing ecosystems as a targets or reference points. The great imponderable is when is the ecosystem reconstruction considered a success. This is a controversial topic as mining companies want to achieve sign-off on the mine lease and the return of bonds held by the state, while regulators and many stakeholders remain unsure of success and may require further monitoring and research to demonstrate a sustainable ecosystem has been achieved.

For TSF and WRD success needs to be judged on how safe and stable the rehabilitation is, where the flora and fauna are considered functional aspects of long-term stability. Unfortunately, ecological processes and physical and chemical changes in the characteristics of stored wastes through time can significantly affect geotechnical structures such as TSF and WRD, and these are too often poorly considered and the consequences can be devastating, in the worst cases this can lead to complete failures such as the at the Córrego do Feijão iron ore mine in Brumadinho, Brazil which suffered a catastrophic failure of its TSF in 2019, killing at least 270 people. This demonstrates how important the monitoring of post-mining environments is now and in the future.

The way forward

Minesite rehabilitation is critical to mining as it underpins the social licence for mines to operate. Mining is often viewed in a negative light by the public rather than an essential supplier of materials without harming people, places and nature. To change this perception real improvements in mining practices and rehabilitation is needed. Current practices in mining are ever improving but the industry retain an enormous legacy of harmful and polluting sites left for nation states to remediate; if they have the will and resources to do so. Linking new mining projects to the rehabilitation of legacy sites is one way forward, and has been employed, but to date these practices barley scratch the surface. Addressing unrehabilitated legacy mine sites is a major aspect of mine rehabilitation globally and applies to wealthy countries like Australia and the UK as well as less developed nations such as Zambia and Papua New Guinea.

Recent steps forward in rehabilitation have seen the development of models that support better post-mining outcomes. Two recent examples include improved materials tracking and use and geomorphic landscape design.

Improved characterisation, tracking and handling of mined materials for rehabilitation can now be fed into an integrated waste control model. This is used to inform waste material placement in accordance with the material characteristics to allow appropriate use of the suitable materials for construction of WRD and TSF. This type of system can keep track of all mined material (including soils), on a mine site and allow informed decisions to be made on the placement of wastes in newly constructed landscapes.

Geomorphic landscape design intends to reduce erosion and increase long-term stability by reconstructing post-mining landscapes (TSF and WRD) in such a way that they have similar forms and functions to that of a natural geomorphic system (Figure 5). This attempts to find the best geomorphic fit, given the new post-mining conditions where the designed drainage is based on geomorphic principles. Geomorphic landscape design mandates that the new landscapes have slope lengths, gradients and forms that match a natural system with both slopes and drainage channels having geomorphologically effective profiles.

A new theoretical model for mining as a temporary land use, employing the concepts above, where all mined materials have value, have recently been proposed. Instead of the current life-of-mine or cradle-to-grave approach to mining, the new approach been termed *cradle-to-cradle* mining (C2C). The C2C concept will require moving from an exploit-and-repair form of mining to a new mining philosophy integrated with the local geography and global resource needs, and that utilises more than one target element, with an objective to find markets or uses for all materials. There would no waste, just resources of different value that are all part of the mine's economy. The ambition is to create a new mining paradigm where mines are not seen as cradle-to-grave but C2C operations, leaving the landscape with forms and functions, that may be different, but at least equal in utility to the pre-mining state. In such a new paradigm, mining and rehabilitation become part of one continuous operation in service of human ambitions. This early concept requires much development, but it serves to direct thinking as to what might be possible in future.

Further Reading

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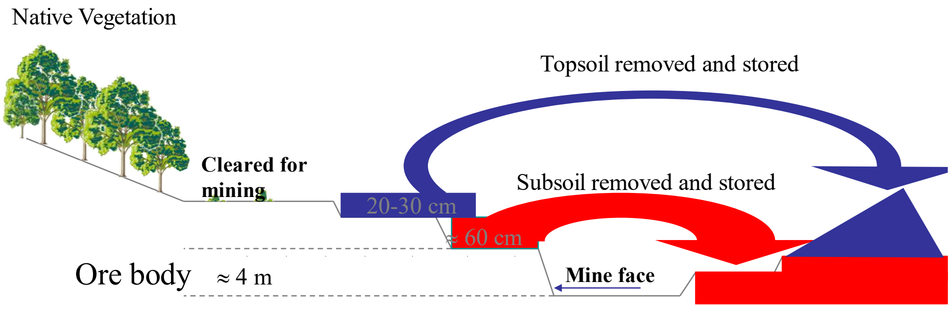
Figures

Figure1- Debbie - I think this would work well as one side by side figure. I'm sure your colleagues in India could make a much cleaner and clearer job. The image needs tidying and balancing. The colours are arbitrary and can be changed to whatever looks clear and presentable.

Figure 1 Conventional soil handling in mine site rehabilitation where double stripping of topsoil and subsoil is stored during strip-mining and is replaced in sequence after stockpiling. Stockpiling maybe for weeks, months, years and, not uncommonly, decades.

Conventional model for open -cut mine site rehabilitation with double stripping of topsoil and subsoil

– **During mining**



Conventional model for open -cut mine site rehabilitation with sequenced return of subsoil and topsoil

– **After Mining**

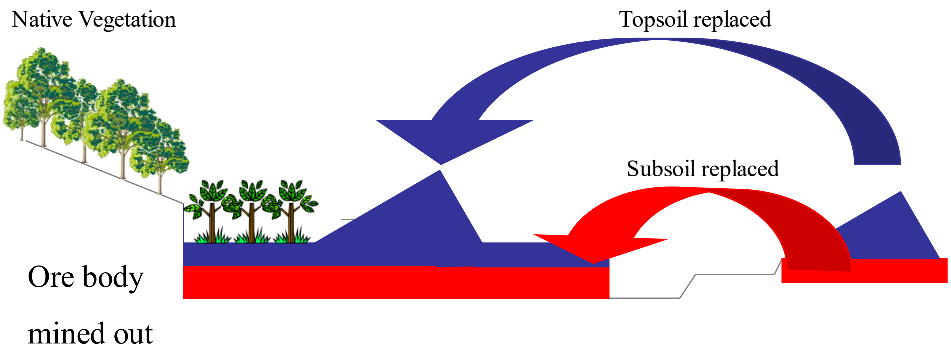


Figure 2 Direct return model of soil handling in mine site rehabilitation where double stripping of topsoil and subsoil is returned in sequence. This may occur on the same day or as soon as practically feasible.

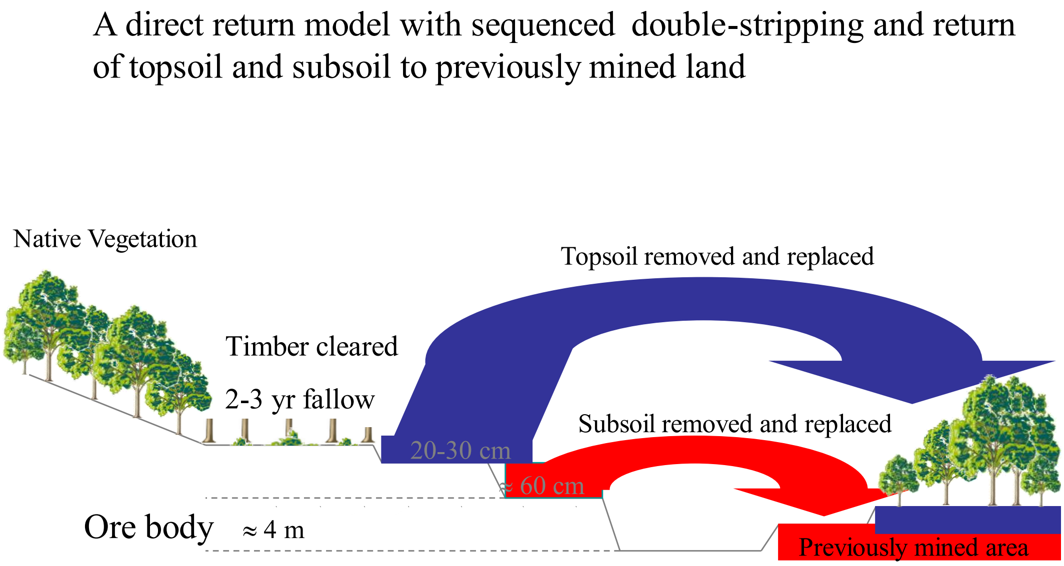


Figure 3. A schematic of progressive rehabilitation of a stratified coal mine deposit and waste rock dump showing the collection, dumping, regrading, and respreading of soil, overburden and interburdens taken from above and between coal seams. Waste rock (over and interburdens) are deposited in the mine void to create a new landscape as rehabilitation progresses behind the direction of mining by a defined lag distance.

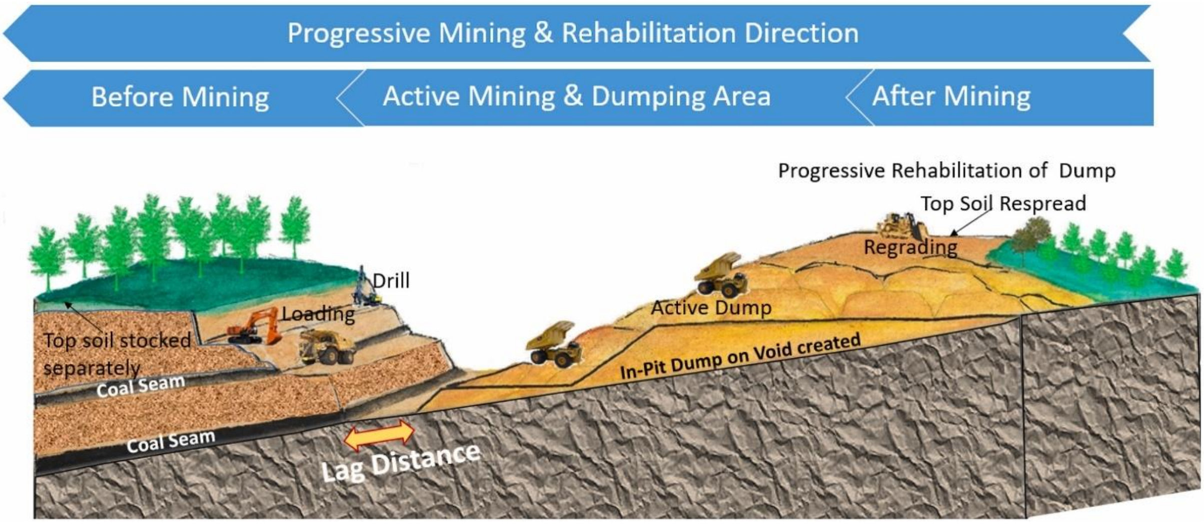


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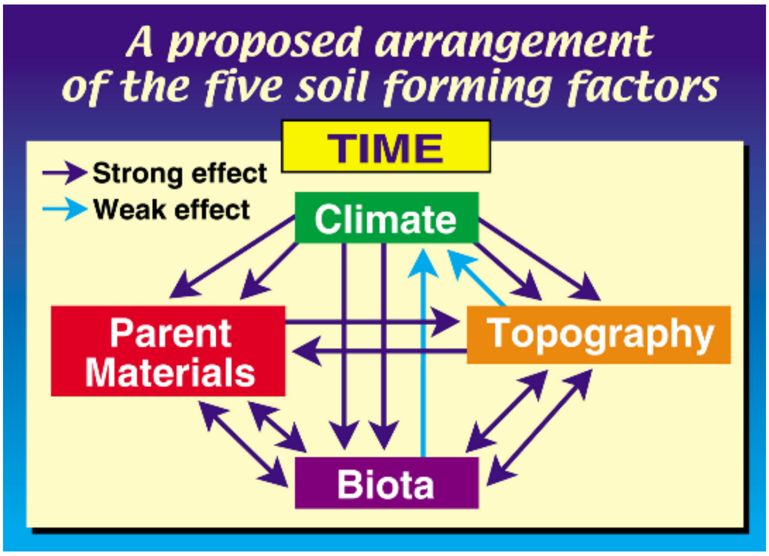
Figure 5. The fundamental pedogenic or soil forming factors and the direction of their interactions. Parent material is native rock in natural soils and post-mining wastes in a mine rehabilitation context. The critical difference for pedogenesis is that crushed wastes have a much higher surface area allow for greater reactivity and more rapid soil formation under benign conditions.



Notes for redrawing –

The Title should be only "Soil Forming Factors" – the last three word only.

Strong and weak effects can be the same colour, but all arrows must be kept. Also, "Parent Materials" should be relabelled "Parent Materials or Mine Wastes"

Colours in figure can be changed

Figure 5. A modelled visual comparison of a traditional mine rehabilitation landform (left panel) and alternative geomorphic rehabilitation landform (right panel). The traditional landform has a minimized disturbance footprint which leads to piling the waste material as high as possible into a terraced landform that is unstable and subject to erosion. It offers no variation in storm water harvesting and sunlight exposure that will lead to reduced floristic diversity. The geomorphic alternative design for the same area has an extending toe to accommodate the volume of waste material needed to create the drainage valleys required to convey storm water runoff, minimising erosion that would occur in the traditional terraced landforms.

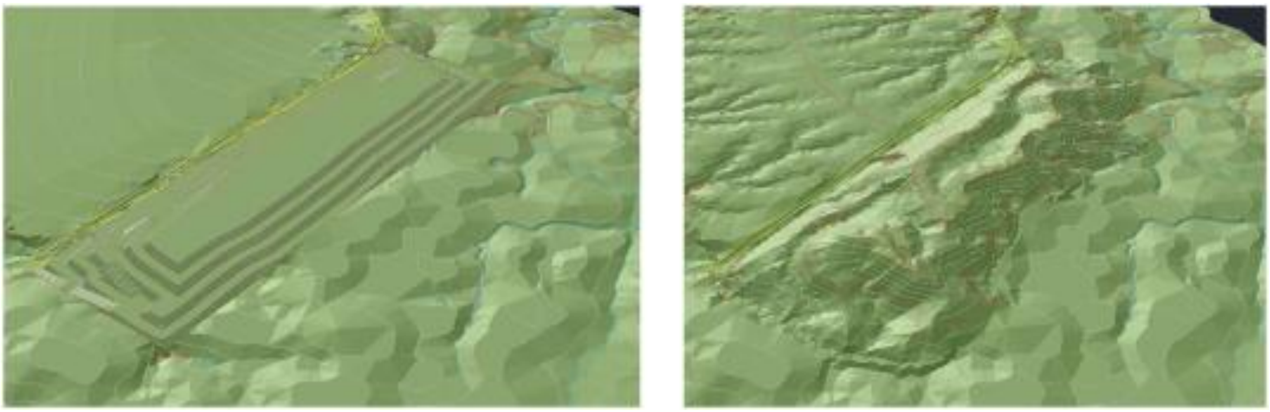


Figure 5. from: Hancock, G. R., Duque, J. M., & Willgoose, G. R. (2020). Mining rehabilitation–Using geomorphology to engineer ecologically sustainable landscapes for highly disturbed lands. *Ecological Engineering*, *155*, 105836.

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