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Review

An Approach to Thresholds for Evaluating Post-Mining Site Reclamation

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Abstract: Here, a time-scale conceptual threshold model for assessing, evaluating, documenting, and monitoring post-mining sites reclamation progress was developed. It begins from initial state I_0 down to degraded state D_0 (which depends on the mining). Reclamation starts with soil reconstruction R_{-2} up to revegetation R_{-1} (red zones) to reach minimum threshold R_0 (amber zone). Beyond R_0 are green zones R_1, R_2, and R_3 representing soil/abiotic conditions, biological, and improved threshold, respectively. The model also identifies potential drivers, land-use options, targets, and endpoints along the threshold reclamation ladder. It is applicable to all degraded ecosystems and adoptable in national and international laws. In this approach study, we identified threshold biotic/abiotic indicators for ascertaining success from R_0, future work focuses on measurement and ascribing of threshold values to each of the threshold stage.

Keywords: restoration; sustainability; ecological indicators; land-use options; drivers; targets; endpoints

Citation: Adesipo, A.A.; Freese, D.; Zerbe, S.; Wiegleb, G. An Approach to Thresholds for Evaluating Post-Mining Site Reclamation. *Sustainability* **2021**, *13*, 5618. https://doi.org/10.3390/su13105618

Academic Editors: Massimiliano Fabbricino and Marc A. Rosen

Received: 14 April 2021
Accepted: 14 May 2021
Published: 18 May 2021

1. Introduction

Life survival and the development of human societies depend directly or indirectly on exploration of the abundant resources within the ecosystem [1,2]. Examples of typical parameters affected include topography, vegetation, air, soil and water quality, human health, habitation, and aesthetics values. The subsequent impacts are not restricted only within the mined area boundaries [3], but may affect the landscape far beyond the mining areas. The impacts differ based on differences in the type and purpose of mining, law regulations, site conditions, surface area, level of disturbances, geology, depth, mining technologies, and the site and landscape hydrology. These differences determine the type of reclamation measure required and its progressive stages, while the various disciplines in science and practice view reclamation with different perspectives. This ranges from improving the aesthetic values of degraded sites, to the ecological restoration of habitats, to reclamation or rehabilitation of post-mining sites, to rewilding extensive landscapes for restoring the structure, function, or the ecological complexity of ecosystems and land-use systems [4]. Its terminologies (restoration, remediation, reclamation, and rehabilitation) are sometimes used interchangeably, but these have been well defined by several authors [5–7]. Nevertheless, the increasing global awareness and efforts towards sustainable land management, restoration, and its potentials in achieving the Sustainable Development Goals (SDGs) makes a comprehensive consideration of reclamation process necessary and timely [1]. Therefore, a broadly efficient evaluating and monitoring threshold, with multidisciplinary approaches and multiple stakeholders, capable of defining the success of reclamation progress such as what level has been crossed and to be crossed, is necessary.

Approaches to reclamation differ around the world. In a number of countries, with well-structured and monitored regulations guiding reclamation, the mining companies are forced by law to reclaim the sites. Reclamation is not for profit making and takes time (several decades). Occurrences showed that soil reconstruction and revegetation are the main traditional targets (Box 1). While there are no international regulations guiding reclamation of post-mining sites, the few countries with functional national laws regarding post-mining reclamation have identifiable differences in their approaches, with some crucial omissions. As a result, several reclamation schemes have been developed. The first scientific evaluation system for coal mine derelict sites was developed during the annual meeting of the 'American Society of Surface Mining and Reclamation' in 1990, entitled "Evaluating Reclamation Success; The Ecological Consideration" [8]. Other related schemes include Reclamation Success Evaluation System (RSES) developed for field assessment of reclamation success by the Bureau of Abandoned Mine Reclamation, Pennsylvania Department of Environmental Resources (PA DER) [9]; the indicator parameters highlighted by Maiti [3] as well as related soil-quality evaluation systems [10–12]. These schemes showed limited ecosystem attributes for evaluating reclamation success and not sustainability efficient. More so, it has no clear evidence in most practical evaluation scheme.

On the other hand, there have been extensive studies on restoration and use of ecological indicators in the last decades [13,14]. However, the existing panoply of developed ecological evaluation techniques does not sufficiently integrate the complexity and/or multidimensional nature of a characterized post-mine site ecosystem. Majority of the practical restoration projects are on sites degraded by agricultural activities or similar anthropogenic disturbances [15,16]. The assessments are region-specific without relation to the degree of degradation [14]. More so, the use of ecological indicators only can create a form of bias or imperfect conclusions in the evaluation process. Variations in the indicator species frequency and cover could be indecisive, and this might limit certainty of recovery [17]. While a modified model for incorporating imperfect detection was proposed [18], integration of a multi-variant threshold, especially when species representing both failure and success co-occur within the same site is necessary. In addition to that is the low reflection of sustainable attributes and guidelines for assessing restoration projects, established by the international Society for Ecological Restoration (SER) [15]. Moreover, monitoring post-mine site reclamation success ought to be scientifically defensible and sustainable. Although it has been argued that mining cannot be done sustainably rather responsibly, nevertheless, reclamation can be sustainable. The establishment of an evaluation system that unequivocally identifies success, in consideration of its entire ecosystem and sustainability suggests enhancing efficient prediction of restoration success rather than false success claims, e.g., Rooney et al. [19].

Adequate incorporation of these gaps demands active involvement of multidisciplinary stakeholders characterizing attributes of the new ecosystem and integrating both the ecological integrity and human well-being in a single framework [20,21]. It is interdisciplinary, cutting across traditional subject boundaries, and predicated on the hypothesis that ought to create an enabling avenue for diverse ecosystems and land-use systems with its sustainable and cultural values [4,14,15,22]. In that light, this study presents a time-scale conceptual model that highlights essential considerations and thresholds for reclamation schemes and is capable of assessing, evaluating, documenting, and monitoring the overall long-term success of post-mine sites reclamation progress. With respect to the model, each highlighted threshold was briefly discussed with essential considerations at each stage. Additionally, the status assessments, land-use options, and decision-making are discussed, and they are to be considered at each threshold level as well as the targets and endpoints at the end of each threshold level.

Box 1. Traditional reclamation scheme.

Landscape reclamation schemes are in several cases trial-by-error and sometimes entail rebuilding the ecosystem from bedrock. The traditional targets are (1) backfilling and soil reconstruction using machines, energy, and geological materials followed by (2) biological materials for revegetation [3] (Figure 1). Summary of its key objectives is to reduce potential damage, prevent negative impacts to the environment within and near the mined areas, restore the viability and vegetation potentials of the soil, compensates, and maintain or improve the landscape aesthetic values coupled with few functional qualities [4,23]. These efforts have resulted in the development and improvement of several evaluation schemes [3,8,9,24], which are mostly limited to the analysis of the reclaimed sites' revegetation cover or plant community, soil erosion protection, landscape hydrologic functions, and aesthetic values [3]. Several ecosystem components and processes are not considered which are crucial for ecosystem functions, services, and sustainability [25]. The soil properties are mostly below standard. Additionally, so are the air and water quality, climatic conditions, and other essential ecosystem components [26–29]. Therefore, due to its characterized challenges, most post land-use options cannot cater to the downstream ecological hierarchy and productivity demands.

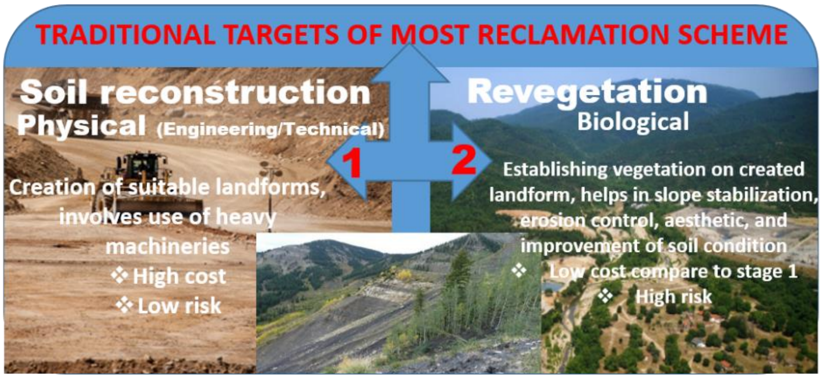

Figure 1. Common targets of most reclamation scheme.

2. Reclamation Success Evaluation Conceptual Model

The conceptual model for assessing, evaluating, monitoring, and documenting the long-term post-mining sites reclamation success is presented in Figure 2. The model has been adapted from the ecosystem degradation and restoration concept model by Whisenant, and Parks Canada and The Canadian Parks Council [30,31]. It is a time-scale model with different threshold levels ranging from the initial state I_0 down to the low degraded and/or non-functional stage D_0. The condition of D_0 depends on the type of mining and its involved attributes, and since degradation cannot be measured directly [32], experiences on each site vary. However, reclamation efforts start with soil reconstruction R_{-2} up to revegetation R_{-1} (the red zones), which serves as the basis in attaining the minimum threshold stage R_0 (amber zone). Above the amber zone are the green zones (R_1, R_2, and R_3), representing soil/abiotic condition, biological and improved threshold, respectively. R_{-2} and R_{-1} are basic reclamation measures, which have been well studied, but from R_0, we identified threshold indicators for ascertaining and monitoring reclamation success. Land-use options strongly depend on the threshold level reached, as well as adequate considerations and decisions by the multidisciplinary stakeholders involved. Considerations of positive and negative drivers which exerts up/down pressures along the reclamation progress is necessary. Examples of such drivers include climate, potential biota changes (e.g., invasive species), uncontrollable anthropogenic disturbances and encroachment, natural occurrences such as draught, temperature variance within the seasons (winter and summer), precipitation, etc. These drivers can influence some ecosystem properties attain targets quickly, dawdle, or follow either linear or threshold response [6,18,33–35]. However, beyond R_3 the endpoints can be (1) improved, (2) maintained, or later (3) degraded, especially due to the unending demand for its resources. These three endpoints are also applicable at the end of each threshold level. Further elucidations of each stage are highlighted in the following subchapters.

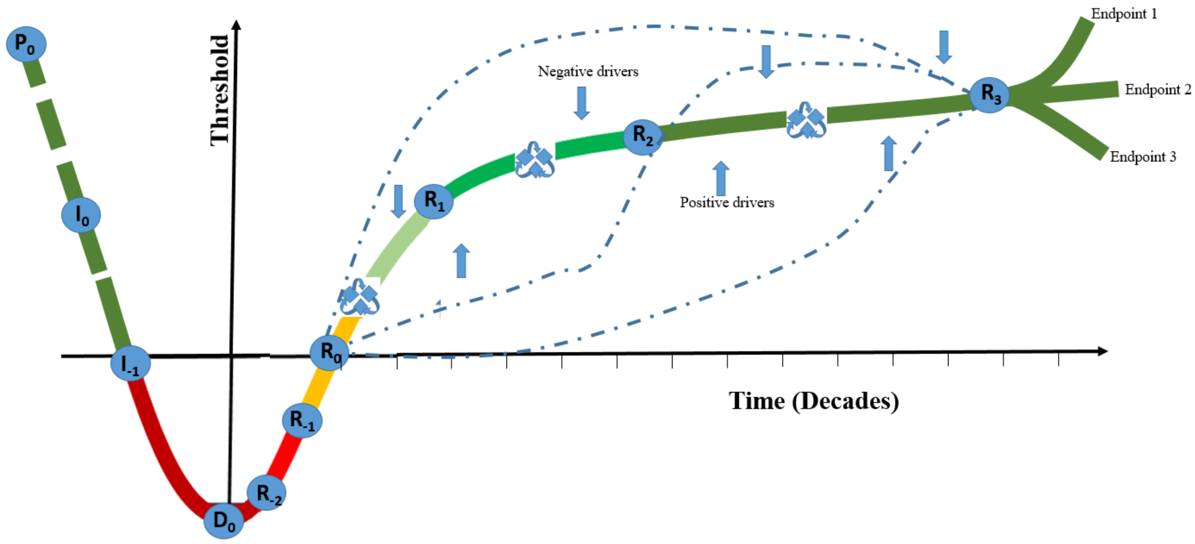

Figure 2. Time-scale conceptual model for evaluating successful reclamation progress. It starts from the Initial state I_0 down to the very low, non-functional, Degraded state D_0 (depending on the type of mining), and rising up to Soil Reconstruction R_{-2} and Revegetation R_{-1} (Red zones) to reach Minimum reclamation threshold R_0 (amber zone). Above R_0 are the increasing green zones R_1, R_2, R_3 representing Soil/Abiotic condition, Biological, and Improve threshold stage, respectively. Beyond R_0, assessments and decisions (i.e., the blue boxes along the threshold ladder) are made considering the drivers along the reclamation ladder. Endpoints 1, 2, and 3 represent improved, maintained, and deteriorating endpoints, respectively.

2.1. Initial/Reference State (I_0)

The pristine state (P_0) is a critical issue, as it no longer exists in many countries. Several occurrences causing degradation are in most circumstance not recorded, these reduce the ecosystem to the initial state (I_0), then further to I_{-1}, which begins the intentional degradation condition. Most countries have not record of the pristine state, and only few developed countries keep this record before degradation, especially countries with functioning reclamation laws such as Germany, where the mining companies are to present an efficient reclamation plan prior to mining. Alongside this, an adequate record of the site's initial state is also necessary. Nevertheless, identification of a sustainable cultural landscape (reference or baseline plots) as representative of post-reclamation conditions, for comparisons and other correspondence during the reclamation period, is necessary. Ruiz-Jaen and Aide [36] recommend a minimum of two reference sites for capturing potential ecosystem variations and inclusion of crucial ecosystem attributes (diversity, vegetation structure, and ecological processes) in relation to ecosystem functioning. Additionally, influencing factors such as the distance to the mined sites, vegetation zone, geology, weather, encroachment, and disturbances should be considered. However, the traditional comparison to reference sites for similar composition and/or condition [37,38] is not enough; reclaimed sites rarely have similar biotic and abiotic conditions [21], and it may lack or degrade due to unavoidable disturbances (natural/anthropogenic), or fluctuate over time.

2.2. Soil Reconstruction (Backfilling) R_{-2}

The landscape condition and soil physicochemical properties are the basis of ecosystem structure [8,39–41]. Approaches towards soil reconstruction depend on the type of mining, e.g., opencast mining using conveyor belt technology [42] or others [43,44]. At this stage, the essential considerations, which were to be ensured include the landscape, reclaiming waterways, handling soils, removal of potential threats and contaminants, capacity to sustain biological populations, integration with the landscape, resilience of natural disturbances, aesthetic values (the affected community), and influencing drivers such as landscape, weather, erosion, etc. These considerations and procedures have been extensively discussed [45–47]. Damage from underground mining primarily occurs due to subsidence over-extracted areas and pollution/contamination (e.g., spillage). It is influenced by factors such as the minerals horizon, its thickness, depth, the employed mining method, etc. Another concern is its created cavity if not well managed. Prominent areas with soft soil, e.g., in Singapore [48], require ground improvement works. Against compaction [29,49], soils should be handled neither in a too dry nor too wet state (10–15% moisture content). Techniques such as deep gouging, ripping, extreme roughening, pocking, and surface scarification can be employed, or use of manual tools for small-scale mines [50]. It is a pedogenetically young soil, with traceable developments from mixtures of fragmented and pulverized rock materials (anthropogenic soil and Technosols), and can be enhanced by topsoiling, amendments, afforestation, and plantation [51,52]. The later interest at this stage are essential soil properties that support plant growth such as soil nutrients, soil organic carbon, pH, N-pools, etc. The soil condition at this stage does not give a direct assessment of ecological functioning; it provides information and/or indication of the soil's potential long-term vegetation productivity and successional trajectories.

2.3. Revegetation R_{-1}

Revegetation remains the most common well-known strategy to improve the soil and environmental conditions of degraded sites [53–56]. Prior to revegetation, goals and objectives need to be established and coupled with plans towards utmost success. It involves planning, implementation, evaluation, and adequate monitoring. Essential considerations include site assessment, goals and standards, site preparation, topsoiling, species selection and source, plantation and revegetation techniques, conservation and water treatments, the cost, timing and climatic conditions (temperature, rainfall), proneness to anthropogenic disturbance, soil development, and natural recruitment [57,58]. Adequate and continual topsoil management is necessary and has been extensively discussed [26,59–62], along with its strategies and recorded success within the arid region [27]. For an adequate monitoring, the selection of an efficient manager is essential.

2.4. Minimum Reclamation Threshold R_0

R_{-2} and R_{-1} are basic reclamation measures common on post-mining sites to reach the minimum reclamation threshold (R_0). R_0 partially corresponds to the status of most marginal or degraded sites. Occurrences show that the soil properties and environmental conditions are usually below standard range of values [39,49,50,62,63]. The effective practices in R_{-2} and R_{-1} make the appearance and characteristics (especially at the early period) of mine soils seldom resemble native soils or normal agricultural soils, thereby making it difficult to ascertain its quality, and other ecosystem functions and services. However, further reclamation efforts are needed. From R_0, the use of efficient indicators to ascertain success is recommendable. The use of ecological indicators has evolved efficiently [33,34,64–66]. Selective indicators should be sensitive to variations in agro-ecological regions, representative of the physical, chemical, and biological properties of the environment, easy to assess, time and cost-effective, accessible, assessable by both quantitative and qualitative approaches and reflect relevant existing data. Other considerations include the cost (budget), adequate equipment, expertise, stakeholder's interest, the reclamation goals, and land-use potentials.

The identified R_0 abiotic indicators include accessibility, sustainability, erodibility, safety, contaminants-free, waterways network, hydrology (water quality and quantity), aesthetic value, and the soil physicochemical properties necessary for plant growth such as soil nutrients, salinity, pH, infiltration/penetration resistance, bulk density, aggregation, etc. These parameters are essential as a proxy for soil fertility, nutrient availability, plant-available nutrients and potential nutrient loss, indicatives of productivity and environmental quality, water and nutrient availability, understanding the proneness to erosion, variability, as well as the general landscape and geography. The habitability and productivity at this stage is also important.

R_0 biotic indicators include dispersal, rate of decomposition, pollination, recruitment, symbionts (e.g., the popular mycorrhizae), exotic species, diversity (genetic, taxonomic and functional), nitrogen fixation, soil microbial biomass C and N, potentially mineralize-able N and soil respiration as well as the pattern (which involves the patch size, vegetation type, etc.). All these factors are important for understanding the microbial catalytic potential, repository for carbon and nitrogen, productivity, estimates of biomass, microbial activity, prior warning towards organic matter, etc., and they are vital indicator parameters. Worthy of note is that attainment of these biotic components comprehensively at this minimum threshold stage is very difficult with several limitations. However, significance of its evidence is necessary.

2.5. Status Assessment/Decision Making

The importance of restoring the ecological value of mine soils cannot be overemphasized [67]. However, considering the ecological hierarchy, cost, and other requirements, it is not all mined sites that can be efficiently reclaimed ecologically. Agriculture and forestry are the most land-use options globally. They remain the basic natural wealth of the earth and are of irreplaceable importance to fight against food shortage, poverty, and other principal environmental components. More so, they significantly contribute to achieving the SDGs and its equity internationally. For example, within the European Union, about 50% of reclaimed mine lands are used for forest and grassland, while in China due to shortage of land; over 70% is used for agriculture [50,68]. Beyond R_0, progressive status assessments in line with precise decisions making are important along the thresholds ladder. An adequate monitoring is imperative to success. Further reclamation effort will likely fail if the causes (e.g., positive and negative drivers) are not well addressed [26,69]. These drivers can influence decision-making and effective response to policy [66]. Some may be direct or relatively straightforward while others may be indirect and complex. Nevertheless, decisions should be made without partiality, interdisciplinary, involving multiple stakeholders, cut across boundaries "thinking outside the box", and sustainable (Box 2). Examples of sustainable target indicators, recommendable for considerations are presented in Table 1. The well-known pressure-state-response model is recommendable for continuous monitoring. The back-and-front conceptual framework developed by Nilsson et al. [23] for evaluating the ecological restoration process is also applicable for evaluation and decision-making. Furthermore, the inclusion of social values [35] and alternatives that are sustainably balanced [70] is important.

Table 1. Examples of sustainable target indicators.

Environment		Economy		Social	
Class	**Recommendable Considerations**	**Class**	**Recommendable Considerations**	**Class**	**Recommendable Considerations**
Soil	The soil physicochemical and biological conditions, land use options and other supporting functions and services.	Costs	Pros and cons of direct costs (e.g., capital, operational cost), indirect cost (e.g., legal actions) and alternatives	Health and safety	Human health risks, on/off-site workers risks, public and neighbors, hazardous emissions, etc.
Water	Portability based on regulatory standards (e.g., contaminants), ecological (e.g., ecosystem functions), chemical, water abstraction effects, groundwater tables, acidification, etc.	Benefits	Internal investment, multiple stakeholders, collaboration, international funding, etc.	Ethical and equity	Social justice, equity, ethical values, aesthetic, culture, spiritual and vitality (e.g., 'polluter pays principle').
Biota	Both direct and indirect influence on flora, fauna, and food chain, invasive/alien/native species, alterations in ecological community, structure, services and functions, etc.	Risk and life span	Unpredictable project life span, unforeseen project risks (e.g., community, contractual, environment, procurement, technology, etc.)	Community	Compensations, services (residential, transportation, occupation, education, etc.), public participation, transparency, compliance/satisfaction assessment, national/local authority policies, etc.

Table 1. *Cont.*

Environment		Economy		Social	
Class	**Recommendable Considerations**	**Class**	**Recommendable Considerations**	**Class**	**Recommendable Considerations**
Air	Emissions influencing climate change/ozone/air quality, e.g., CO_2, CH_4, N_2O, NO_x, SO_x, O_3, VOCs, etc.	Socio-economical influence	Employment opportunities short/long term education, innovations, training, seminars, workshops, skilled laborers, etc.	External Impacts	Off-site impacts on neighborhoods and region (dust, GHG emissions, odor, vibrations, traffic, etc.), operational inconveniences (e.g., weekend and night shift), loss (e.g., environmental, archaeological)
Natural resources depletion /Waste	Ratio of exploited resources, left overs and substitutions, renewable energy and alternatives, etc./Measures of waste disposal, short and long term management, etc.	Flexibility	Project flexibility to time-scales, additional contamination, etc., and economic beneficial robust plan.	Laws and regula-tions	Policies compliance, regulatory standards, evidences showing quality assessments and accuracy, and plans for uncertainties.

Box 2. Status assessment and decision-making.

Prior to extraction of natural resources and its characterized disturbances, adequate planning towards reclamation is essential. This is important for impact assessment and establishment of targets and goals, which serve as a benchmark to define, identify, and measure success with potential unambiguous occurrences. Considerations for reclamation should be sustainably balanced (Figure 3). An example is the post-coal mining policies and practices in the Eastern USA as highlighted by Skousen and Zipper [55], which follows the 1977 Federal Surface Mining Control and Reclamation Act (SMCRA) in the USA [71], as well as the Federal Mining Law in Germany [72]. Consideration of the guiding principles and major pillars of sustainable development is significant [73–76]. Inadequacy of its social values is non-marketable [77], are also the cultural values (aesthetic, spiritual, etc.).

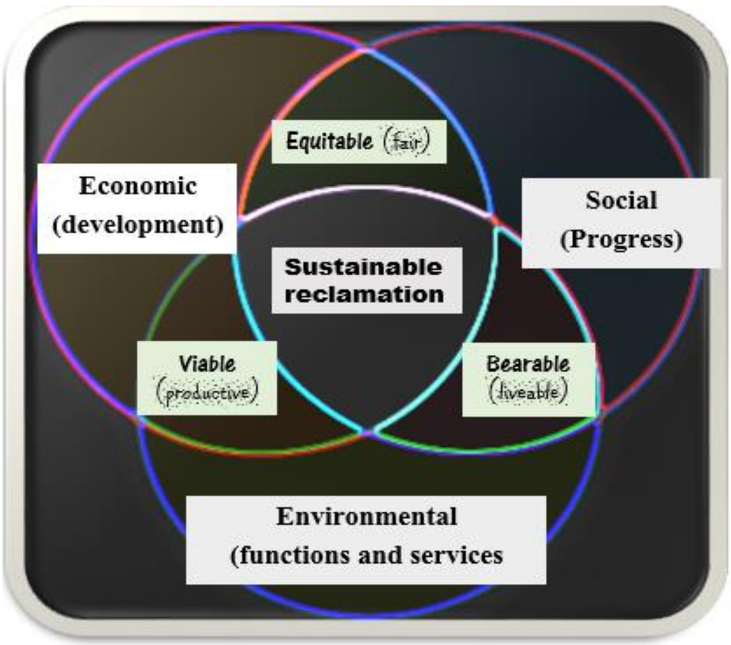

Figure 3. Considerations for sustainable reclamation.

2.6. Reclamation Threshold 1 R_1

R_1 focusses on the landscape, soil, and abiotic conditions of the site. Occurrences have shown that mine soils are characteristically different from normal agricultural soil; they have poor soil-use properties (e.g., soil texture, void ratio, and pH) and behavioral qualities (e.g., infiltration, hydraulic conductivity, and soil strength). Additionally, the temperature [78] and presence of leftover contaminants/foreign materials may influence the soil pH and nutrients. However, an interacting and functioning balance is necessary within the soil components (physical, chemical, and biological) as well as its constituents (solid, liquid, and gas). Similar to experiences from Rosebud mine and Dave Johnson mine [79], this stage might take over three or four decades. Healthy soil function promotes robust productivity, functions and services. It requires collective efforts of multidisciplinary experts in both field and laboratory. In addition, is the identification of influencing drivers and trends such as socio-economic, biophysical, and technological [80], which brings about both quantitative and qualitative changes (pressures) and influence soil processes and functions (state).

The abiotic threshold indicators involve the landscape, micro-topography, contour and landforms, geology, soil profile and aggregates' formation, decomposition rates, basic net primary productivity, soil water (quality, quantity, and network), air quality (especially with crude oil exploration and gas flaring), and the soil sustainable properties. The key soil sustainable management indicators include the soil productivity (e.g., yield), soil organic carbon, physical properties (e.g., bulk density), and biological activities (e.g., soil enzymes, respiratory rate). Additionally, of importance are nutrients (e.g., Phosphorus being a stable and less mobile element), salinity, pH, exchangeable ions, and soil biodiversity such as microorganisms (bacteria, fungi, protozoa), meso-fauna (acari, springtails), and macro-fauna (earthworms, termites). Though R_1 focuses on the abiotic components, some biotic components are involved. This is due to the interlink between soil physicochemical properties and biological components, which is strong and cannot be overlooked [81]. These indicator thresholds can be categorized into different classes such as structure, composition, functions, etc. Ascribing values for the indicators is complex, as it depends on the spatial and temporal scale, data availability, as well as regional differences in climate, soil characteristics, and sophistication in measurements [82–84]. Moreover, an open and flexible approach is important [85]. Soil quality framework is an example of suggested tools for assessing site-specific soil conditions and developing adaptive management strategies, in addition to the use of indicators [86–88], soil quality index [12] as well as Status of the World's Soil Resources (SWSR), and Voluntary Guidelines for Sustainable Soil Management (VGSSM). Recommendable land-use options at R_1 are limited to less bio-demanding land use such as recreational, industrial, airports, schools, shopping centers, solid waste or rubble storage area, etc. This is due to its low biological integrity, resilience, and low self-improving capacity.

2.7. Reclamation Threshold 2 R_2

R_2 focusses on the biological properties of the ecosystem. It considers the community stands such as flora and fauna, functional aspects, which are enhanced by plantation, immigration and colonization. Attainment of this threshold stage strongly depends on the level of achievement or success in R_1, time (decades), goals/targets of the reclamation projects and land-use, and active involvement of expertise and stakeholders. A good example of immigration of species was reported in the Rhenanian brown coal post-mine district in Berzdorf region [89,90]. Though colonization depends on the immigration potential of the ecological species, other potential constraints exist such as:

(1) Activation of sulfuric acids by oxidation (e.g., lignite mine sites), it affects species (e.g., integument of earthworms), even if lime is used to increase the pH. Colonization of species with better acid tolerance is recommendable.
(2) Potential dry condition of most mine sites that influence substrate water repellent ability, vegetation, etc., and are detrimental to ecological species (e.g., mucous cover of epidermis).
(3) Limited availability of food especially at the beginning stage (e.g., litter falls) and microorganism biomass.

The biotic components at R_2 include nutrient cycling, energy flows, decomposition, recruitment (through reproduction and/or migration/colonization), available pollinators and dispersers, efficient symbionts (i.e., epiphytes, mycorrhiza), soil micro-biocenoses, animal biomass, survival of early successional native species that can develop into a structurally complex and diverse ecosystem. Additionally, population size of flagship species and key species might increase. These indicators can potentially measure complex interactions and significant ecosystem services return. Soil organisms are also good indicators [91–93]. This is due to their high sensitivity to anthropogenic perturbations, changes in land management practices, ecosystem functions, and climate. They can also be used to explain ecosystem processes simply and cost-effective [92]. The few species of soil taxa that remarkably and historically met this criterion include earthworms, insects such as mites, molds, bacteria, fungi, and Collembola. Although, representation of the key attributes and functional groups (more or less than taxa) in a way gives a picture of the threshold attainment and what to be identified, monitored and improved, only the use of indicators does not explicitly adapt probability of detection into its abundance or occupancy estimates. The recommendable land-use options at this stage include bioenergy croplands, forest, developed water resources, recreation (parks, hunting, bird watching, etc.), residential use/settlement, site improving, special reserve, etc. These land-use options are in response to its revamped biological integrity.

2.8. Reclamation Threshold 3 R_3

The arguments that mined site cannot be restored back to its pre-mining state, it can only be rehabilitated suggests true. However, a more improved condition can be reached. R_3 involves improving and refitting the sites to a defined endpoint. Similar to other threshold stages, it takes a long time. Take, for instance, spectrum of earthworm species inhabiting Berzdorf mine sites as presented in Table 2 [90]. It focuses on the ecosystem functioning, which depends on the integration of structural and functional components such as energy flow, nutrients/biogeological cycles, food web, diversity patterns, etc. It entails several considerations (e.g., new species introduction), practices (e.g., rotation/mixed cropping), and monitoring. The indicator threshold employable at R_3 focusses on improving the quantity and quality of R_1 and R_2 in relation to their structure (such as age, size, habitat quality and quantity, as well as connectivity). It includes composition (such as genetic diversity, sex ratio, etc.) as well as functions and services (such as reproduction, breeding rate and success, population viability, gene flow, adaptation, productivity/mortality, etc.). All land-use options are recommendable at this stage, especially croplands, and other agroecosystems including pasture, rangelands, which require high quality for its economic demands and adequate for human health.

Table 2. Spectrum of earthworm species inhabiting Berzdorf mining region.

Species	Brief Description	Years
Lumbricus rubellus rubellus	Epigeic species, saprophage, exhibit preference for high organic substrate	After 7 years
Lumbricus terrestris	Potentially used in stabilizing organic materials.	After 14 years
Dendrobaena octaedra	Small (2–4 cm), litter dwelling species, native to Europe.	After 6 years
Dendrodrilus rubidus rubidus	Native to Europe, small (<10 cm), pigmented epigeic species.	After 33 years
Aporrectodea caliginosa caliginosa	Endogeic species, found in first 15 cm temperate zones, used in ecotoxicological tests.	After 3 years
Aporrectodea rosea rosea	Has distinct seasonal clone structure, which proves ecological differentiation of clones.	After 10 years
Octolasion tyrtaeum	Cosmopolite species with two genetic forms small (4–8 cm) and large (10–14 cm).	After 10 years

3. Anticipated Targets and Endpoints

Setting endpoints and targets is a complicated task [79]. This is necessary at each threshold scale end. It is best achieved by active involvement of multidisciplinary stakeholders targeting a set of feasible ecosystem structures, compositions, functions and services, which then have to be discussed in a round table. Example of an applicable methodological approach is LDA (Linear Discriminant Analysis) [34]. Representation of success does not necessarily have to be static. It could be a successional trajectory towards a self-regulating functional ecosystem. Here, we identified three endpoints; (1) improved stage, (2) maintained state, and (3) deteriorating status (Figure 3). These endpoints are not only applicable at the end of R_3, it applies to each threshold level and depends on the land-use options and sustainable decision made by the multidisciplinary stakeholder's consortium. Deterioration might occur due to global increasing demand for the site's potential ecological resources, or insufficient/non-continuous monitoring, and this might cut across its sustainable values (i.e., social, economic, and environment).

4. Conclusions

This study gives a comprehensive approach applicable to national and international regulations guiding reclamation of post-mining sites. Although it is a step-by-step process with identifiable threshold describing the reclamation stages, however, it should be kept flexible as there could be possibilities of overlap from one threshold indicator to the other. This is true considering the differences in the causes and state of degradation. The identification of each threshold indicators does not explicitly adapt probability of a perfect condition, however, representation of the key attributes and functional groups can give a picture of the threshold attainment, what to be identified, monitored and improved while climbing the reclamation success ladder. With this approach, ascribing values for each threshold stage is complex with several limiting constraints; however, access to related datasets can be of help. In addition, future studies should focus on being detailed on the threshold values, measurements, assessments, and its harmonization. This time-scale conceptual model is not limited to post-mining sites; it is also applicable to other degraded ecosystems. It has representative pictures of levels that have been crossed and are to be crossed, and can be widely employed in restoration-related studies globally.

Author Contributions: Conceptualization, methodology, resources, writing—original draft, writing—review and editing, visualization, A.A.A.; supervision, validation, resources, writing—review and editing, visualization, D.F.; supervision, validation, resources, writing—review and editing, visualization, S.Z.; supervision, validation, resources, writing—review and editing, G.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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