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RESEARCH

Sustainable reclamation practices for a large surface coal mine in shortgrass prairie, semiarid environment (Wyoming, USA): case study

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Abstract

Sustainable reclamation practices for large surface coal mines in USA semiarid environment contribute to the quality of the environmental on a long term basis where environmental resources are protected for future generation. Land, after reclamation, must be suitable for the previous use of greatest economic or social values to the community area. In the semiarid climate of USA, non-developed land is mainly utilized for crops, grazing, and wildlife. Completion of various stages of the reclamation processes includes verification and approval of reclamation criteria and performance standards created by state agencies. The sustainable reclamation practices were investigated at the USA's largest surface coal mine of the semiarid environment in Wyoming. These practices include building post-mining topography to the approximate original contour and reestablish a stable hydrologic system to drain surface water. All available spoil material is backfilled and graded to achieve the post-mining topography which closely resembles the pre-mining topography. No overburden material or other coal waste material is left in stockpiles at the mine. Detailed planning until the end of mining, the knowledge of available volumes of suitable backfill material and soil is necessary for sustainable management practices. Diverse and permanent vegetation capable of stabilizing soil surfaces and capable of self-regeneration is established. Sustainable management of the reclamation effort is achieved by enforcement processes developed by the state and federal agencies. Monthly inspections of mining and reclamation operations and reviews of annual reports submitted by the operator help determine if the reclamation processes are occurring according to the permit plan.

Keywords Post-mining topography · Revegetation · Hydrology · Soil salvage · Inspections · Enforcement

Abbreviations

AOC	Approximate Original Contour
LQD	Land Quality Division
NARM	North Antelope Rochelle Mine
PMT	Post Mining Topography
OSMRE	Office of Surface Mining and Reclamation Enforcement
SMCRA	Surface Mining Control and Reclamation Act
WDEQ	Wyoming Department of Environmental Quality

1 Introduction

Sustainable practices means practices that contribute to the quality of environment on a long-term basis and environmental resources are protected and maintained for future generations (Kates et al. 2005). Information on reclamation efforts of surface coal mines including complex approach and discussing rebuilding topography, soil management, restoring hydrology, re-vegetation strategies for the North western High Plains of mountain western states is rare (USA Congress, Office of Technology Assessment 1986; Steward et al. 2006).

A surface coal mining permit must comply with regulations and performance standards of the USA Federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Public Law 95-87, referred to as SMCRA), state programs and other federal environmental acts (USA Government Publishing Office 2016). SMCRA's major components were incorporated into the specific state laws.

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Such as e.g. Wyoming Quality Act and Industrial Development Information and Sitting Act giving the Wyoming Department of Environmental Quality (WDEQ)/Land Quality Division (LQD) authority to establish standards for reclamation (Wyoming Statues Annotated 2018).

The major reclamation criteria and performance standards include as follows: rebuilding approved Post-Mining Topography (PMT) and drainage systems, reconstructing stream channels, applying soil, establishing vegetation, restoring approved post-mining land use, evaluating post-mining groundwater and surface water quantity and quality to support land use (Krzyszowska Waitkus 2018).

The performance of reclamation requirements is secured by the operator through submitting financial assurances to the state agency sufficient to pay for the reclamation (reclamation bond) in case of company bankruptcy (Bonogofsky et al. 2015). Reduction of the reclamation bond occurs after verification and approval by the state and federal regulators specific bond release criteria and performance standards. In Wyoming, there are the following bond release phases: Area bond, Phase 1, Phase 2, and Phase 3 (Krzyszowska Waitkus and Blake 2011; Krzyszowska Waitkus 2018). Area Bond and Phase 1 is defined when the operator completes backfilling, regrading, soil replacement, and drainage control of bonded areas. Phase 2 includes verification and approval of an erosionally stable area where the permittee has established vegetation cover with species that are commensurate with that of the seed mixes of the approved reclamation plan. Construction of all permanent impoundments approved in the permit must be completed. For Phase 3, all surface coal mining and reclamation activities including successful revegetation, rebuilding a hydrology system that supports post-mining land use, rebuilding wetlands and establishing tree regrowth are completed (Table 1). These phases are indicators of completed reclamation phases of mining disturbed land. The reclamation plan coordinates with the mining plan and contains a time schedule to complete reclamation phases as quickly as possible.

In the USA, any mining permit can't be approved without presenting a reclamation schedule. Mining and reclamation information is included in the mining permit approved by state and federal agencies (Krzyszowska Waitkus 2018). Surface coal mining permits are issued for a term of five years, after which the operator (permittee) must submit a revised permit for the next term renewal. Field and annual report verification of permit commitments, reclamation criteria and performance standards allow the state control and final approval of land that has been reclaimed (Fig. 1).

WDEQ/LQD inspectors and permit coordinators verified state rules and regulations, permit commitments, and performance standards through monthly field inspections and reviews of annual reports submitted by the operator. On the basis of such activities, the WDEQ/LQD, can ask for permit revisions. Also, the state agency can issue a formal notice of violation where site conditions constitute an existing or potential danger to the health and safety of the public, or can cause or be expected to cause environmental degradation (Fig. 1).

Table 1 Major criteria and performance standards for various stages of reclamation (bond release phases)

Stages of reclamation (bond release phases)	Major criteria and performance standards
Area bond	Backfilled and graded to the approved PMT
Phase 1	Stream channel reconstruction and drainage system functionality established
	Salvaged soil applied
Phase 2	Vegetation established (no quantitative data)
	Surficial stability achieved
	Design of permanent ponds approved
Phase 3	Post-mining land use restored
	Revegetation, shrub and tree replacement approved (quantitative data)
	Post-mining groundwater recharge capacity and surface water quantity and quality evaluated to support the land use
	Functional post-mining roads
	All temporary structures removed
	Wetlands mitigated

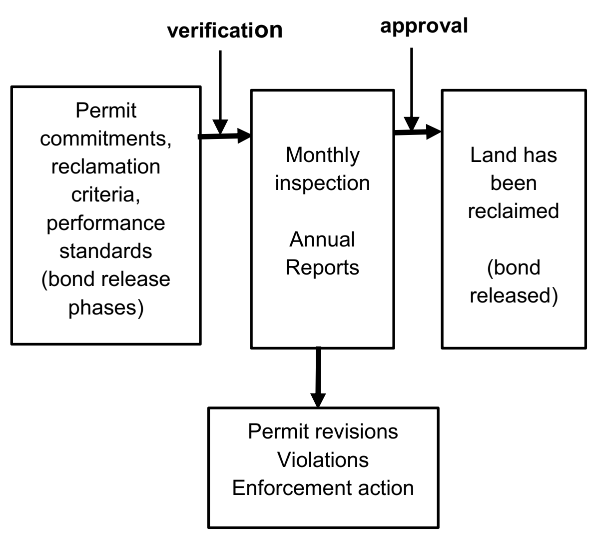

Fig. 1 Management of a surface coal mine permit

This paper discusses sustainable reclamation management practices for a large surface coal mine located in a semiarid environment (less than 300 mm rain/year) of the shortgrass prairie in Wyoming (one of the US western states). The North Antelope Rochelle Mine (NARM) located in northeast Wyoming is the world's biggest coal mine by reserves producing over 66 million tons of clean coal (0.2% sulfur) in 2020. Since the initial operation began in 1982, approximately 12,667 ha have been disturbed as of 2020. Total reclaimed areas, as of 2020, included 5764 ha of areas backfilled and graded with various phases of reclamation (North Antelope Rochelle Mine, Annual Report 2020). Information included in the NARM permit is referred as Permit 569-T8 (Permit 569-T8 2014).

2 Sustainable reclamation management practices

Reclamation of all affected coal mining lands should be restored to a condition equal to or greater than the "highest previous use" in western states of the USA (Wyoming Administrative Rules 2012). The operator of western states mines must restore land to the Approximate Original Contour (AOC) by backfilling, grading and compacting, minimizing disturbance to the hydrologic system, establishing permanent vegetation cover according to the approved post-mining land use while reclaiming land as soon as possible.

Reclamation of a large surface coal mine can be successful in a disturbance sensitive, semiarid environment (Steward et al. 2006). The critical part of the reclamation planning is the knowledge of the pre-mining environmental conditions (Norton et al. 2010). In the NARM's permit more than 60% of the information consists of pre-mining baseline data. According to rules and regulations the following information is required for the baseline portion of the permit: land use, archeological data, climate, topography, geology and overburden assessment, hydrology, soil assessment, vegetation inventory and wildlife use (Krzyszowska Waitkus 2018; Wyoming Statues Annotated 2018; Wyoming Administrative Rules 2012). Rebuilding post-mining topography to blend with surroundings, reconstructing drainage system that tie into existing drainage pattern outside the disturbed area, replacing soil to achieve required thickness according to the approved permit, and establishing permanent vegetation cover will be specifically discussed on the basis of this large surface coal mine to show various sustainable reclamation management practices.

2.1 Approximate original contour

The recontoured surface design has critical effects on post-mining vegetation (Fleisher and Hufford 2020), land stability (Bell et al. 1989), and post-mining land use (USA Congress, Office of Technology Assessment 1986). The creation of a stable land landscapes supports reclamation goals and subsequent land uses (Toy and Black 2000).

Operators of coal mines in majority of the USA states must rebuild topography to the Approximated Original Contour (AOC) unless specifically exempt due to excess of lack of sufficient overburden material. According to SMCRA definition's of the AOC, the surface configuration is achieved by backfilling and grading of the mined area so that the reclaimed area, including any terracing or access roads, closely resembles the general surface configuration of the land prior to mining and blends into and complements the drainage pattern of the surrounding terrain. All highwalls, spoil piles, and coal refuse piles are eliminated and are not allowed to be left at the reclaimed mine (Electronic Code of Federal Regulations 2022). The significance of building AOC affects the necessity of analyzing pre-mining topography and slope distribution, volumes and suitability of the overburden material, volumes and suitability of backfill material, measurements of swell factor, and pre mining and post-mining slope distribution analysis (Table 2).

Decisions regarding landform shaping usually are a balance between mine planning, mining methods, geomorphic processes, and economics (Stowe 2006). Some operators use custom designed software programs created by specialized consulting companies for these procedures. Traditional landform reconstruction is characterized by uniform topography and linear slopes. A novel approach to landform grading is called GeoFluv that is the basis of the Natural Regrade computer software module (Bugosh 2009). This fluvial geomorphic approach to land reclamation creates a landform that would naturally tend to erode under the climatic conditions, soil types, and slopes present at the site. The resulting slopes and stream channels are stable because they are in balance with these conditions. The geomorphic reclamation approach combines hydrologic and hydraulic engineering analyses with geomorphic design tools to stabilize and reclaim mining area (Spotts et al. 2013; Hutson and Thoman 2014; Carlson et al. 2014). This is a reclamation alternative to uniform slopes with terraces and down-drains (Bugosh 2004). It was found that geomorphic reclamation leads to greater species diversity and richness with a higher percent cover of shrub species in reclaimed sites in Wyoming (Fleisher and Hufford 2020).

At NARM post-mining topography design is created using aerial photos collected monthly (from a plane) and

Table 2 Important factors to rebuild topography (AOC)

AOC	NARM's permit
Rebuilding post-mining topography (various models)	Maptek Vulcan for an Open Pit
	Mine Planning and AutoCad with QUICKSURF and Auto List (custom design)
Volumes of needed backfill material (end of mining)	8.4 billion m^3
Swell factor range	11.8%–19%
Swell factor average	15%
Suitability of overburden and backfill material	Guideline No. 1 (Wyoming Department of Environmental Quality 2021)
Post-mining slopes	Slopes flatter than 25% (14°)
	Shape: complex
	Length < 150 m

through a trial and error process to find the correct volume to fill specific voids and using various computer programs.

Such computer programs are e.g. Maptek Vulcan for the Open Pit Mine Planning and AutoCad with QUICKSURF and Auto List (custom written language) (Table 2).

According to the permit prediction, by the end of mining (2039), the volume of material needed for backfill was estimated as 8.4 billion m^3 (Permit 569-T8 2014). It was estimated that by the end of mining, there will be a need to borrow approximately 3% of the total backfill volume. The operator demonstrates the ability to achieve AOC through estimation of backfill material volume available for backfilling and the calculation of bulking factors (swell factors). The swell factor affects the amount of borrow material required to fill the final pit and the elevation and relief of the post-mining topography. The average swell factor for NAMR was estimated to be 15% (Permit 569-T8 2014), while the swell factor for material compacted by shovel/truck operation was 11.8% and by a dragline was 19% (Table 2).

The studies of the significance of the chemical properties of backfill material in western states on revegetation success (Sheley et al. 2008) and water quality (Murphree 2005) are rare. All backfill material must be suitable according to chemical properties described in Guideline No. 1 (Wyoming Department of Environmental Quality 2021). A specific monitoring program for overburden/backfill sampling and unsuitable mitigation procedures is presented in the permit (Krzyszowska Waitkus 2018; Permit 569-T8 2014). Best sustainable management practices concerning successful revegetation are directly involved with chemical properties of backfill material where unsuitable backfill material are buried under at least 1.2 m of suitable material. In some cases lime is mixed with backfill material to lower the acidity. Backfill suitability is accounted for when designing mining benches and when overburden is removed by truck/shovel operations. Material removed by the dragline operation is not specially handled based on the suitability criteria due to mixing overburden material in several ways.

The goal of rebuilding landscape is to minimize production of sediment and to create erosionally stable slopes. In Wyoming's semiarid environment, a complex (convex on top and concave at bottom) slope of less than 25% (14°) has been found to be least prone to erosion (Stowe 2006). Slopes steeper than 33% (18°) should be reduced to 33% or less while maintaining ridge break lines and channel flow lines if possible (Hutson and Thoman 2014). In Wyoming, to avoid long uniform slopes, constructed slope lengths should not exceed pre-mining lengths and should be shorter than 150 m long (Table 2). No highwalls may be left unless they are approved by the Administrator of the WDEQ/LQD. In NARM's permit, slope distribution analysis (pre- and post-mining) is performed using a remote sensing method (LIDAR) for the slope distribution analysis data (Permit 569-T8 2014).

2.2 Hydrology

The rebuilt topography and rebuilt drainages must tie into established drainage patterns of the terrain existing outside the mining area. In Wyoming, the hydrologic control plan for the large surface coal mines include monitoring plans for surface water and groundwater prior to mining, during the mining and post-mining environments. Sustainability of reclamation practices, in the case of hydrology, involves monitoring water quantity and quality (Table 3). Reclamation at the mine is controlled by points where drainages meet the pre-mining drainage elevations. Drainage divides must match those of the approved post-mining topography presented in the permit to restore watersheds. Water originating upstream from the mine must be available for downstream use. Therefore, at the large surface coal mines, during the mining process, it is essential to construct erosionally stable stream diversions that are designed to withstand flooding events together with other sediment control structures used to prevent water pollution (Ferris 2006).

At NARM, the surface water control plan includes building sedimentation reservoirs, sediment traps, culverts, stream diversions, flood control reservoirs and permanent reservoirs to minimize the effect of mining on surface water quality and quantity. Design requirements for each of the structure are listed in Guideline No. 8 (Wyoming Department of Environmental Quality 2021) and design statistics for sedimentation reservoirs for specific pits are listed in the permit (Permit 569-T8 2014).

At NARM, watershed and stream channel characteristics for the pre-and post-mining conditions are described in the approved permit (drainage area, stream length, elevation

Table 3 Watershed parameters for major drainages at NARM (Permit 569-T8 2014)

Watershed parameters	Pre-mine	Post-mine
Major drainage basins	24	24
Drainage area (km^2)		
Range (km^2)	0.2–246	0.8–248
Average (km^2)	11	17
Maximum basin relief (m)		
Range (m)	19–221	26–221
Average (m)	85	93

difference). There are 24 major drainages at NARM and the reconstructed drainage basins areas are similar with higher elevation differences for post-mining drainages (Table 3) (Permit 569-T8 2014).

At NARM during mining and post-mining five monitoring stations are setup on upstream and downstream drainages passing through the disturbed area to control water flow and collect water samples to be analyzed for chemical properties according to Guideline 8 requirements (Wyoming Department of Environmental Quality 2021) and permit commitments (Permit 569-T8 2014). At NARM, surface water quantity is monitored by continuously recording data of drainages flowing through the mine permit. These data are collected both prior to mining and during mining and are used to run models for surface runoff (Permit 569-T8 2014). Results are presented in annual reports and analyzed by the WDEQ/LQD specialist to determine if the area can achieve the post-mine land use.

Mining and reclamation procedures result in the replacement of the overburden material and coal groundwater storage formation with unconsolidated backfill materials. The lithological materials in the backfill aquifer will be the same as the overburden but the bedding and arrangement of materials will be different. The backfill aquifer is predicted to saturate over time. The differences between the reclaimed and pre-mine aquifer characteristics may alter the groundwater flow regime. In Wyoming, according to Guideline No. 8 (Wyoming Department of Environmental Quality 2021), the primary goals of the long-term monitoring strategy is to track mine related impacts to, and recoveries of the groundwater system throughout the mining and the post-mining monitoring periods. NARM's groundwater well locations depended on the local geology of the area and permeability of the material. At NARM, there are 67 wells in 5 aquifers where approximately one well is located on 260 ha (Wyoming Department of Environmental Quality 2013). Static groundwater level and water quality data are collected from the monitoring wells on a quarterly, semi-annual or annual basis depending on individual locations. Groundwater drawdown analysis are performed in the overburden material to analyze the impact of coal mining (Permit 569-T9 2014) on groundwater resources.

The goal of the reclaimed mine land is to support the post-mining land use by minimizing disturbance to the hydrologic balance. For a large surface coal mine, an evaluation of groundwater level recovery and groundwater chemistry in the backfill aquifer is modeled. The specialist at NARM performs Probable Hydrologic Consequences (PHC) studies during and for post-mining conditions and produces a groundwater model including estimates of recovery time in the cumulative impacted area (Permit 569-T8 2014). The WDEQ/LQD specialist also performs a Cumulative Hydrologic Impact Assessment (CHIA) of coal mining in the basin where multiple coal mines are operating (Wyoming Department of Environmental Quality 2013). All modeling and assessment are completed to provide answers to questions whether groundwater quality of the backfill aquifer within the mine permit boundaries is able to support the approved post-mining land use and if there is a significant long-term or permanent adverse change to the surface water quality according to their use.

2.3 Soil salvage

The importance of salvaged soil in achieving successful reclamation results in the arid environment is well documented (USA Congress, Office of Technology Assessment 1986; Steward et al. 2006; Norton and Strom 2011). Important factors of soil management include the knowledge of soil mapping units before mining, soil suitability, soil salvage and application depths.

Soil physical and chemical properties indicate the suitability of the soil for plant survival and growth (Wright and White 2000). In Wyoming prior to mining, according to Guideline 1 A, all soil is surveyed and at least one soil sample for each soil series is collected and analyzed for pH, conductivity, textures, particle size, sodium absorption ratio, selenium, and boron (Wyoming Department of Environmental Quality 2021). In NARM's permit, the following information is presented for each soil mapping unit: surface of areas from where soil is salvaged, average soil depth, and volume of soil being salvaged (Krzyszowska Waitkus 2018). NARM's permit map titled Topsoil Resource, has approximately 194 soil mapping units identified where the soil depth varied from 5 to 150 cm (Permit 569-T8 2014) (Table 4).

At NARM, ahead of mining, the suitable soil depth is marked (marker, stakes) in the field by the operator's specialist for equipment operators. During salvaging, pedestals of soil are temporarily left for inspection purposes to verify salvage depths (one per 0.8 ha or on 150 m centers). Each pedestal is labeled with the actual soil removal depth. Such knowledge of the balance of all suitable and available soil is a very important step for successful reclamation and is used for the calculation of the necessary soil depth application according to the permit commitments (Table 4). Salvaged soil is stored in stockpiles or is hauled directly to graded areas (Steward et al. 2006). At NARM the volume of cumulative soil at the end of mining (2039) is estimated to be 123 million m^3 (Permit 569-T8 2014) (Table 4).

It was found that the best reclamation result in Wyoming is achieved by direct haul of suitable soil from a stripped area to an area of soil application (Schuman 2002; Anderson et al. 2008). Caution should be taken if noxious weeds are present in an undisturbed area.

After soil is salvaged, the overburden material before being removed is ripped to prevent dust erosion. Ripping overburden material by heavy equipment significantly improves dust control of bare areas without vegetation.

2.4 Soil application and seedbed preparation

After area is backfilled, salvaged soil is applied on graded and scarified areas as soon as possible. According to state rules (Wyoming Administrative Rules 2012), the backfill surface is scarified by deep ripping along the contour to minimize erosion and instability before soil is replaced on the regraded area. According to the operator's experience, best results for soil salvaging and replacement occur when soil is dry. This is in accordance with results found in eastern states preparing soil for tree growth (Sweigard et al. 2007).

Soil structure and properties are changing during salvaging, storing and application at surface coal mine operations (Feng et al. 2019; Ingram et al. 2007). Respreading soil increases mineralization and mineral nitrogen rapidly mineralizes to nitrates and ammonium (available for plants). Therefore, fertilizing with nitrogen after respreading of soil is not necessary due to the fast mineralization of nitrogen in contact with oxygen (Mason et al. 2011). There was no significant differences in plant or soil characteristics compared to nitrogen fertilizer treatments (24 years after amendment) (Bowen et al. 2005). Adding nonessential nitrogen can reduce important mycorrhizal activity and encourage heavy weed growth. Rarely is nitrogen needed for native species, such as bluebunch wheatgrass (*Pseudoroegneria spicata*) (Sheley et al. 2008). At coal mines in Wyoming, additional sources of nitrogen are not added to soil.

Table 4 Soil salvage management

Soil management	NARM's permit
Soil mapping units prior to mining	195 soil units
Soil suitability (chemical and physical properties)	Guideline 1A (Wyoming Department of Environmental Quality)
Marking suitable soil depth in the field	range: 5–150 cm
Suitable soil volumes (end of mining)	123 million m^3
Soil depth application	Variable 15–76 cm—typical 76–122 cm—deep

In some mines e.g. New Mexico, mycorrhizal inoculant is one of the bioengineering methods used to promote plant growth, increase uptake of mineral nutrients, and reduce tolerance to stress (Harrington et al. 2001). The addition of biotic soil amendments, in semi-arid environments, such as: mycorrhizal inoculum, fertilizer, humates, biochar, manufactured growth media could be considered for specific sites (Fresquez and Lindemann 1982; Vogelsang et al. 2004; Koide et al. 2015; Xiao et al. 2016).

After a reclaimed area is backfilled and graded to the approved post-mining topography, soil is replaced to achieve thickness according to the approved permit. Usually, soil is applied at the uniform depth calculated from the pre-mine volumes of the specific soil mapping units. However, NARM introduced the variable soil depth application method to increase the revegetation effort (Permit 569-T8 2014) (Table 4). Some studies indicate that variable soil depth can improve revegetation productivity or species diversity (Redente et al. 1997; Buchanan et al. 2005; Bowen et al. 2005). Soil variable depth is needed more for the initial establishment than for long-term development of plant communities (Wick et al. 2005). It takes approximately 10–15 years for the reclaimed soils to recover structurally towards a native soil condition (Wick et al. 2009).

The most important factor after soil application is to avoid soil compaction. The compaction of soil affects soil physical properties: texture, porosity and permeability, density, and infiltration rate. It was found that the pre-mining infiltration rate of soil will recover in 20–25 years in reclaimed surface coal mines in Wyoming (Reynolds and Reddy 2012).

NARM's operator committed to leave soil in a roughened condition until establishing revegetation cover (Permit 569-T8 2014). Soil is roughened to decrease compaction, increase water infiltration and increase plant rooting depths. It is well known that the degree of compaction could be lessened through proper soil handling procedures using e.g. various types of ripping equipment (Phelps and Holland 1987). To minimize compaction of replaced soil, the operator committed to minimize equipment travel over the reclaimed area (Permit 569-T8 2014).

Preparing soil before applying seed is a very important sustainable reclamation practice in semiarid climate where seeding on properly prepared soil, without watering, is extremely important for achieving revegetation success (Carlson et al. 2014). Seedbed preparation management creates firm soil beneath the seeding depth, increases water infiltration and soil moisture, improves soil texture and root growth, and controls weeds (Neff 1980; Monsen and Stevens 2004).

In semiarid environments seedbed preparation include applying three phases of tillage (primary, secondary and finish), growing a cover crop (temporary vegetation), mulching and mulching alternatives, erosion and sediment control techniques. At NARM, the seedbed preparation method depends on the desired seeding method (Table 5). For instance, for broadcast seeding only primary tillage is used (roughened seedbed), while secondary tillage or final tillage is used in areas utilizing drill seeding (Permit 569-T8 2014).

The primary tillage using deep riper and deep chisel plows rips soil while loosening compacted soil and backfill material increasing water infiltration deeper into sediment. Secondary tillage using disking and chisel plowing breaks soil clods and incorporates any plant residue (Strom et al. 2010). Ripping or disking soil should always be done on the contour and preferably when soil is relatively dry (Wright and White 2000). The finish tillage with a cultipaker or roller harrows firms and makes soil smooth in preparation for seeding.

In semiarid environments, when establishment of permanent vegetation takes time, operators use cover crops as a temporary management measure. Cover crops are small grain crops (barely, millet, oats) seeded to prevent soil erosion and suppress weeds prior to perennial forage establishment. At NARM such temporary seeding at the rate of 11–28 kg/ha occurs usually by the end of May or in June (Table 5). Later, at NARM, the cover crop (barely, wheat or millet) is disked into the soil and act as mulch or left as standing stubble before final seeding (Table 5). For example, it was found that barely stubble mulch resulted in significantly higher biomass of seeded grass species than crimped straw mulch (Pinchak et al.1985).

Mulching is a very important management practice when moisture is the primary limiting factor for revegetation (Dooley and Perry 2013). Mulching creates an environment that provides conditions encouraging seed germination and seedling growth by increasing soil stabilization and moisture retention, increases organic matter, insulates seed and seedlings against extreme climate conditions and prevents erosion (absorbs energy of raindrops). At NARM, mulch, after application is anchored immediately by crimping, tacking, disking or covering with netting to avoid being lost through wind activities. Additionally, riprap, gabions, geoweb, hydromulching, soil binders and tackifiers, erosion control blankets or bonded fiber matrix help prevent erosion and reduce sedimentation (Rivas 2006; Permit 569-T8 2014) (Table 5). Their uses depend on site accessibility, soil characteristics, and slope configuration. Mulching alternatives include rock mulching and pitting (gouging) in harsh geological conditions.

Table 5 Seedbed management techniques

Seedbed preparation management	NARM's permit
Tillage: primary, secondary, final	Depends on the seeding method
Cover crop (temporary vegetation)	barely, wheat, millet 11–28 kg/ha
Mulching and other erosion control techniques	Stubble mulch, native hay, other method (e.g. hydromulching, rock rip-rap, gabions, erosion control blankets)
Sediment control techniques	Straw bales, check dams, silt fences, berm, contour furrowing, pitting, sediment basin, mulching/revegetation, containment diches

All these conservation seedbed practices reduce soil erosion. However, in case of creating sediment from erosion there are techniques for containing sediment. Sedimentation following erosion requires a pond or structure designed to capture runoff from disturbed areas for the purposes of treating water for sediment and suspended solids removal. Besides, sediment pond structures, other methods are implemented in the mine areas. All of them are temporary such as silt and filter fences, straw bale barriers, rock riprap, gabions, wattles or filter socks (Lorch and Wyatt 2000). At NARM alternate sediment control measures such as straw bales, check dams, silt fences, berms, contour furrowing, pitting, sediment basins, mulching/revegetation, and containment diches are used to prevent sediment from leaving a disturbed area (Table 5). They are removed when sedimentation processes are eliminated from the site by establishing permanent vegetation cover.

The main method controlling surface water runoff during the life of the mine are flood control and sedimentation reservoirs. At NARM, the amount of the sediment potentially eroded from a drainage basin and stored by sediment ponds is calculated using Revised Universal Soil Loss Equation (RUSLE) (Toy and Foster 1998) and/or using Sediment Erosion, Discharge by Computer Aided Design (SEDCAD) software program (Hoomehr and Schwartz 2013) or by actual field measurements. This way the operator calculates the sediment pond capacity preventing sediment from leaving a disturbed area and creating sustainable management practices. In Wyoming sedimentation reservoirs may be removed with the permission of the WDEQ/LQD if the predicted average sediment yield is less than the pre-mining estimated sediment yield.

The process of soil formation, which is slow in nature, is presumed to occur faster on reclaimed mine sites when vegetation is successfully established (Spasić et al. 2021). In Wyoming it takes approximately two to three years for native plants to start growing following the time of planting seeds. According to the Guideline No. 25 (Wyoming

Department of Environmental Quality 2021), the time period for bond release of an area seeded with permanent vegetation cover is 10 years. For such dry climate, the revegetation will develop sufficient plant cover after an average of 10 years where plant production and species diversity is comparable to adjacent undisturbed areas.

2.5 Revegetation

In mountain western states revegetation management methods vary depending whether it is for grazingland, cropland, or wildlife use. Permanent revegetation must be diverse, effective, and comprised of species native to the area. The plant cover should be capable of stabilizing soil surface and capable of self-regeneration and plant succession. Most wildlife habitat restoration plantings contain a mixture of woody and herbaceous species differing from the typical livestock range planting with a limited number of herbaceous plants, mostly grasses. The revegetated area must support the approved post-mining land use.

In cases where the land is reclaimed using native plant communities, vegetation is established through planting designed seed mixes, with specific seeding rate, seeding depth, and during specific time periods (Sheley et al. 2008; Strom et al. 2010).

Native species represent a genetic product of an environment and are adapted to the means and extremes of an area (Hufford and Mealor 2014). Especially, in semiarid climate drought tolerant seeds have evolved to such conditions. Therefore, native species tolerant to dry condition do not required watering. At NARM, planted seed mixes have never been watered. Uses of native species promote ecologic stability and plant community integrity and reduce the risk of seeding an aggressive or invasive species (Mangold et al. 2008).

The dominant native plant species are well adapted to low soil nutrient conditions (Ingram et al. 2007). Selection of adapted seed sources may improve the short-term establishment of plants as well as the long-term sustainability of plant and animal communities at reclamation sites (Hufford and Mealor 2014). Certain introduced species might also express excellent drought tolerance. Therefore, species seeded in arid sites must be carefully chosen (Monsen and Stevens 2004). Typically seed mixes include shallow- and deep-rooted forbs and grasses that grow early and late in the year, maximizing nutrient and water use.

The pre- and post-mining vegetation communities are delineated on the NARM's permit map. NARM's permit includes the list of reclamation seed mixes and various types depend on the pre-mine plant communities and post-mine topography. NARM's permit include a table of areas planted with various seed mixes and estimated locations shown on a map. The operator established various post-mining vegetation type seed mixes comparable with pre-mining vegetation types that are typical for: grassland, sagebrush grassland, riparian, playa, sagebrush mosaic as well as wetland (Table 6).

The use of native species has been maximized with necessary introduced species (Permit 569-T8 2014). The list of seed mixes include cool season grasses e.g. western wheatgrass (*Pascopyrum smithii*), warm season grasses e.g. blue grama (*Bouteloua gracilis*), forbs e.g. northern sweetvetch (*Hedysarum boreale*), and shrubs e.g. rubber rabbitbrush (*Ericameria nauseosa*).

The operator plans ahead where to plant specific seed mixes. Seeding rates are calculated for specific seed mixes. The seeding rate varied from 5 to 14.5 pure live seed kg/ha (average 13.1 kg/ha) (Permit 569-T8 2014) (Table 6). Seeding rates depend on seedling vigor, site conditions, and components of seed mixes (Williams et al. 2002). Also, competitive interactions should be considered when e.g. a high rate of grass seed application might prevent establishment of shrubs (Schuman et al. 2012). Shrub reestablishment on reclaimed mined lands is a very important factor for improving wildlife habitat (Olson et al. 2000). Deep rooted shrubs such as e.g. big sagebrush (*Artemisia tridentata*), rubber rabbitbrush (*Ericameria nauseosa*) or fourwing saltbush (*Atriplex canescens*) can utilize resources from the lower soil profile throughout the growing season (Sheley et al. 2008).

Timing of seeding is a very important element for the revegetation success (Mangold et al. 2008). The correct time of seeding depends on the soil texture and the species being seeded (Sheley et al. 2008). The best planting season is just before the favorable conditions for the specific plant species. In the semiarid western states, this is a period of sufficient moisture and soil temperature high enough to encourage germination. For example, dormant seeding between October 15 and April 15 is the most effective across Wyoming because early spring is the most reliable period for moist soil conditions (Strom et al. 2010) (Table 6).

Seeding techniques depends on: site accessibility, topography, seedbed characteristics, and economy (Vogel 1987; Steward 2006). Several seeding methods utilized at NARM includes drill seeding, broadcast seeding, hydroseeding and transplants (Table 6). At NARM, drill seeding dominates over broadcast seeding in mining reclamation. Drill seeding allows for more rapid seed germination with a more precise seeding rate capability and controlled seeding depth. Broadcast seeding works well with mixtures of different size seeds requiring a more shallow planting depth and usually requiring a higher seeding rate than seed drilling (Permit 569-T8 2014). Very important is also the depth of seeding, e.g. shrub seeding prefers shallower depths. At NARM, this requirement is utilized by different seeding equipment. Hydroseeding has typically been utilized for steep slope

Table 6 Seeding factors, NARM

Revegetation	NARM's permit
Pre-mining vegetation types	Big sagebrush grassland, breaks grassland, meadow grassland, playa grassland, salt grassland, scoria grassland, upland grassland
Post-mining vegetation types	Grassland, riparian grassland, sagebrush grassland, playa grassland, 10% shrub mosaic, 20% sagebrush mosaic, and tree/shrub complex
Seeding rate	5–14.5 (13.1 average) pure live seed kg/ha
Seeding time	Mid-October to mid-April
Seeding methods	Drill seeding, broadcast seeding, hydroseeding and transplants

stabilization or hard to reach areas. Transplants of containerized or bare root stock can be utilized on special areas along drainages as was done in case of willows at NARM.

There is a commitment at the NARM's permit regarding weed control. All revegetated areas is managed to prevent weed and/or insect infestation. During the first two growing seasons, mowing prior to seed maturity is utilized and later appropriate herbicides and/or pesticides are utilized (Permit 569-T8 2014).

Most successful sustainable reclamation practices involve seeding native plant species at the specific depth, specific rate, and at the best time which in semiarid areas is usually spring or fall. The measure of the revegetation sustainability is achieved by comparing data (vegetation cover, production, density and distribution, species diversity and species composition) from an undisturbed area (reference area) with the revegetated area (Bilbrough and Howlin 2012).

3 Contemporaneous reclamation

According to WDEQ/LQD rules and regulations "*Reclamation must begin as soon as possible after mining commences and must continue concurrently until such time that the mining operation is terminated and all of the affected land is reclaimed*" (Wyoming Administrative Rules 2012). Planning time schedules of specific phases of mining and reclamation is the key for a sustainable reclamation effort. The permit must contain a time schedule to address the following: mining progression, soil removal, overburden removal, backfilling, grading, contouring, soil application, and seeding. At NARM's permit, the time schedule uses yearly blocks overlaid on disturbed areas for five years followed by blocks of five year periods until the end of mining (Krzyszowska Waitkus 2018). These plans in a form of maps are included in the permit from the beginning of the operation. Mining companies need to plan for, prepare, and actually "mine for closure" right from the start of a project (Slight and Lacy 2015). Detailed mine planning including detailed land use plan requires involvement of many specialists including mining, environmental and civil engineers, hydrogeologist, or plant specialists (Kuter 2013). Detailed reclamation planning requires detailed knowledge of the baseline (pre-mining) conditions (Norton et al. 2010; Krzyszowska Waitkus 2018). Pre-disturbance database information is very important for reclamation planning. NARM's permit contains 62% information regarding baseline data on topography, soil assessment, geology, overburden assessment, and vegetation inventory (Permit 569-T8 2014).

Reclamation shall begin as contemporaneously as practical following coal removal and then continue concurrently with mining activity. It is often necessary to consider future expansion by amendment in the scheduling of backfill progression and design of post-mining topography. Backfill and graded areas are designed for contemporaneous reclamation and the operator will backfill and grade areas as they become available. In the case of NARM, as overburden removal sequence progresses into newer mining areas, some borrow material is required. The borrow volume is presented in the reclamation plan. Temporary overburden stockpiles will need to be constructed and rehandled to achieve final post-mining topography. Material handling summary including volume and areas from where soil is salvaged and to where it will be replaced, volume and hectares of material being backfilled, hectares of area being seeded, and volumes of material in overburden stockpiles is listed in the NARM's permit for every year of the permit term (five years) and later for five years blocks until the end of mining. Such mass balance together with spatial presentation on maps is helping to achieve contemporaneous reclamation results.

4 Enforcement

The WDEQ/LQD representatives are verifying permit functionality and compliance features as well as bond release requirements through monthly field inspections and reviews of NARM's annual reports.

4.1 Inspections

According to the SMCRA federal act (USA Government Publishing Office 2016) and state rules (Wyoming Administrative Rules 2012) all active surface coal mining and reclamation operations must be inspected on an irregular basis every month. All inspections must occur without prior notice. As a result of the inspection, the state inspector submits a list of maintenance, recommendation and monitoring items as well as issuing any violations.

In Wyoming, the majority of the reclamation criteria and performance standards are verified in the field during monthly inspection. The WDEQ/LQD inspector assesses mining and reclamation activities, assesses all compliance features, and verifies compliance with regulatory requirements and with permit commitments. Additionally, specific reclamation criteria and performance standards (e.g. backfilling, soil replacement, drainage construction, revegetation, etc.) for bond release purposes are verified in the field by joint inspection of the land owners, permit operator, WDEQ/LQD inspectors, and Office of Surface Mining and Reclamation Enforcement (OSMRE) representatives.

The goal of inspections is to compare mining and reclamation progress occurring in the field with the approved permit plan. The WDEQ/LQD inspector reviews e.g. the progress and locations of grading, soil salvage and soil application, hydrological control, revegetation rate (phases of seedbed preparation, seed mixes, planting etc.), erosion and sedimentation control structures. For example, the state inspector verifies in the field if constructed PMT's match approved topography in the permit. The restored stream channels and permanent diversions in the field are compared with the approved design. All slopes are inspected for the erosional features and checked if eroded sediment is not leaving the permit boundary (off-site impact). All sediment ponds are inspected for adequate capacity to store sediment. The WDEQ/LQD inspector checks if the plant species being seeded are compatible with the post-mine land use, if weeds are present and require control, if revegetation is capable of self-generation and if mulching and other soil stabilizing measures are being used. These are just examples of the inspection goals requiring detailed knowledge of all reclamation phases, permit commitments and state rules and regulations (Vogel 1987).

Keeping track of all of this information on hundreds of parcels or reclaimed land represents a challenge for the regulatory agency, especially for large mines. A Geographic Information System (GIS) database and supporting mobile Global Positioning System (GPS) tracking system was developed for mine inspection duties at NARM. The inspection GIS utilized an ESRI Personal Geodatabase integrated with ESRI ArcPad mobile GIS software operating on a Trimble GeoExplorer Series handheld GPS to collect and update information about inspection features. Feature classes were defined and the associated data requirements for each feature class were then developed using attribute tables (Krzyszowska Waitkus and Calle 2008). The use of ArcMap maps and Excel attribute tables in the geodatabase streamlined preparation of the field inspection report. Using this system the time needed to prepare an inspection report was reduced by approximately 2/3. Compliance information stored in the geodatabase also improved communication between the regulator, operator, and federal agencies. The geodatabase accelerated the process of compliance assessment by documenting the locations and circumstances of incidents.

Additionally, query tools allowed the extraction of specific information using this geodatabase. For example, the history of the sediment capacity of specific sediment ponds allowed creating an additional sediment trap due to the frequency exceeding storage capacity. Tracking the development of erosional features aided choosing the correct maintenance action. The ability to querying features according to their compliance status within the developed inspection GIS assisted in being able to identify and correct problems before they become enforcement actions. Use of the GIS/GPS system enhanced the inspector/coordinator's ability to identify, inventory and track necessary components required for inspection purposes (Krzyszowska Waitkus and Calle 2008).

Inspections of bond release requirements and criteria were assisted by developing a bond release geodatabase for NARM. This geodatabase was the first spatially supported database developed in the USA for reclamation bond release processing purposes (Krzyszowska Waitkus and Blake 2011). GIS and GPS mobile computing technology proved to be an efficient and time saving means of tracking all phases of the bond release process. The geodatabase simplified field data collection, organization, and tracking bond release information. It enabled the spatial presentation of information and supported technical and scientific applications necessary for bond release decisions.

Additionally, the inspector of such large mine, developed a method of tracking changes by collecting photos from the same points marked by the GPS coordinates. The most significant phases of reclamation within shortest time were observed at the location in West Pit (Fig. 2).

All violations observed in the field are identified in the inspection report, including comments on the abatement of the violations. Besides state inspectors, citizens have rights to request an inspection without prior notice if they believe that conditions or practices at the mine have resulted in violations. Enforcement options from the state agency range from the least severe, notation in an inspection report, through penalties and to the most severe, criminal sanctions (Wyoming Administrative Rules 2012).

4.2 Annual reports

The coal mine operator must submit an Annual Report with the state regulatory agency, according to the Wyoming Environmental Quality Act WS §35-11-411 (Wyoming Statues Annotated 2018). The major purposes are to review the fulfillment of permit commitments, evaluate reclamation bond adequacy and set the bond amount for current and projected disturbances, document deviations from the permit, and evaluate monitoring data (Wyoming Department of Environmental Quality 2019).

Annual Report provides reclamation status for the current annual report and since the beginning of mining including the hectares of disturbed areas, active mining hectares, and areas release for specific phases of bond. Results of monitoring data are submitted in NARM's annual report for each monitoring location documenting surface and groundwater quality and quantity, overburden and backfill quality, and permanent vegetation results data. Additionally, the operator compares the data gathered during the baseline inventory with data gathered from the reclaimed land. WDEQ/LQD specialist reviews data annually and decides if the groundwater quality and quantity are trending toward baseline and groundwater uses. The state agency reviews data annually of backfill quality and agrees if operators are following their commitment on backfill sustainability. Vegetation data is collected annually and the WDEQ/LQD specialist decides if the operator is following monitoring commitments. On the basis of submitted information, the state agency is contemporaneously analyzing reclamation efforts and concluding if the operator follows permit commitment and state rules and regulations. Some violations or recommendations of some action might originate from the review of the Annual Report.

5 Summary

Sustainable reclamation practices utilized at the largest surface coal mine in USA semiarid environment could contribute to the quality of the environment on a long term basis where environmental resources are protected for future generations. The land after reclamation must be suitable for the highest previous use of greatest economic or social values to the community area. In the semiarid climate of USA, non-developed land is mostly utilized for crops, grazing, and wildlife. Coal mine permit commitments include the most recent methods and technologies to achieve the best reclamation results following specific planning. The reclamation plan for a coal mine permit includes information on soil salvage, storage, protection, and replacement, along with a schedule for backfilling, grading, contouring, and soil application. Permit planning with a detailed time schedule of all reclamation stages including spatial presentation is the key for successful establishment of sustainable stable vegetation communities on chemically suitable soil and backfill materials.

Fig. 2 Photos view east at the northern portion of West Pit collected from the same location **a** May 2005, **b** July 2006, area backfilled, **c** July 2010 area permanently seeded

The example of the reclamation efforts of the largest surface coal mine in USA is proof that through permit commitments, sustainable reclamation management and work with the state agency it is possible to reclaim large surface coal mine to the approved land use (Fig. 3).

Sustainable reclamation management practices for a large, surface coal mine include fulfillment of reclamation criteria and performance standards for specific phases of reclamation that become phases for reclamation bond release. Sustainable topography is achieved by following AOC requirements where surface configuration is achieved by backfilling and grading of mined areas that closely resemble the general surface configuration of the land prior to mining and complement the drainage patterns of the surrounding terrain. No overburden material or other coal waste material is left in stockpiles at the mine. These require knowledge of volumes of backfill and borrow material.

Monitoring hydrology plans during the mining and post-mining time provides data on surface and groundwater quality and quantity which allows developing a timetable to control and treatment of surface and ground water. The sustainability of surface water originating upstream from the mine must be maintained for a downstream use.

Sustainable methods of salvaging all suitable soil for replacement to the approved depth is a very important element in achieving successful revegetation results. Applied soil has to be prepared by various seedbed management techniques before planting seeds. This is very important step in semiarid climates and includes three phases of soil tillage, applying mulch, and growing a cover crop.

On properly prepared soil a diverse and permanent vegetation cover capable of stabilizing soil surfaces, capable of self-regeneration and plant succession is established. The revegetation plan approved in the permit is designed to establish a self-sustaining vegetative cover of various grassland and shrubland component species. A self-sustaining cover is achieved by planting native seed mixes mostly without introduced species (native grasses cannot typically compete in a mixture with introduced grasses) that is suitable for wildlife land uses.

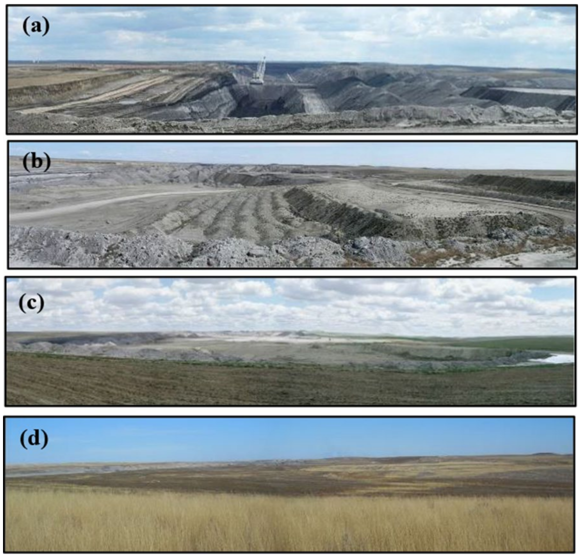

Fig. 3 Photos view north at the Oil Well West Pit collected from the same location **a** May 2008 still mining, **b** September 2009 backfilled, **c** July 2010 partially graded and soil applied, **d** September 2014 permanently vegetated

Sustainable management of the reclamation effort is achieved by enforcement processes developed by the state and federal agencies. Monthly inspections of the mining operations and reviews of annual reports submitted by the operator help determine if the mining and reclamation processes are occurring according to the permit's approved plan. A GIS/GPS system developed for NARM helped the state inspector and the operator in spatial tracking all requirements and performance standards for successful reclamation purposes.

As a results of inspections and Annual Report reviews, the state agency, can request revision of the permit. Also, the state agency can issue a formal notice of violation where site conditions constitute an existing or potential danger to the health and safety of the public, or can be expected to cause environmental degradation. These enforcement options from the state agency range from the least severe, notation in an inspection report, through penalty and to the most severe, criminal sanctions. Sustainable management practices utilized in semiarid environment allowed mined lands to be fully reclaimed in 10 years after planting species acceptable for the post-mining land uses.

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