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REVEGETATION OF RECLAIMED MINE SOILS UNDER WEATHER UNCERTAINTY: A STOCHASTIC DYNAMIC OPTIMIZATION APPROACH

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CONTENTS

A physically-based stochastic dynamic optimization model (SDOM) was developed to determine optimum mine soil depths and spoil mixture ratios required to achieve successful revegetation of mine soils. The SDOM combines a perennial grass growth model (PGGM) and a plant available soil moisture (PASM) model to predict vegetative growth on reclaimed mine soils. The SDOM was applied in Virginia, to find the optimum combination of soil parameters required to meet revegetation standards with weather uncertainty. The model found that a 90.3 cm layer of 2:1 sandstone/siltstone soil mixture was the minimum soil depth required to meet the revegetation standard. This prediction was supported by field observations.

1. INTRODUCTION

In the United States, about 2.3 million hectares of land were devastated by strip mining before passage of Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA) of 1977.[1] This act established a uniform national standard that requires all surface mined areas be returned to the approximate original contour of the land prior to mining. Under this law, miners are required to establish permanent vegetation for the release of performance bonds or deposits.

Public law 95-87 provides authority for revegetation regulations in a permanent regulatory program. Under these regulations surface mine operators must establish a diverse and permanent vegetative cover on disturbed areas that will minimize erosion and reduce off-site water quality impacts. Requirements for revegetation under PL 95-87, vary depending on the planned long-term land use and conditions prior to mining. With respect to pastureland and rangeland, the revegetated ground cover and productivity of the area must be at least 90% of the cover or production of an undisturbed reference area with 90% statistical confidence. Eighty percent statistical confidence is required on shrubland, and when technical guides are used, 90% of the standard approved by the regulatory authority is considered equal. Reference areas must be representative of the soils within the permit area.

Reclamation of surface-mined soils is a complex process which can be described as a rebuilding or reconstruction of the soil profile followed by a series of agricultural or silvicultural activities to revegetate the soil. Mine soil is defined as soil formed from mine spoil material. Mine spoil is created from disintegration of overburden during mining operations. The spoil material is usually blasted sandstone (SS), siltstone (SiS), and shale and contains a mixture of particles ranging in size from colloids to large boulders. The natural A and E horizons are saved for reclaimation and are used as topsoil over minespoil. In the Appalachians, 'topsoil' is officially designated as the A, E, B and C horizons.

Vegetative establishment and sustained plant growth on mine soils are often difficult because of low water holding capacity, poor soil chemical properties and deficiencies in organic matter content. Studies have shown however that through proper mixing and handling of the overburden materials, the water holding capacity of mine soils can be improved and with proper agronomic practices, mine soils can be nearly as productive as agricultural soils.[2,3]

Revegetation of reclaimed mine soils is especially difficult during low rainfall periods because evapotranspiration demand is usually high during these periods. Plants grown in low water holding capacity soils often experience water stress between rainfall events. Thus, if soil water holding capacity is low and rainfall is undependable, frequent periods of plant water stress may occur and successful revegetation may be difficult.

Under nonirrigated conditions, soil moisture is a function of partially controllable soil water holding capacity and uncontrollable weather conditions. Soil water holding capacity can be increased by proper selection of soil particles and by increasing the soil organic matter content. Therefore, available soil moisture can be defined as a stochastic geo-hydrologic phenomenon which changes with time in accordance with the law of probability as well as with the sequential relationship between occurrences. Since vegetative growth is a function of available soil moisture, vegetative growth can also be treated as a stochastic variable. Therefore, miners must make decisions which consider the uncertainty inherent in the revegetation process and select reconstructed soil depths and spoil mixture ratios which, combined with proper agronomic practices, will create a favorable plant growth media.

The goal of the research presented in this paper was to develop a comprehensive physically based stochastic dynamic optimization model (SDOM) to assist planners in making decisions concerning mine soil depths and soil mixture ratios required to achieve successful revegetation at a given probability level of success subject to an uncertain weather regime. The developed SDOM consists of four submodels: (i) a plant available soil moisture (PASM) model which considers infiltration, surface runoff, percolation and evapotranspiration; (ii) a model which combines precipitation and other pertinent climatic data to characterize the stochastic daily plant growth environmental regime; (iii) a perennial grass growth model (PGGM) which combined with the stochastic daily environmental regime predicts plant growth and daily dry matter yield; and (iv) a SDOM model which combines the above models into a stochastic dynamic optimization framework for finding the best combination of mine soil parameters required to achieve successful revegetation.

2. MODEL DEVELOPMENT

2.1 Perennial Grass Growth Model (PGGM)

There are two basic types of dynamic plant growth models. The most common plant growth models are regression models based upon site specific experimental data. The other type of plant growth model uses deterministic equations based upon fundamental plant growth physiology and the physics of the environment. Regression models are usually site and crop specific and their usefulness is often limited to the physiographic area, crop, and management regimes from which the regression equations were derived. As a consequence, deterministic plant growth models are more flexible in their applicability.

Biomass production and resultant ground cover are generally used to measure revegetation success, because rapid biomass production helps in establishing ground cover needed for erosion control on mine soils. A deterministic PGGM based on continuous relationships between plant growth, air temperature, daylength, leaf area, photoperiod and plant-soil-moisture stress, was selected and modified for mine soil application.[4] This PGGM was selected because it is deterministic and has received widespread verification.[4,5,6] The original model considered a rainfall factor to reflect the random effect of rainfall on the growth rate of crops. This approach indirectly considers differences in soils, water movement in soils, water utilization by plants, soil surface evaporation, and plant transpiration. This rainfall factor logic is inadequate when evaluating situations where specific soil parameters must be considered as with mine soils. In the present study, a water balance model was incorporated into the PGGM to estimate a daily soil moisture stress factor which considered the soil-plant-water relationship. In developing such a complex relationship between plant growth and soil moisture stress, a sigmoidal relationship between soil moisture deficit and biomass production was hypothesized and is presented in the following section.

2.2 Plant Available Soil Moisture (PASM) Model

Plant available soil moisture is a function of several complex processes including infiltration, evapotranspiration, and drainage. Richardson and Ritchie's soil moisture model was used to predict daily PASM using initial soil moisture, soil properties, plant characteristics, and climatic data as input variates because it appears to be one of the best soil moisture models, it is widely used and because of some evidence of its applicability under Virginia conditions.[7,8] An indepth discussion of the original Richardson and Ritchie soil moisture model is presented elsewhere.[7,9]

The PASM model's first function is to compute daily potential evapotranspiration (PET). The model contains two alternatives for estimating daily PET: Penman's equation or pan evaporation data. Penmans' equation needs daily values of net radiation, maximum and minimum temperatures, wind movement and vapor pressure. In areas where data for Penman's equation are unavailable, or when a simpler input is desired, pan evaporation data can be used to estimate PET. The relationship between pan and potential evapotranspiration depends on the type of evaporation pan, geographical location, pan exposure and season. Pan coefficients can be determined using the method developed by Cuenca.[10] The daily evapotranspiration, which is the sum of soil evaporation and plant transpiration, is estimated by assuming that the soil moisture does not limit evaporation. When soil water is limited, plant transpiration is reduced. Ritchie developed a procedure to define a two stage drying process for soil evaporation.[11] Evaporation occurs at a potential rate during Stage I until a pre-defined accumulative evaporation quantity has been reached. Stage II drying is then entered, which is more dependent upon the soil's hydraulic properties than the climatic conditions. Daily soil moisture is then computed with a continuity equation using soil moisture for the previous day and daily rainfall, runoff, evapotranspiration, and soil drainage.

Infiltration and runoff are partitioned using a form of the SCS runoff curve number procedure.[12] The model assumes that the water entering the soil in excess of the upper limit of soil water storage drains out the same day. Although soil drainage takes place over several days the error caused by the assumption is small and is corrected within a few days when soil water storage reaches its upper limit.

Climatic data required by the model include daily maximum and minimum temperatures, rainfall, and pan evaporation (or solar radiation when available). Soil properties include the depth of the soil profile being considered, initial soil moisture, upper limit of stage I evaporation, a soil evaporation parameter based on soil water transmission characteristics, and soil albedo. Plant characteristics which must be considered are plant population, row spacing, and leaf area index as a function of season.

To estimate the effect of soil moisture stress on potential plant growth it was hypothesized that a sigmoidal relationship existed between dry matter yield and PASM. With this assumption plant growth increases slowly with increasing PASM up to a certain point, after which there is a rapid increase in plant growth with further increase in PASM until plant growth reaches its maximum potential rate. A sigmoidal relationship between plant growth and PASM was selected because better data for developing a more sophisticated relationship was not available. Also, for an established perennial grass crop (e.g. tall fescue), soil moisture could be a limiting factor if the average soil moisture falls below a critical level (i.e. below 50% of maximum PASM), and the plant response to moisture stress between wilting point and the 50% of maximum PASM is best represented by a non-linear function.[13]

The predicted daily PASM was used to estimate a soil moisture factor (SMF) using a sigmoidal relationship and is used in the PGGM to calculate the actual dry matter yield. The sigmoidal relationship can be stated as:

$$\mathrm{SMF} = \frac{\mathrm{SMAC}}{2}, \text{ if SMAC} < 0.25 \tag{1}$$

$$\mathrm{SMF} = \mathrm{SMAC}*2, \text{ if } 0.25 \leq \mathrm{SMAC} < 0.50 \tag{2}$$

$$\mathrm{SMF} = 1.0, \text{ if SMAC} \geq 0.50 \tag{3}$$

where, SMAC is the fraction of maximum plant available soil moisture.

The PGGM and PASM models were combined to form VPIGRO. To demonstrate the usefulness of VPIGRO, data from Wise County, Virginia, was used because of the author's familiarity with the area and because a good deal of revegetation research has been completed or is in progress in this area. Required model input parameters were collected from field observations, the literature, and personal contacts with mine soil reclamation experts. The observed values were compared with experts' understandings and finally a reasonable parameter value was fixed. The PGGM parameters for tall fescue include the minimum air temperature below which plant does not grow (T_1 = 4.4°C), the optimum air temperature for plant growth (T_2 = 18.3°C), the maximum air temperature above which plant growth does not occur (T_3 = 32.2°C), the optimum plant growth rate (R = 6.50 Mg/ha-hr), and the maximum accumulated dry matter of fescue (Q_3 = 6196.0 Mg/ha). The PASM model parameters include the upper limit of the soil water content, the lower limit for potential evaporation with a fully developed canopy, the upper limit of Stage I soil evaporation, the Stage II soil evaporation constant, estimates of pan coefficients, plant leaf area index for specific days during the growing season, daily values of maximum and minimum temperatures, rainfall, pan evaporation and day-length hours.

The VPIGRO model was used to generate dry matter yield data for a 50 year period (1930–79) in the study area. It is expected that the dry matter yield in a given year will depend to some extent on the dry matter yield of the previous year, i.e., there will be a positive correlation between the dry matter yield y_i of year i and the dry matter yield y_{i-1} of year i-1. It would also be expected that this correlation would be higher if the time lag between the two time periods is small and environmental conditions and soil properties are not significantly different. Higher correlations would be expected between soils with high PASM or successive years of similar precipitation and other climatic factors. To determine this correlation an auto-correlation test was performed.[7] The auto-correlation test showed that the correlation between successive years of dry matter yield was not statistically significant. This confirmed that the dry matter yields followed a stochastic process and therefore, dry matter yield in a given year can be treated as an independent stochastic variate dependent primarily on climate for a given soil type.

2.3 The Probability Model for the Successful Revegetation Event

Under SMCRA, successful revegetation, (event E) is defined as a success if revegetation is successful in at least the 1st and 5th years of the 5-year bond release period in the eastern United States. This allows the 2nd, 3rd and 4th years either to be a success, failure or any possible combinations thereof, but the 1st and 5th years, must be a success. If y_i is defined as the dry matter yield in year i for which the probability of revegetation success needs to be estimated, then the event of a success S_i on year i can be represented as:

$$S_i = \{y_i > y_{ref}\} \tag{4}$$

where y_{ref} is the dry matter yield in kg/ha/year for the reference area.

The probability of revegetation success in a given year i can be expressed as:

$$P_{S_i} = P(S_i) = P(y_i > y_{ref}) = P \tag{5}$$

and the probability of revegetation success of event E can be expressed as:

$$P(E) = P^5 + 3\,P^4\,(1 - P) + 3\,P^3\,(1 - P)^2 + P^2\,(1 - P)^3 \tag{6}$$

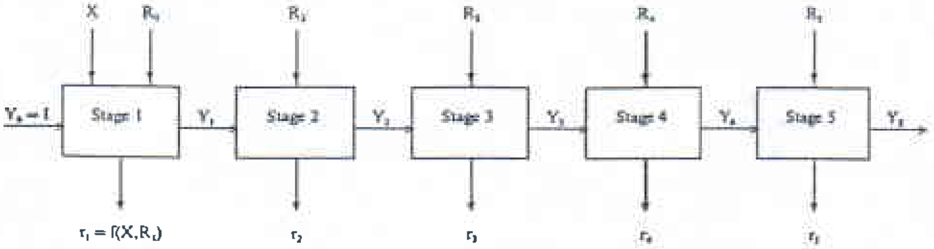

FIGURE 1. Stagewise representation of SDOM.

2.4 Mathematical Formulation of SDOM for Strip Mine Revegetation

The problem objective is to find the optimum combination of spoil depth and spoil mixture, which will achieve successful vegetation for reclaimed mine soils, under non-irrigated conditions, considering that weather is the only random element of the system. The model considers a tall fescue grass for vegetation purposes. The dry matter production and/or percentage cover of vegetation was computed as a function of soil moisture, photoperiod, daylength, and temperature regime. The objective function is to find the optimum depth of PASM which will result in a successful stand of vegetation at the end of the 5-year performance bond period. The problem is unique in a sense that the decision needs to be made only once at the beginning of the decision period and the outcome of this single stage decision needs to be optimized through the end of the decision period (at the end of the 5 year period).

The problem of revegetation success can be categorized as a Markov process with rewards where the response or outcome fluctuates because of the operating environment over which there is no immediate control. Nevertheless, if one has some notion of the probabilities of certain events and the factors that influence them, it is possible to influence or determine longer term profits or rewards. For the case of the revegetation process, the desire is to determine a reward structure, expected vegetation yield or percentage cover over the next n transitions, given that the system is currently in state i. Now suppose that a Markov process with N states has a reward structure associated with the transitions from one state to another. Call ω_{ij} the reward associated with a transition from state i to state j. The matrix $\Omega = \{\omega_{ij}\}$ is the matrix of the rewards associated with all possible state transitions. The Markov process will generate a sequence of rewards as it moves from state to state. Hence the reward is also a random variable with a probability distribution dependent upon the probabilistic nature of the Markov process.

The physical process of the problem in a dynamic framework can be viewed as a stochastic dynamic process and represented as a stagewise process as shown in Fig. 1. Where the vector X is the decision vector which represents combinations of soil depth and soil mixture ratios. The decision vector can be represented as $X = [X_1, X_2]$, where X_1 and X_2 are the soil depth and soil mixture ratio, respectively. R_i, $i = 1, 2, \ldots,$

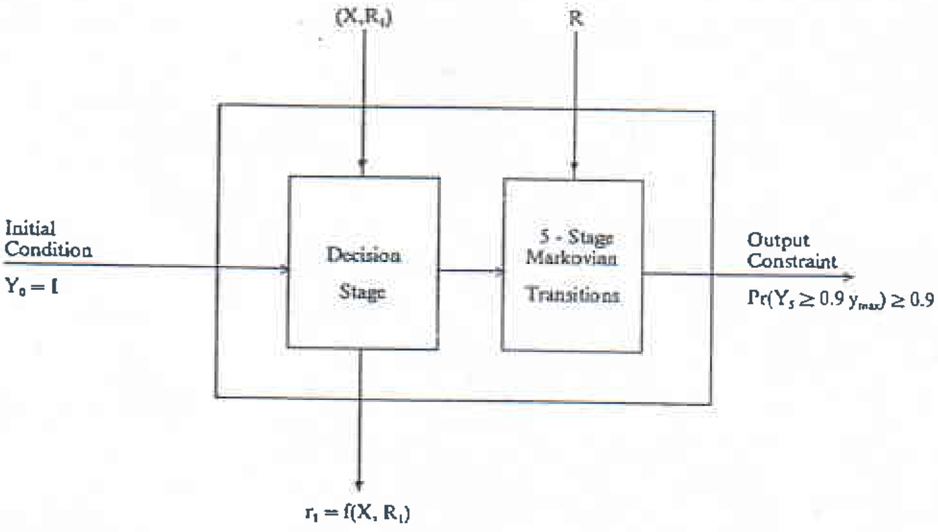

FIGURE 2. Single stage markovian decision problem.

5, is the random weather input vector to the system in the i^{th} year or period and r_i, $i = 1, 2, \ldots, 5$ is the cost in dollars for the 1st to i^{th} year due to a decision X. Note that there is cost involved only during the first year. After the first year, no cost is involved which essentially implies that $r_2 = r_3 = r_4 = r_5 = 0$. Y_0 is the initial condition of vegetation, that is, at the beginning of the 5-year bond release period. Y_i, $i = 1, 2, \ldots, 5$ is the vegetation yield in terms of dry matter or percentage cover at the end of the i^{th} year and is a function of decision vector X and the initial vegetation conditions Y_0 and Y_{i-1}.

Figure 1 shows that the problem requires a decision only in year or stage 1. From then on, stages 2 to 5, the system operates under certain stochastic inputs and as a consequence the system response at the end of each year is random or stochastic. Considering the nature of the problem, the five stage stochastic dynamic problem as shown in Fig. 1, can be simplified into an equivalent single stage decision problem plus a 5-stage Markovian transition process as shown in Fig. 2. The single stage Markovian decision problem can be formulated as a mathematical optimization algorithm as follows. The objective of the decision problem is to find the optimum combination(s) of the decision vector $X = [X^*_1, X^*_2]$ which will satisfy the required vegetation standard at the end of the 5-year period of performance bond release. The stochastic disturbance or input to the system is weather. The revegetation success at the end of each year will be conditional on the success or failure in the previous year(s). Therefore, for each combination of decision vector and random weather input, there will be a probability of success and its complementary event (i.e., the probability of failure) in the revegetation process.

Furthermore, to minimize the computational effort, the above mentioned two-dimensional decision problem was reduced to an one-dimensional decision problem by introducing a new one-dimensional decision vector D. The new decision vector D, represents the plant available soil moisture (PASM) and is expressed as a function of soil characteristics. After finding the optimum D, the actual soil depth for five soil mixtures were calculated using the following equations:

$$X_i = \frac{D*10}{PASM_i} \tag{7}$$

and,

$$PASM_i = BD_i*(1.0 - CF_i)*WC_i \tag{8}$$

where: X_i = actual soil depth for mixture i, m; D = optimum plant available soil moisture, cm; $PASM_i$ = plant available soil moisture for mixture i, kg/m^3; BD_i = bulk density of soil mixture i, kg/m^3; CF_i = fraction of coarse fraction present in mixture i; and WC_i = water content of the soil particle size fraction less than 2 mm in diameter (between 33 and 1500 KPa) for mixture i, kg/kg.

The advantage of this technique is that it allows the planners to choose any soil mixture and calculate the required soil depth by computing the optimum D^* only once for an area and a given crop.

SDOM mathematical formulation of the revegetation problem can be expressed as:

Objective function:

$$D^* = \min_{D_1 \leq D_k \leq D_{n+1_k}} \{D_k\} \tag{9}$$

Subject to:

$$P^5 + 3\,P^4\,(1 - P) + 3\,P^3\,(1 - P)^2 + P^2\,(1 - P)^3 \geq 0.9 \tag{10}$$

$$P_{S_i} = Pr(y_i > y_{ref}) = P \tag{11}$$

$$P = Pr\left\{Z_k \geq \frac{y_{ref} - \bar{y}_k}{\sigma_k}\right\} \tag{12}$$

$$\bar{y}_k = \alpha + \beta\,\ell n\,D_k \tag{13}$$

$$\sigma_k = \sigma_{i-1} + (\bar{y}_k - \bar{y}_{i-1})*\frac{\sigma_{i+1} - \sigma_{i-1}}{\bar{y}_{i+1} - \bar{y}_{i-1}} \tag{14}$$