Stochastic Dynamic Optimization Approach For Revegetation Of Reclaimed Mine Soils Under Uncertain Weather Regime

by

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(ABSTRACT)

This study presents a comprehensive physically based stochastic dynamic optimization model to assist planners in making decisions concerning mine soil depths and soil mixture ratios required to achieve successful revegetation of mined lands at different probability levels of success, subject to an uncertain weather regime. A perennial grass growth model was modified and validated for predicting vegetation growth in reclaimed mine soils. The plant growth model is based on continuous relationships between plant growth, air temperature, day length, leaf area, photoperiod and plant-soil-moisture stresses. A plant available soil moisture model was adopted to estimate daily soil moisture for mine soils.

A general probability model was developed to estimate the probability of successful revegetation in a 5-year bond release period. The probability model considers five possible bond release criteria in mine soil reclamation planning.

A stochastic dynamic optimization model (SDOM) was developed to find the optimum combination of soil depth and soil mixture ratios that met the successful vegetation standard under non-irrigated conditions with weather as the only random element of the system. The SDOM was applied for Wise County, Virginia, and the model found that 2:1 sandstone/siltstone soil mixture required the minimum soil depth to achieve successful revegetation. These results were also supported by field data. The developed model allows the planners to better manage lands drastically disturbed by surface mining.

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The preparation of this report necessitated spending many hours at night and on weekends away from my wife. Realizing that this lost time can not be recovered, I wish to thank my wife for her understanding and support.

Lastly, I wish to dedicate this work to my parents who have been a source of inspiration throughout my life.

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INTRODUCTION

Coal mining in the eastern United States has a significant deleterious impact on water resources, especially in mountainous Appalachia. Several studies have shown that during surface mining and before reestablishment of vegetation, peak runoff rates are higher from mined watersheds than from undisturbed areas. Higher runoff rates and highly erodible disturbed soils contribute large quantities of sediment to streams and rivers and damage aquatic ecosystems. In areas with acidic mine spoils, chemicals such as calcium, magnesium, potassium, sodium, phosphorus, aluminum, nitrogen, and iron have polluted streams.

In Virginia, about 29,000 hectares of land were devastated by strip mining before passage of Public Law 95-87, the Surface Mining Control and Reclamation Act of 1977 (U.S. Dept. Interior, 1978). This act established a uniform national standard that requires all surface mined areas be returned to the approximate original contour (AOC) of the land prior to mining. Under this law, miners are required to establish permanent vegetation for the release of performance bonds or deposits. Studies have shown that after surface-mined areas are fully revegetated, peak runoff values are lower in mined watersheds than in nearby unmined forested watersheds. Also, the establishment of vegetation improves the visual aesthetics of mined areas and returns mined lands to a productive use. Therefore, through good revegetation, one can achieve the three most important goals of reclamation -- erosion control, land productivity, and aesthetics.

Sections 102, 201, 501, 503, 504, 507, 508, 515 and 519 of PL 95-87 provide authority for revegetation regulations in the permanent regulatory program. Under these regulations surface mining operators must establish a permanent vegetative cover on the disturbed area that will minimize erosion and reduce water pollution to prevent environmental degradation. 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, rangeland and other areas not included in the exceptions, revegetated ground cover and productivity of the area must be at least 90% of the cover or production of the 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 will be considered equal. Reference areas must be representative of the permit area.

The Office of Surface Mining (OSM) reclamation and enforcement rules and regulations have exceptions on the percentage cover required for measuring revegetation success. These exceptions apply to :

1. previously mined areas;
2. areas intended for industrial or residential use within two years after grading is completed;
3. areas to be used for cropland; or
4. areas to be developed for fish, wildlife or forestland.

On previously mined land, cover shall not be less than what can be supported by the best available topsoil or other suitable material or less than the ground cover that existed before the area was redisturbed and shall be adequate to control erosion. Temporary ground cover is required for erosion control if the land is to be developed for residential and industrial land uses within two years after regrading is completed. For cropland, crop production is based on a reference area or other standards that are based on technical guides approved by the regulatory authority. Areas established for fish and wildlife management and forestland must attain a ground cover at least 70% of the ground cover of the reference area with 90% statistical confidence or, if the regulatory authority determines that another amount of ground cover will control erosion, that amount can be determined acceptable.

Much useful literature on reclamation has been published (Bennett, 1975, 1977; Armiger, 1976; Bell, 1982; Robinson, 1984; Roberts, 1986), but additional research is needed to improve successful revegetation of mine soils. 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 silvicultural or agricultural activities to revegetate the soil. Mine soil or topsoil results from disintegration of overburden during mining operations. The spoil material is usually blasted sandstone and shale and contains a mixture of particles ranging in size from colloids to large boulders. Vegetative establishment and sustained plant growth in mine soils are difficult because of low water holding capacity and deficiencies in organic matter content. Studies have shown 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 (Roberts et al., 1988 and Van Lear, 1971).

Mine soils in the eastern United States vary greatly in physical characteristics from one region to another and even within a region depending on mining procedures. Most mine soils contain a large proportion of coarse fragments ($>$ 2 mm in diameter), some as much as 80% by volume. This results in low water-holding capacity and causes problems in vegetation establishment. Textures of the soil-size fraction of mine soils range from sand to clay, but most mine soils textures are loamy. Mine soils with $<$ 50% coarse fragments and a loamy soil-size fraction texture are best for plant growth. Bulk densities of mine soils have been reported to range from 1.2 g/cm^3 to 2 g/cm^3. These densities are usually higher than those of adjacent undisturbed soils. Daniels and Amos (1981) observed highly compacted layers of soil ($>$ 1.8 g/cm^3) within 70 cm of the surface on more than half of the soils studied on reclaimed land in Virginia. These compacted layers severely limit air, water, and root penetration, thereby limiting the growth and survival of vegetation. The presence of highly compacted soil layers and their detrimental effects on vegetative growth have been reported by several mine soil investigators from different coal producing regions (Fehrenbacher et al., 1982; Daniels and Amos, 1981; Pedersen et al., 1980; Howard, 1979; Barnhisel et al., 1979). Thurman and Sencindiver (1986) studied mine soils in Monongalia County, West Virginia and reported high rock fragment content (33-45%), low water holding capacity (0.07 to 0.12 kg/kg), and high bulk density (1.55 to 1.86 g/cm^3). For comparison purposes, they also reported properties of adjacent native soil's bulk density (1.05 - 1.65 g/ cm^3), porosity (37.9 - 57.3%), moisture retention capacity (0.12 - 0.24 kg/kg), and rock fragment content (5 - 37%). Field investigation results of Pedersen et al. (1980) showed that most mine soils retained about one-fourth as much water as natural soils, between 10 and 1,500 kPa soil moisture tension.

Most of the mine soil water budget studies neglect the moisture content of the coarse fragments. Hanson and Blevins (1979), however, found that the available water contained in sandstone fragments (11% by volume) and the siltstone fragments (23% by volume) may be utilized by growing plants, especially under drought stress conditions. Plant available water in coarse fragments may therefore play a significant role in the water budgets of plants growing in soils that contain a high percentage of coarse fragments, such as those of southwestern Virginia forest soils and surface-mined lands.

Revegetation of reclaimed mine soils is especially critical during low rainfall periods because evapotranspiration demand is usually high during these periods. Soils with low water holding capacity may 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.

Water holding capacity of mine soils can be controlled through proper reconstruction of mine soils by organic matter additions, but precipitation and other climatic factors can not be controlled or predicted with any certainty. Under nonirrigated conditions, soil moisture is a function of controllable soil water holding capacity and uncontrollable weather conditions. 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 soil mixture ratios which combined with proper agronomic practices will create a favourable plant growth media.

Dynamic programming has been used to solve a wide range of deterministic and stochastic decision making problems in agriculture and natural resources management (e.g., crop, livestock, land, forestry and fishery management). These applications show the scope of dynamic programming as a decision making tool. Dynamic programming is a research technique particularly suited for obtaining numerical solutions to problems which involve nonlinear and stochastic functions, and state and decision variables which are constrained to a finite range of values. Application of stochastic dynamic programming helps identify priorities in scientific research. From an extensive review of the literature it is found that dynamic programming can be used as an universal research technique for solving many agricultural and natural resources problems involving nonlinear and stochastic functions.

This study is the first of this kind which considers uncertainty in the revegetation process and should allow miners to make decisions about the optimum soil depth and soil mixture ratios required for successful revegetation at a predetermined confidence level. The developed model is verified using limited data from southwestern Virginia. The model can also be used in other areas where required input parameters are available.

Objectives

Formulation of a comprehensive model for revegetation of mine soils requires a sound understanding of geo-hydrologic water balance components such as precipitation, infiltration, surface runoff, percolation, and evapotranspiration. The principal goal of this study is to formulate a comprehensive physically based stochastic dynamic optimization model which will assist planners in making decisions concerning mine soil depths and soil mixture ratios required to achieve successful revegetation at different probability levels of success for the release of performance bonds, subject to an uncertain weather regime.

To accomplish this goal, the following specific objectives were accomplished.

1. A soil moisture model was selected for surface mine soils which considers infiltration, surface runoff, percolation, and evapotranspiration.

2. The soil moisture model was combined with precipitation and other pertinent climatic data to characterize the stochastic daily plant growth environmental regime.
3. A crop growth model was selected and combined with the stochastic daily environmental regime to predict plant growth and the daily dry matter yield.
4. Finally, the above models were combined into a stochastic dynamic optimization framework for finding the optimum combination of soil depth and soil mixture ratios required to achieve successful revegetation.

The most difficult problem facing the user of the model presented herein is the scarcity of relevant input data. However, it should be understood that data are not collected unless there is a perceived need for them, and the need is often not perceived until models designed to answer practical questions are developed. The purposes of this research are to estimate mine soil properties required for successful revegetation, to identify data needs, and to identify future research priorities and strategies for improving mine soil revegetation. This study presents a methodology for making strip mine reclamation decisions using stochastic dynamic optimization models (SDOM).

Organization of the Study

The following chapters present the methodology and results of the study. Chapter II presents a review of goals and specifications for successful revegetation as stated in the 1977 Reclamation Act, the different ways of solving the problem of uncertainty inherent in mine soils revegetation, hydrologic research on surface mine soils, published soil moisture models, vegetation yield prediction models, and the theory behind SDOM in general.

Chapter III describes the perennial grass growth model, the plant available soil moisture model, mathematical-logic flow, required input parameters, development of a probability model for the events of interest in mine soil revegetation, and mathematical formulation of SDOM for strip mine revegetation.

In Chapter IV, procedures and data used to validate the SDOM are presented. A sensitivity analysis of model parameters is also presented.

Chapter V presents the results of this research including validation of the perennial grass growth model (PGGM), statistical analysis of long-term biomass yield, non-linear relationship between biomass yield and plant available soil moisture (ASM), and the optimum soil depth required for each combination of soil materials studied in this research.

This chapter has presented an overview of the entire study. As in any study, some elements are borrowed and some are original. Among the borrowed features of this study are:

1. Adaption of PGGM for biomass yield prediction.
2. Use of Ritchies' PASM model for predicting daily soil moisture.
3. Use of basic principles of dynamic programming in the development of SDOM.
4. Use of experimental data obtained by others for soil and biomass yield.

Among the original contributions of the current study are:

1. Validation of PGGM for mine soil revegetation.
2. Development of five random events of revegetation success to assist in planning revegetation programs under uncertainty.
3. Combining the PGGM, the PASM model, and five random events of revegetation success into a stochastic dynamic optimization framework for finding the optimum combination of soil depths and mixture ratios required to achieve successful revegetation.
4. Introduction of the universal concept of stochastic dynamic optimization approach in planning mine soil revegetation efforts under weather uncertainty.

LITERATURE REVIEW

The first section of this chapter presents a brief history of mine soil revegetation under uncertainty and decision criterion generally applied in decision making under uncertain conditions. The second section gives a brief review of hydrologic research to date on surface mine soils and future research needs in this area. The third section describes soil moisture models available in literature and their usefulness in predicting soil moisture on a daily basis. The fourth section describes models used for crop yield predictions. The last section describes stochastic dynamic optimization modeling (SDOM) theory and reviews SDOM applications in agriculture and natural resources management.

Uncertainty in Mine Soil Revegetation

Most mine soil studies are concerned with the ability of a mine soil to support vegetation after mining is completed. A detailed review of mine soil revegetation was presented by Roberts (1986). His review involved grasses and legumes grown for early stages of reclamation. Previous studies have shown that fescue is very suitable for revegetation of mine soils for first ground cover and reduction of soil erosion and environmental degradation (Van Lear, 1979; Powell et al., 1982; Hanson et al., 1982). A mixture of fescue and legumes generally results in increased biomass yield. Nitrogen and phosphorous are the most important nutrients needed for vegetation establishment. Sewage sludge amendments provide added organic sources of nitrogen and phosphorus and increase the water holding capacity of the mine soils (Halderson and Zeng, 1978; Sopper et al., 1981; Haghiri and Sutton, 1982).

An important regulatory objective of the SMCRA of 1977 is the revegetation of reclaimed mine soils. Permits for mining according to the Act, will not be issued unless a revegetation program has been approved. The effectiveness of the permitting and regulatory procedures depend on weather during the revegetation process and models or regulations used to specify revegetation practices. These decisions involve considerable uncertainty. These uncertainties make it difficult to predict the probability of success of a revegetation program and its environmental impacts.

The weather regime has a natural variability which can have deleterious effects on mine soil revegetation. Most revegetation studies have been conducted over short periods of time (5 to 10 years). These short data bases are not likely to consider extreme or rare events, therefore, parameters used for model development based on data from short time periods will have considerable uncertainty.

The most common way of handling uncertainty is to determine a "best" estimate and to use that estimate in predictions as if it were the true value. A more useful technique may be to give the "best" estimate and a statistical measure of the variation expected. Depending on the type of decision to be made, and on the decision maker's evaluation of the possible consequences, three general types of criteria are used to determine the risk associated with each decision alternative: the test of hypothesis, the minimax criterion, and the expected value criterion.

A test of hypothesis, in statistical terminology, is a test, based on statistics, that a certain hypothesis is true. Since the test statistics are random variables, there is a probability that will indicate that the hypothesis is true when it is not, or that the hypothesis is not true when it is true. Therefore, the test specification includes bounds on these types of errors. In the context of the SMCRA of 1979, the hypothesis is a regulatory goal and the test is a regulatory specification. In revegetation, the regulatory goal is ground cover and productivity equal to an undisturbed reference area. The regulatory specification is for the amount of ground cover and productivity to be within 90% of the reference area amount with an adjustment so that there is only a 10% chance that a revegetated area meeting the 90% requirement will be rejected due to natural variations in vegetation growth patterns.

Congressional criteria for resolving uncertainty is that of minimizing the maximum harm to the environment which is called minimax criteria. The OSM recognizes many uncertainties in the regulation of mining. First and foremost, the uncertainty in the ability of various types of regulations to protect the environment: "Thus the question of 'goals versus design standards' is one of balancing the need for increasing certainty of protection against increased flexibility for the operator" (Federal Register, 1979). The agency believes it has "in almost all cases supplied substantial flexibility even where design standards are provided" (Federal Register, 1979). The regulation concerning the adequacy of ground cover and productivity on the revegetated land is a test of the hypothesis: "the ground cover and productivity of the revegetated area shall be considered equal if they are at least 90% of the ground cover and productivity of the reference area with 90% statistical confidence" (Permanent Regulatory Program, 1979). The objective of this research is not to evaluate the SMCRA, but to determine how the uncertainties inherent in the technical inputs to the regulatory process affect achievement of the goals.

The regulation required that the ground cover and productivity of the plants on the reclaimed land be equal to that on undisturbed reference lands. Further, the land must maintain a satisfactory level of vegetation for 5 years in humid climates and 10 years in semiarid climates. The test of hypothesis approach is used to determine whether the ground cover and productivity of the revegetated area is equal to that of the reference area.

The use of the test of hypothesis criteria to determine the equality of revegetated areas, as outlined in the regulations, reduces the probability of falsely rejecting a revegetated area due to natural variations to under 10 percent. In so doing, the probability of accepting deficiently revegetated areas is high: areas whose vegetation is only 90% of equality will be accepted as equal 90% of the time. When the natural variation is high, the probability of false rejection is lowered, and of false acceptance is raised. If the random variation in the vegetation has a standard deviation of 10% of reference values, based on the normal distribution the probability of rejecting truely equal vegetation is 1%; while the probability of falsely accepting vegetation at the 90% level is 90%; and the probability of falsely accepting vegetation at the 80% level is 61%. For a 10% standard deviation and assuming a normal distribution, the probability of falsely accepting vegetation at the 70% level is 23%; and the probability of falsely accepting vegetation at the 60% level is 4%. Thus, the use of the test hypothesis criterion leads to a large probability of accepting deficient vegetation.

The problems lie with the inconsistencies which result from a lack of complete understanding of uncertainty and the means for dealing with it. The nature of uncertainty, its affect on desired goals and the criterion to be used in judgement of the possible outcomes must all be known if optimal decisions are to be made (Devis et al., 1979).

The combined use of the test of hypothesis and minimax criteria in the regulations concerning revegetation led to a situation where there is a large probability that deficient ground cover and productivity will be accepted, but small probability that the resultant vegetation will fail after the mine operator is no longer responsible.

Hydrologic Research on Surface Mine Soils

In recent years considerable attention has been focused on the reclamation of surface mined soils. Particular attention has been placed on the surface mining of coal and concern for the protection of the hydrologic balance on disturbed watersheds. It has been estimated that 32 percent of the national coal reserves are mineable by surface mining on 10 million acres of land (Public Land Law Review Commission, 1970). Modeling the hydrologic cycle on reclaimed lands presents some unique problems and research in this area is in its infancy.

Reclamation of a surface mined land is a complex process which may be described as a rebuilding or reconstruction of the land profile followed by a series of silvicultural and agricultural activities to revegetate the land surface. The reconstructed soil and spoil profile may range in depth from a few feet to over a hundred feet and will usually contain a variety of materials and a wide range of particle sizes. Under provisions of the new regulations, a surface layer of topsoil ranging from 0.1 to 1.0 meter will overlay the reconstructed land profile. The spoil material is usually blasted sandstone and shale and contains a mixture of particles ranging from colloidal sizes to very large boulders. Depending on the nature of the replacement operation, the final profile may be very porous or highly compact. The topsoil layer will also vary widely in hydraulic properties depending on the depth of the layer, the topsoil material, and handling procedures. One of the important factors that affects the hydrologic balance of reclaimed mine soil watersheds is the infiltration rate. For most mine soils, infiltration rate is low compared to agricultural soils. Because of the low infiltration rates both the runoff volume and the sediment loads are high in steeply sloping reclaimed lands. Therefore, it is important to understand the infiltration characteristics of reclaimed mine soils. A review of the limited amount of research on infiltration in mine soils is presented in the following section.

Rogowski and Jacoby (1979) and Pionke et al. (1978) discuss various aspects of a study on a Pennsylvania coal mine. Large caissons (3.6 m deep by 2.4 m diameter) were used to measure water movement in reconstructed spoil profiles. Spoil material was obtained from a reclaimed surface mine and the field spoil profiles were recreated in the laboratory. The caissons were instrumented with both gamma and neutron probe, porous cup tensiometers, and thermocouples. Lysimeters were installed at selected depths and each one was connected to a manometer-outflow assembly. Two caissons were used in the study and different soil and spoil profiles were reconstructed in each caisson. In the first caisson, a 0.5 m topsoil layer was placed over the spoil profile and in the second profile, a 0.4 m layer of acid shale was placed under the spoil profile. A pump and sprinkler system was used to simulate rainfall. An average rainfall rate of 300 mm/h was applied to the first caisson in two applications. One from time 0 to 70 minutes and the second from time 102 to 124 minutes. Some surface ponding occurred at this application rate. For caisson 2, 300 mm/h was applied for the first five minutes and 1890 mm/h was applied for 16 minutes 47 minutes after the start of the test. No surface ponding was observed. Considerable settling occurred during the application of water. Settlement in the first caisson was six percent and in the second caisson, ten percent. In caisson 1, the density increased most near the surface and in caisson 2, it increased progressively with depth. The authors suggest that the changes in density might be due to the movement of fine sediment with the infiltrating water. Caisson 1, which had a topsoil surface layer, contained higher sediment concentration in the effluent flow (subsurface) collected by the lysimeter system. The authors comment that the two-probe gamma density probe was better for monitoring the wetting front than the neutron probe because the sphere of influence is considerably smaller and only a 25 mm slice is monitored at any one time. In both caissons, the infiltrated water reached the water table faster than expected from observations of the movement of the wetting front, indicating that flow occurred through large channels in the profile. Water redistribution profiles indicated fast drainage in the spoil profile and delayed drainage in the topsoil profile. The water quality of the flow collected in the lysimeters was analyzed in an accompanying project and the results are described by Pionke et al. (1978).

Rogowski and Weinrich (1981) presented a paper describing the infiltration and redistribution results for the large caisson study. The results of the caisson infiltration tests were compared with results predicted with a numerical solution of Richards' equation. They found that the numerical model worked well for the topsoil/ spoil profile, but gave poor results for the spoil profile. The poor fit was attributed to saturated channel flow through large fissures in the spoil material. Hydraulic conductivities determined from desorption laboratory tests and from measured flow times in the caissons indicated that the hydraulic conductivity of the spoil material was 14 times that of the topsoil. Spoil saturated conductivities ranged from 0.52 to 2.10 mm/s. The authors also reported that a correction had to be made to the laboratory desorption suction data to account for the coarse spoil material.

Rogowski (1979) describes a laboratory study using small 0.3 m by 0.5 m test boxes. Soil or spoil profiles with a depth of 0.15 m were created in the test boxes and the boxes were then placed at a slope of 24 percent. A scaled down model of the Nassif and Wilson (1975) rainfall simulator was used to apply water to the test boxes. Tests were conducted with a soil, a spoil, and a topsoil material. The main objectives of the study were to evaluate the effects of surface armoring on runoff, infiltration, and erosion. The author indicated that the laboratory apparatus was probably too small to adequately evaluate armoring effects. Infiltration was much larger through the spoil material and piping losses were observed on the spoil material.

Fogel et al. (1979) describe a study to evaluate sediment yields from Black Mesa coal spoils in Arizona. While the study does not attempt to monitor infiltration, runoff was predicted using SCS procedure and was compared with field data. It was noted that the correction factors to vary the curve number between wet and dry antecedent moisture conditions might be too high. It was suggested that the initial abstraction term in the SCS equation should be reduced to 0.15S on reclaimed lands.

Briggs et al. (1979) evaluated the effects of deep tillage practices on reclaimed lands. The main focus of the study was on crop production and no real infiltration measuring was conducted. It was noted, however, that deep tillage significantly reduced runoff from corn plots and that a cracking pattern, which occurred following tillage, intercepted much of the overland flow. The effectiveness of deep tillage in reducing soil and water loss was, however, marginal and was only significant during the first year.

Lusby and Toy (1976) conducted a rainfall simulation study on surface mined spoils in Wyoming. The Colorado State University (Dickinson et al., 1967) rainfall simulator was adapted into a portable field design and was used in this study. A steady rainfall rate of 5 cm/h was applied for 45 minutes over a 340 square meter area. Runoff was measured using calibrated collection barrels or Parshall flumes. Experimental studies were conducted at two different mining operations. For high antecedent soil moisture conditions, runoff was substantially higher from the reclaimed areas.

Schafter et al. (1979) describe a comprehensive study on surface mine spoils in Montana. A limited amount of infiltration data is presented in this report. Again, a rainfall simulator study was conducted and surface runoff was monitored. The rainfall simulator was developed by Meeuwig (1971) and applied water from a height of 0.5 m over a 0.31 square meter area. Runoff was measured every four minutes and infiltration was estimated as the difference between rainfall application and runoff. Soil water content was measured using a Troxler 1255 neutron probe. A total of 32 measurements were made for each depth increment. Readings were taken every 15 minutes for the first 90 cm and every 30 cm down to a depth of 210 cm. Psychrometers were also used to measure soil water potential and soil temperature. Tests were conducted on spoils which were 1 to 50 years old. The results indicated that there were no significant differences between infiltration rates on undisturbed soils and minespoils. These results are very different to the results presented in the studies previously discussed and differ from several other studies in this region (Gilley et al., 1976; Arnold, 1977; and Miyamoto, 1977). The results reported in these other studies indicated that infiltration rates through the spoils are slower than natural soils. Water redistribution and use was found to vary significantly in old and new spoils and in natural soils. The difference in the water movement and water use patterns is attributed to the different plant species found on the different soil materials. Like the previously discussed studies, no attempt was made to model the infiltration process.

McWhorter et al. (1979) conducted an extensive study of the surface and subsurface hydrology of surface mined watersheds. The study was conducted on a surface mine in Colorado and an extensive monitoring program on a 110 km² watershed. Field test plots were also established at the Colorado mine and also at a mine in Montana. Large volumetric lysimeters were installed and rainfall was simulated with two different methods. The first method used shrubbery nozzles and the second method used Rainjet sprinkler heads. Maximum rainfall intensities were 57.4 mm per hour with a simulated rainfall period of 50 minutes. The field lysimeter systems were installed with tensiometer cups and a neutron probe access tube. A surface runoff trough system was installed to measure surface flow. The neutron probe was calibrated in a laboratory study. Hydraulic conductivities were measured both in the field and in the laboratory. The laboratory study used a constant head permeameter and measured the saturated hydraulic conductivity for several bulk densities. In the field the infiltration rate during constant surface runoff was assumed to be equal to the saturated hydraulic conductivity. The values of the saturated hydraulic conductivity estimated in this manner were too large. The Brooks-Corey (1964) equation (Eq. 1) was used to estimate unsaturated hydraulic conductivities. Moisture retention curves were developed by conducting laboratory tests. The data was then fitted to the Su-Brooks parametric equation :

$$\psi = \psi_i \left[\frac{S - S_r}{a} \right]^{-m} \left[\frac{1 - S}{b} \right]^{bm/a} \qquad [1]$$

where:

ψ = capillary pressure (suction) head,

ψ_i = capillary pressure head at inflection point,

S = saturation,

S_r = residual saturation,

m = shape factor of the curve,

a = domain of saturation associated with concave portion of curve, and

b = domain of saturation associated with convex portion of curve.

Infiltration was modeled by solving the flow equations. Flow in the partially saturated zone was estimated using the following form of the Richards equation :

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\ [\,(D(\theta)\ \frac{\partial\theta}{\partial z})]\ -\ K(\theta) - S_s \qquad [2]$$

where:

$D(\theta)$ = diffusion coefficient,

θ = soil moisture content,

K = hydraulic conductivity (L/T),

t = time dimension (T),

S_s = sink term used to simulate evapotranspiration,

Z = depth.

A backward implicit finite difference scheme was used to solve the equation for the boundary and initial conditions of the experimental system. Flow in the saturated zone was simulated using the following form of the continuity equation and Darcy's law:

$$\frac{\partial}{\partial x}\left(Kh\ \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kh\ \frac{\partial H}{\partial y}\right) = S\ \frac{\partial H}{\partial t} + \frac{Q}{\partial x \partial y} \qquad [3]$$

where:

h = saturated thickness of aquifer or confined aquifer thickness (L),

H = water table elevation or piezometric head, referred to an established datum (L),
S = storage coefficient for confined case or effective porosity for unconfined case (dimensionless),
Q = net groundwater withdrawl (L^3/T),
x,y = space dimensions (L), and

The equation was solved using a central finite-difference scheme. Close agreement was found between the measured and calculated infiltration volumes. A simulation run was made for a period of over 50 days and good results were obtained based on the initial parameter estimates.

Overton and Crosby (1979) conducted an extensive study on the effects of steep contour mining on stormwater response and pollutant yield for small watersheds. The study was conducted in the New River basin in Tennessee and six watersheds were monitored. The watersheds ranged in size from 160 to 1200 hectares and the watershed slopes varied from 31 to 39 percent. Infiltration was not monitored, but estimates can be made based on the measurement of rainfall and surface runoff. The storm runoff was modeled using a computer model, TENN-I (Troxler, 1978). The model uses the SCS curve number procedure for estimating initial abstractions and surface runoff. Results of an evaluation made with five different storm events are presented in the report. Generally, the model gave good estimates of surface runoff. It should be noted, however, that model parameters were optimized based on data from these watersheds.

Lersch (1979) describes a study conducted on reclaimed land in Pennsylvania. The tests were conducted on a reclaimed fly ash disposal site and the soil profile consisted of a 107 cm layer of fly ash and surface layer of 15 cm of shaley silt loam. A rainfall simulation study was conducted and an infiltration equation was developed by fitting the data in a regression analysis. The equation can be expressed as :

$$\ln f = 63.65 - 107.85\,(\coth (d/d_f) + 44.92\,(\coth (d/d_f))^2 \qquad [4]$$

where d is the depth of available water in the root zone at time t and d_f is the depth of available water in the root zone at the end of the field test. Although the equation gave a very good fit to the experimental data ($R^2 = 0.975$) , application of the equation would be very questionable. It can be seen that the equation is a function of the change in water deficit in the soil profile and it is therefore probable that the Green-Ampt equation for a layered soil profile would give good estimates for this location.

Younos and Shanholtz (1980) conducted a laboratory study to determine physical and hydraulic properties of surface mine soils and spoils from a West Virginia surface mine. Saturated hydraulic conductivities were determined by a constant head method and water retention curves were determined using pressure-plate procedures. A, B, and C horizon pre-mining bulk densities were 1.18, 1.62, and 1.83 g/cm^3, respectively. Post-mining topsoils exhibited a bulk density of 1.78 g/cm^3. The authors concluded from their study that the water holding capacity of the reclaimed profiles showed a significant decrease from pre-mined values and there was also a significant decrease in saturated hydraulic conductivity.

Hydrologic research on drastically disturbed surface mined lands has only just begun to see widespread interest. Very few studies have been conducted, and in most of the studies insufficient data was collected to model hydrologic processes. The work by Rogowski (1979), Rogowski and Weinrich (1981), McWhorter et al. (1979), Lersch (1979), and Schafter et al. (1979) appear to be the only comprehensive hydrologic studies which have been conducted on surface mined lands. None of these studies present recommended models for use in these areas and all the studies show widely different results. Considerably more research is required in this area.

Soil Moisture Models

Recent development of soil moisture models based on column mass balance provide an alternative to directly or indirectly measuring soil moisture in the field. Using conservation of mass, the soil moisture in the system at any time can be determined using the relationship:

$$SM_t = SM_{t-1} + P - R - L - E - T + C - Q \qquad [5]$$

where:

SM_t = soil moisture volume at time t;

SM_{t-1} = soil moisture volume at previous time;

P = precipitation;

R = surface runoff;

L = net lateral subsurface outflow;

E = evaporation or condensation;

T = transpiration;

C = capillary rise from lower levels;

Q = percolation.

This generalized model represents only a single column that is horizontally homogeneous at all levels. Actual systems are heterogeneous and can be represented by spatial averages or by linked columns that account for the spatial variability.

Soil moisture models vary in the level of detail used in representing the physical system and temporal variations of the driving forces. Some of the important differences between models are (1) method used for computing infiltration and runoff, (2) temporal definition of evaporative demand and precipitation, (3) consideration of saturated and unsaturated levels, (4) number of soil layers used, (5) method used for computing soil evaporation and plant transpiration, and (6) consideration of the thermal properties of the soil system.

Many of the published models that simulate soil moisture were developed for agricultural applications. Holmes and Robertson (1959) presented a simple model considering the soil as a single homogeneous layer. Potential evapotranspiration is computed empirically, and the actual evaporation is set equal to this as long as moisture is available. All precipitation becomes infiltration and groundwater interactions are ignored. All computations are performed on a daily basis.

Jensen et al. (1971) developed an irrigation scheduling model that takes into account soil moisture. Evapotranspiration is computed on a daily basis using one of several alternative procedures. Actual evapotranspiration is not affected by moisture deficits. Infiltration must be computed externally. Percolation is computed using an empirical relationship. The model treats the soil as a single layer.

Holmes and Robertson (1959) presented a second model which is more sophisticated than those described above. This model uses a two-layer soil system and considers the fact that actual evaporation will generally not equal the potential due to moisture deficits. The two are set equal until the moisture in the upper soil zone is depleted. Thereafter, moisture is extracted from the lower zone at a reduced rate proportional to the moisture level. This model also allows a simple runoff computation.

Baier and Robertson (1966) presented a versatile soil moisture budget model. This model divides the soil into several layers, and the available water capacity of each layer is taken to be the difference between soil's field capacity and wilting point. Evapotranspiration can occur simultaneously from each layer and depends on the soil moisture present and the particular soil and root distribution of the plants involved, which are represented by coefficients. Flow between layers is considered; however, the technique used is empirical, as is the procedure used for computing infiltration.

Ritchie (1972) developed a model to predict daily soil and plant evaporation, drainage, and soil moisture using initial soil moisture, daily climatic data, and model parameters that are based on physical characteristics of the soil being studied. From here on Ritchie's model will be refered as the plant available soil moisture (PASM) model.

The PASM model is divided into five major components. For details of the mathematical relationships the reader is referred to the original papers published by Richardson and Ritchie (1973), Ritchie and Jordan (1972), and Ritchie (1972). Only a brief description of the PASM model and equations are given in the following paragraphs.

The models' first function is to compute daily potential evaporation. The model contains two alternatives for estimating daily potential evaporation: Penman's equation or open pan evaporation data. Neglecting the soil heat flux, Penman equation can be written as:

$$E_o = \frac{(\Delta H_o + Y E_a)}{(\Delta + Y)} \qquad [6]$$

where E_a is given by

$$E_a = 0.35\,(e_a - e_d)\,(1 + 0.0098U_2) \qquad [7]$$

where:

E_o = potential evaporation, mm per day;

Δ = slope of the saturation vapor pressure curve at the mean air temperature, mm Hg per °F;

E_a = a measure of the drying power of the air, mm per day;

e_a = saturation vapor pressure at the mean air temperature, mm Hg;

e_d = actual vapor pressure of the air, mm Hg;

H_o = net radiation, mm per day;

U_2 = wind speed at 2 meters above the ground, miles per day.

Penmans' equation needs daily values of net radiation, maximum and minimum temperatures, wind movement and vapor pressure. In areas where data needed for Penman's equation are not available, or when a simpler input is desired, pan evaporation data can be used to estimate potential evaporation. The relationship between pan and potential evaporation depends on the type of evaporation pan, geographical location, pan exposure and season. Pan coefficients were determined using the method developed by Cuenca (1982).

Evaporation of water from a wet soil surface is limited by the evaporation potential at the soil surface. When the soil surface is bare, the potential at the surface is equal to E_o as defined by equation (6). When a plant canopy shades part of the soil surface the potential below the canopy is reduced because of increased humidity, and decreased net radiation and wind speed. Several researchers have reported values of the fraction of net radiation below a plant canopy for several crops with various leaf area index values. Ritchie (1972) summarized previous researchers results and defined net radiation as:

$$H_{so} = H_o e^{-0.40LAI} \qquad [8]$$

If E_a in equation (6) is assumed zero due to increased humidity and decreased wind speed below the canopy, Penman's equation for potential evaporation below a plant canopy may be written as:

$$E_{so} = \Delta H_{so}/(\Delta + Y) \qquad [9]$$

When potential evaporation is calculated from pan evaporation data, the reduction in potential evaporation below a plant canopy is assumed equal to the reduction of H_o given by equation (9). Potential evaporation at the soil surface is calculated from the equation:

$$E_{so} = E_o e^{-0.40LAI} \qquad [10]$$

where E_o is the above - canopy value calculated from pan evaporation.

The soil evaporation process has been considered to take place in two stages: the constant rate stage and falling rate stage (Penman, 1956 and Philip, 1957). During the constant rate stage (Stage I) soil evaporation is limited only by the energy available at the soil surface. The amount of drying that occurs during the constant rate stage depends on the water transmission characteristics of the soil and may be practically defined by an upper limit of cumulative evaporation from an initially wet soil (U). When cumulative evaporation exceeds U, the soil evaporation rate drops below E_{so} and the falling rate stage (Stage II) begins. Soil evaporation during Stage I may be defined by:

$$E_S = E_{so} \ , 0 \leq \sum E_{SI} \leq U \qquad [11]$$

Soil evaporation during the falling rate stage is dependent on soil water content near the surface and the water transmission characteristics of the soil. Because of declining soil water, cumulative evaporation during Stage II is related to time and may be approximated by:

$$\sum E_{sII} = \alpha\, t_s^{1/2} \qquad [12]$$

Ritchie (1972) showed that values of U and α for four soils were related to soil hydraulic conductivity at -0.1 bar soil matric potential. Daily soil evaporation during Stage II is computed by calculating $\sum E_{sII}$ for a given day and subtracting $\sum E_{sII}$ for the previous day. If daily values of E_s obtained by use of equation (12) exceeds E_{so}, E_s is limited to E_{so}.

On days that rain occurs, $\sum E_{sII}$ must be redefined by subtracting the effective rainfall so that the proper value of t_s can be determined. If the rain on a given day is greater than $\sum E_{sII}$ for the drying cycle, soil evaporation is again placed in Stage I and $\sum E_{sI}$ is redefined. When rains during Stage II are less than $\sum E_{sII}$, E_s should be greater than that indicated by equation (12). When such a rain occurs, E_s for the day of the rain is computed by:

$$E_s = 0.8\, P \qquad [13]$$

where P is the precipitation in mm per day.

The portion of the rain that does not evaporate is assumed to go into equilibrium with the soil water near the surface. If E_s obtained from equation (13) is less than E_s from equation (12) the value for equation (12) is used. In either case if E_s exceeds E_{so}, E_s is limited to E_{so}.

The plant evaporation during the plant development is computed by the following equation:

$$E_p = E_o\,(-0.21 + 0.70\sqrt{LAI}\,), \quad 0.1 \leq LAI \leq 3.0 \qquad [14]$$

The sum of E_s and E_p for each day is limited to E_o. Equation (14) indicates that E_p is approximately equal to E_o when an LAI value of 3.0 is reached. An LAI value of 3.0 is the upper limit of LAI for equation (14) to apply and represents the minimum LAI to provide an apparent 'full cover'. For LAI values greater than 3.0, plant evaporation is computed according to the following equation provided soil water is not limited:

$$E_p = E_o - E_s, \quad LAI > 3.0 \qquad [15]$$

The sum of the computed daily plant and soil evaporation is equal to the daily total evaporation if the soil water is not limited. However, van Bavel (1967) and Ritchie et al. (1972) suggest that a soil water threshold exists, below which the soil water potential limits plant evaporation rates. van Bavel's data indicate that for the soil and climate in his study, 167 mm of water was evaporated at the potential rate following irrigation of alfalfa. After reaching the threshold, another 62 mm was extracted at a decreasing rate. The threshold, called the lower limit for potential evaporation, LLE_o, by Ritchie et al. (1972), was reached in Houston Black clay soil when 182 mm of water had been removed by cotton and grain sorghum from an initially wet soil profile. An additional 65 mm was extracted at a decreasing rate before evaporation practically stopped and the lower limit of water availability (LL) was reached.

The data of both van Bavel (1967) and Ritchie et al. (1972) indicate that evaporation rate between LLE_o and LL for plants with a fully developed canopy decreases with decreasing soil water and is proportional to the square root of time. The following equation given by Ritchie and Jordan (1972) is used in the model when soil water becomes limited and the plant canopy is fully developed.

$$E_p = \overline{E}_o\left[1 - \left\{\frac{t}{t_L}\right\}^{1/2}\right], \quad 1 \leq t \leq t_L \qquad [16]$$

The value of t_L may be determined by solving the integrated form of equation (16) if LLE_o, LL and $\overline{E}_o$ are known. Integrating equation (16) from 0 to t_L and rearranging terms yields:

$$t_L = 3\sum E_p/\overline{E}_o \qquad [17]$$

where $\sum E_p = LLE_o - LL$, if E_s is neglected.

In using equation (16), t is set to zero on the day LLE_o is reached. The value of t is increased by one each day, and the daily value of E_p is computed from equation (16). If the daily potential evaporation is low, and $E_o - E_s$ is less than E_p from equation (16), E_p is limited to $E_o - E_s$.

If soil water in the root zone is assumed to be uniformly distributed, the water available for plant use is a function of the depth of root development and the soil water transmission characteristics. Therefore, soil water could be limited with a relatively high average soil water content for the entire profile if the crop is young and root development is shallow. Evaporation data for cotton in 1967 (Ritchie and Burnett, 1971) indicates that equation (16) does not apply when water becomes limited and the plant LAI is less than 3.0. Root growth into wet soil in 1969 apparently caused evaporation to remain relatively constant at about 1/3 of that predicted without water limiting conditions using equation (14). Plant water stress began limiting evaporation when the soil water content was approximately 75 percent of the upper limit of soil water storage (UL) and the LAI was 1.0. Assuming that LAI reflects the degree of root development, an equation was developed relating LLE_o to LAI for LAI less than 3.0. If the equation indicates that LLE_o is reached with LAI less than 3.0, E_p is computed in the model as 1/3 of the value obtained from equation (14). If LAI is 3.0 or greater when LLE_o is reached, equation (16) is used.

The soil water accounting procedure used in the model requires that UL be defined. A daily soil water balance is kept using the equation:

$$SW_2 = SW_1 + P_2 - E_2 \qquad [18]$$

If SW_2 from equation (18) is greater than UL; drainage out of the soil profile is indicated and is defined in the model by

$$D = SW_2 - UL \qquad [19]$$

SW_2 is then set equal to UL.

Inherent in equation (19) is the assumption that all water entering the soil in excess of the upper limit drains out the same day. Actually, soil drainage takes place over several days, but the error caused by the assumption is small and is corrected within a few days when soil water drains down to the upper limit.

Infiltration and runoff can be partitioned by a form of the SCS runoff curve number procedure (Kent, 1968). This modification of the Richardson and Ritchie (1973) model was incorporated by Rojiani et al. (1982). The model assumes that the water entering the soil in excess of the upper limit of soil water storage (SWS) drains out the same day. Although, soil drainage takes place over several days, the error caused by the assumption is small and is corrected with in a few days when SWS reaches the upper limit of SWS.

Climatic data necessary to use the model are 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.

Saxton et al. (1974) developed a much more comprehensive model that simulates soil-plant-atmosphere-water systems in greater detail than the models described above. This model considers most factors that influence the system. The soil moisture distribution process is modeled using a physics based approach, while other processes like plant transpiration are semi-empirical.

Many other models which are similar to those mentioned above have been developed. Additional information can be obtained from the works by Saxton and McGuinness (1979), Feddes et al. (1978), Hildreth (1978), Singh (1971), Kanemasu et al. (1976), Stuff and Dale (1978), Shaw (1963), Goldstein et al. (1974), Ritchie (1972), and Richardson and Ritchie (1972).

All the above mentioned models were developed primarily for agricultural applications. Hydrologists have also developed water balance models that include a soil moisture component. Examples of the modeling approaches can be found in the U.S. Department of Agriculture, Hydrograph Laboratory (USDAHL) model (Holtan et al., 1975) and the National Weather Service River Forecast Model (NWSRFS) (Peck, 1976). These models can be used to simulate volumes and rates of water movement occurring in each component of the watershed.

In the USDAHL model, the spatial variability of soils and vegetation is accounted for by using zones within which the hydrologic parameters are averaged. Within each zone the soil is subdivided into several homogeneous layers determined from hydraulic properties. Evapotranspiration is computed daily using an empirical equation which considers crop and soil characteristics, as well as the current soil moisture. Evapotranspiration is drawn from the first two layers, which are considered to be the root zone. These computations are performed daily. Infiltration is also based on soil and crop characteristics and the current soil moisture. A 1-hour time step is used for these computations. The procedure used for soil moisture redistribution and percolation only considers gravity flow.

In the NWSRFS model, two zones are used to simulate soil water storage and movement. The upper layer responds quickly to rainfall and controls overland flow. It is usually very shallow. The lower layer is the balance of the soil column extending to the water table. Soil hydraulic properties are averaged within each layer. Moisture is stored as either tension or free water. Infiltration, percolation and soil moisture redistribution involve the free water. They are computed with empirical equations that use as a controlling factor the ratio of the free water present to the field capacity of the layer involved. Evapotranspiration is computed using an empirical procedure. Actual evapotranspiration is set equal to potential until all moisture in the upper layer is depleted. When this occurs, moisture is extracted from the lower zone using an equation that considers the moisture deficit and crop characteristics. A 6-hour time step is used for simulation.

The above mentioned models have been used for practical problems such as crop yield prediction, irrigation planning, and runoff forecasting. Most of these models were developed to use readily available weather data for inputs, and therefore, usually use a 1-day time step. These models can produce accurate weekly average results, however, the daily results will show some deviation on any given day. Jensen et al. (1971) and Goldstein et al. (1974) stated that the expected daily errors of 10 to 15% should become negligible over 10-20 days.

In some situations, greater accuracy and time resolution is required than these models can provide. Much research has been done on the physics of soil water movement and storage under bare soil conditions. These models usually involve solving the equations describing one- dimensional vertical unsaturated flow and horizontal saturated flow. Most of these models differ on the boundary conditions imposed and the numerical approximations used for solution.

Hillel (1977) described several physically based models designed to simulate soil moisture conditions under bare soil conditions. Freeze (1978) presented a two-dimensional solution to the soil moisture problems. Models with detailed plant effects increase model complexity and have been presented by Van Bavel and Ahmed (1976), Lemon et al. (1973), Makkink and van Heemst (1975), Hanson (1975), Slack et al. (1977), Feddes et al. (1976), Neuman et al. (1975), and Nimah and Hanks (1973). The principal advantage of models is that they can provide timely soil moisture information without the necessity of field visits. A general disadvantage of models is the error of their estimation. This review shows that soil moisture modeling has reached a stage that a model can be adapted to many problems.

Vegetation Yield Prediction Models

To study the problem of optimal selection of mine soil properties for different probability levels of success of meeting the revegetation standards, it is necessary to understand and quantify the vegetation response to the stochastic weather regime. The potential vegetation response of a given species is an extremely complex function depending on weather factors and soil and plant characteristics. Because of these complexities the best way to define weather-vegetation relationships is by means of extensive field experimentation for each particular region and type of vegetation, maintaining the nonclimatic factors as constants.

Most existing plant growth models use evapotranspiration as a growth index. Several researchers have indicated that plant growth is a function of factors that contribute to the plant water stress (Flinn, 1970; Hiler and Clark, 1971; Hagan and Stewart, 1973; Downey, 1972; and Yaron et al., 1972). They conclude that the stress situations occur when the actual rate of evapotranspiration is less than the potential rate. When the actual rate is equal to the potential, the plant is assumed to grow at its maximum rate.

A considerable amount of evidence has been accumulated to support the idea of using the actual evapotranspiration as a surrogate measure of a plant growth. Several experimental studies indicate remarkable correlation between the seasonal evapotranspiration and total yield (Stewart et al., 1974; Morey et al., 1975; and Barrett et al., 1978).

In most of the plant growth models, the basic assumption is that any plant variety has a genetically defined potential yield and that the actual yield is a result of environmental stress on plant growth. The surrogate variable which best reflects the environmental effect in yield reduction is the evapotranspiration rate. The main difference between the plant growth models described in the literature is the way they account for the stress factor, usually taken as the ratio of actual to potential evapotranspiration at each stage of growth. Some of these models consider the stress effect to be additive while other models consider the effect to be multiplicative.

Flinn and Musgrave (1967) presented a model which considers the variation of evapotranspiration with the soil moisture content, maintaining the additive growth assumption and relating the actual growth to the number of days on which the actual evapotranspiration rate is equal to the potential value. They recognized different plant responses at different growth stages. However, their assumption that growth ceases when the actual evapotranspiration rate is less than the potential may not be accurate. Hall and Butcher (1968) postulate a multiplicative relationship between plant growth in different periods. They argue that the multiplicative approach has computational advantage over the additive approach since if plant death occurs in any stage the final yield will be zero regardless of growth in other stages. They define the function $\alpha_k(\theta_k)$ that represents the effect of moisture deficiency during growing period k on the total yield. The resulting actual yield, Y is, expressed as :

$$Y(q) = \prod_{k=1}^{n} \alpha_k(\theta_k)\ Y_M(q_M) \qquad [20]$$

where: q =total amount of water received by the plant per unit area; $Y_M(q_M)$ = maximum yield that can be obtained with the maximum quantity of water q_M ; θ_k = available soil moisture during period k; k = growing period index; n = number of growing periods. The sensitivity function

$\alpha_k(\theta_k)$ must be defined experimentally for all periods ($k = 1, \ldots, n$) by letting θ_k vary over a range of soil moisture values.

Jensen (1968) suggested a multiplicative model which related the yield ratio to the ratio of actual over potential evapotranspiration in each growth stage. The model is expressed as:

$$\frac{Y}{Y_M} = \prod_{k=1}^{n} [\frac{ET}{ETP}]_k^{\lambda_k} \qquad [21]$$

where: ET and ETP = the actual and potential evapotranspiration, respectively, for period k, and λ_k = the crop sensitivity factor to water stress.

Hiler and Clark (1971) developed an additive model which also related the yield ratio to the evapotranspiration ratio. The model is:

$$\frac{Y}{Y_M} = \sum_{k=1}^{n} (SD_k + CS_k) \qquad [22]$$

where: SD = stress day factor, which measures the duration and degree of plant water deficit, $SD_k = 1 - [\frac{ET}{ETP}]_k$, and CS = crop sensitivity factor to water deficit.

Minhas, Parikhm, and Srinivasan (1974) developed another type of multiplicative model which also uses the ratio between the actual and the potential evapotranspiration. The general form of the equation is :

$$\frac{Y}{Y_M} = \prod_{k=1}^{n} (1 - (1 - (\frac{ET}{ETP})_k^2))^{b_k} \qquad [23]$$

where b_k is a plant sensitivity factor to water deficits.

Minhas et al. (1974) fitted their model to the data obtained from 21 experiments involving wheat in Delhi, India, during 6 different years. By using regression analysis, they determined the parameters of the model, concluding that by using the evapotranspiration ratio as an independent variable, they could explain up to 98.7 percent of the variance in yield.

Howell (1974), using experimental data for grain sorghum collected by Hiler and Howell (1973), Lewis et al. (1974) and Stewart et al. (1974), tested three different yield models (Hiler and Clark, 1971; Jensen, 1968; and Minhas et al., 1974). The coefficients of each model were computed by means of a multivariate regression technique. For all cases, the value of the correlation coefficient was higher than 0.96, showing no significant differences between the multiplicative and additive formulations.

Blank (1975) using experimental data from Colorado State University tested the multiplicative model described by Jensen (1968) and a simple additive model given by the following equation :

$$\frac{Y}{Y_M} = \sum_{k=1}^{n} a_k [\frac{ET}{ETP}]_k \qquad [24]$$

where a_k is the plant sensitivity parameter. A standard stepwise linear regression code was employed to fit the coefficients of both models to experimental data. A better fit was found with the additive type of model.

Hanks et al. (1977), using data for corn collected during the experiments carried out in Arizona, Colorado, California, and Utah, tested the validation of the models proposed by Stewart (1974), Hanks (1974), and Hall and Butcher (1968). The additive models proposed by Stewart (1974) were:

$$\frac{Y}{Y_M} = 1 - \beta_0 [\frac{ETP - ET}{ETP}] \qquad [25]$$

and

$$\frac{Y}{Y_M} = 1 - \sum_{k=1}^{n} \beta_k [\frac{ETP - ET}{ETP}]_k \qquad [26]$$

where β_0, and β_k are plant sensitivity parameters.

The multiplicative models proposed by Hanks (1974) were :

$$\frac{Y}{Y_M} = \frac{T_a}{T_p} \qquad [27]$$

and

$$\frac{Y}{Y_M} = \prod_{k=1}^{n} [\frac{T_a}{T_p}]_k^{\lambda_k} \qquad [28]$$

where T_a and T_p are actual and potential transpiration respectively. The main conclusions drawn from their results are that in general the additive Stewart models were better than those proposed by Hanks (multiplicative type).

The plant growth models described above show considerable evidence that the evapotranspiration ratio represents the best independent variable for predicting plant growth and yield. Since evapotranspiration directly depends on the plant available soil moisture and climatic factors, the stochasticity of plant growth due to the different climatic inputs can be analyzed through the randomness of the plant available soil moisture.

There are two basic types of dynamic plant growth models. The most common type is the regression model which is based upon specific experimental data. The other model uses deterministic equations based upon fundamental plant growth physiology and the physics of the environment. A model is usually site and crop specific when it is based upon regression equations developed from site, crop, and/or management specific data. The usefulness of such models is often limited to the physiographic area, crop, and management regimes from which the specific data base was derived.

A model is robust in its applicability when continuous mathematical-logical equations are used to describe the fundamental relationships among the variates that affect time related changes in the attributes considered by the model. Continuous relationships between plant growth, air temperature, daylength, leaf area, photoperiod and plant-soil-moisture stress are considered. Biomass production is the attribute used to signify plant growth. This attribute is generally used to measure the revegetation success, because rapid biomass production helps in establishing a complete ground cover needed for erosion control from mine soils. The growth rate of a crop is the time rate of change in the accumulated dry matter, usually expressed in unit of kg/ha/day of dry matter. Growth rate is the slope of growth function and is also a continuous function. The growth rate can be calculated from accumulated dry matter measurements.

Crop growth is seasonal, because crops are genetically adapted to grow in certain temperature regimes. Plant physiologists (Salisbury et al., 1969) suggest that three characteristic air temperatures affect crop growth. There is a minimum air temperature (t_1) below which growth does not occur. There is a maximum air temperature (t_3) above which growth does not occur. There is an optimum air temperature (t_2) where the growth rate of each crop is optimum. These three characteristic air temperatures and the optimum growth rate (R) are four parameters which partially characterize the genetic potential of each crop. Smith and Loewer (1983) developed and verified a continuous quadratic function to relate growth rate to the three characteristic air temperatures of the form:

$$\frac{dy}{dt} = C_1 + C_2\,T + C_3\,T^2 \qquad [29]$$

where dy/dt = growth rate of a plant, kg/ha-hr; T = air temperature, °F.

The coefficients C_1, C_2, and C_3 were determined using the four crop parameters (i.e., where $T \leq T_1$ and when $T \geq T_3$, $dy/dt = 0$; and when $T = T_2$, $dy/dt = R$) and three relationships were established to describe the hourly rate of biomass production as functions of T_1, T_2, T_3, R, and T:

$$\frac{dy}{dt} = \frac{R}{(T_1-T_2)^2\,(T_1\,(T_1-2\,T_2)-2\,T_2\,T-T^2)} \qquad \text{for } T_1 \leq T \leq T_2 \qquad [30a]$$

$$= \frac{R}{(T_3 - T_2)^2 \; (T_3 \; (T_3 - 2 \; T_2) + 2 \; T_2 \; T - T^2)} \qquad \text{for} \quad T_2 \leq T \leq T_3 \qquad [30b]$$

$$= 0 \qquad \text{for} \quad T \leq T_1, \; \text{or} \; T \geq T_2 \qquad [30c]$$

The following two relationships describe the air temperature for a diurnal period as functions of the minimum (T_{min}) and maximum (T_{max}) daily air temperatures and the daylength (DL):

$$T = T_{min} - \frac{4 \; t(T_{min} - T_{max})}{DL} + \frac{4 \; t^2(T_{min} - T_{max})}{DL^2} \qquad \text{for} \quad 0 \leq t \leq \frac{DL}{2} \qquad [31a]$$

$$= \frac{(T_{min} + T_{max})}{2} + 2 \; t \frac{(T_{max} - T_{min})}{DL} + 2 \; t^2 \frac{(T_{min} - T_{max})}{DL^2} \qquad \text{for} \quad \frac{DL}{2} \leq t \leq DL \qquad [31b]$$

Equations (31a) and (31b) for air temperatures are substituted for T in each of the two rate (dy/dt) equations (equations 30a and 30b) resulting in four differential equations which are homogenous with respect to time (t). These equations are solved by integrating over the period of time when each equation is applicable to obtain the daily growth rate in kg/ha/day based upon the air temperature regime.

A functional relationship was used to relate the leaf area factor (LAF) to the quantity of accumulated dry matter which is the photosynthetically active part of plants. The relationship is:

$$LAF = XLEAF + \frac{2 \; (1 - XLEAF)ADM}{Q_3} - \frac{(1 - XLEAF)ADM^2}{Q_3^2} \qquad \text{for} \quad ADM \leq Q_3 \qquad [32]$$

$$= 1.0 \qquad \text{for} \quad ADM \geq Q_3$$

where LAF = leaf area factor ($0 \leq LAF \leq 1$); XLEAF = 0.001; Q_3 = the maximum quantity of accumulated dry matter that provides enough leaf area for maximum growth; and ADM = the accumulated dry matter which is the sum of daily growth rates.

Holt et al. (1975) defined a photoperiod effect on the growth rate of perennial crops as a physiological phenomenon of storing carbohydrates in the lower portion of the crops after the summer-solstice when the daylength is decreasing. The stored carbohydrates are used to regenerate growth after a period of dormancy. The photoperiod function developed can be expressed as:

$$PF = 1.0 + \frac{C - 1.0}{B - A}\ (DL - A) \qquad [33]$$

where: PF = a photoperiod factor which reduces the daily growth rate as a consequence of a portion of the carbohydrates which are produced by photosynthesis being stored instead of being used for growth ($C \leq PF \leq 1.0$); A = daylength (after the summer solstice) when the crop begins to store carbohydrates; B = daylength when the portion of carbohydrates going into storage reaches a constant value, hours; C = maximum effect of photoperiod as a proportion of the optimum growth rate ($0 \leq C \leq 1.0$); and DL = daylength in hours ($B \leq DL \leq A$).

As the daylength continues to decrease,

$$PF = C \qquad [34]$$

until the winter solstice is reached and then,

$$PF = 1.0 \qquad [35]$$

A, B, and C in equations (33) and (34) are crop parameters which reflect the genetic characteristics of each crop with respect to storing carbohydrates to regenerate growth after a period of dormancy.

Smith and Loewer's (1983) non-specific perennial crop growth model as explained above was based on physical relationships of plant-soil-moisture and environmental factors. This model has been used in several states in the U.S..

Stochastic Dynamic Optimization Approach

Dynamic programming is a particular approach to optimization. Dynamic programming is one method used for solving certain kinds of optimization problems, some of which can, in principal, be solved by other procedures. Dynamic programming is a way of looking at a problem which may contain a large number of interrelated decision variables so that the problem is regarded as if it consisted of a sequence of problems, each of which requires the determination of only one or a few variables. Ideally, a solution is obtained by solving n single variable problems rather than one n variable problem. When this is possible, less computational effort is required. Solving n smaller problems requires a computational effort which is proportional to n, the number of single variable problems if each problem contains one variable. On the other hand, solving one larger problem with n variables usually requires a computational effort which is roughly proportional to a^n, where a is a constant. Hence the desirability of transforming or considering an n-dimensional problem as n one-dimensional problems.

The principal that enables us to carry out the transformation as discussed in the previous section is known as the "principal of optimality". It was first enunciated by Bellman (1957). It has an intuitively obvious basis (Bellman's justification consists of the single statement, "A proof by contradiction is immediate"). The principal of optimality is: "An optimal policy has the property that whatever the initial state and the initial decision are, the remaining decisions must constitute an optimal policy with respect to the state which results from the initial decision."

The dynamic programming approach has several advantages over other optimization methods. One of the main advantages of dynamic programming as explained earlier is the transformation of a single n-dimensional optimization problem into n one-dimensional optimization problems which can be solved one at a time. The classical extremum methods of analysis can not do this. A second extremely important advantage of dynamic programming over almost all other extant computational methods, and especially classical optimization methods, is that dynamic programming determines absolute (global) maxima or minima rather than relative (local) optima. Hence local maxima or minima are of no concern.

In virtually all other optimization techniques, certain constraints can cause significant problems. For example, the imposition of integrality on the variables of a problem cannot be handled by classical methods. However, in dynamic programming the requirement that some or all of the variables be integers greatly simplifies the computational process.

There are, however, certain limitations to the use of dynamic programming. The principal one is the dimensionality of the state space. What this means in simple language is that if there are more than two or three "state" variables (as distinct from decision variables), then there are computational problems relating to the storage of information as well as the time it takes to perform the computation. However, some methods deal with the dimensionality problems and make dynamic programming an unique approach for specific problems.

System analysis techniques such as simulation and dynamic programming have been used in the past to determine the optimal operation policies in irrigation systems (Hall and Butcher, 1968; Anderson and Maass, 1971; Burt and Stauber, 1971; Dudley et al., 1971; Dudley, 1972; Dudley and Burt, 1973; Howell, 1974; Blank, 1975; Van Bavel et al., 1976; Maji and Heady, 1978; Matanga and Marino, 1979; Zavaleta et al., 1980; Rhenals and Bras, 1981; Tsakiris and Kiountouzis, 1982; Tsakiris and Kiountouzis, 1984; and McGuckin et al., 1987). These existing stochastic models compute the probability transition matrices of the soil moisture content within each decision stage by simulating the system for different initial conditions.

Although many research applications of dynamic programming to agriculture and natural resource problems have been reported, there are few reports of the commercial use of dynamic programming on a day-to-day basis. It is always a question whether dynamic programming will retain its status as essentially a research technique, or whether it will eventually come to be regarded as an operational technique, helping to determine actual resource management.

One reason for the lack of operational use of dynamic programming may be that it has not been used to answer the practical questions faced by resource managers. Day and Sparling (1977) made a comment about dynamic programming while reviewing the use of optimization models in agriculture and resource economics: 'After a first flash of excitement induced by the flexibility and potential of Bellman's approach as typified by Throsby (1964), applications have been limited to rather simple subsystems of total farm systems.'

The notion that there are few uses for dynamic programming in practical resource management has to be seriously questioned. Dixon and Howitt (1980) note that 'most emperical natural resource management problems are intertemporal optimization problems under uncertainty'. The same is true of most farm management problems. By definition, intertemporal optimization problems can only be solved by using dynamic optimization techniques. Basically, the techniques available for solving deterministic dynamic problems are: various forms of mathematical programming, such as linear, seperable and quadratic programming, with matrices of dated activities; non-linear programming or gradient methods; and dynamic programming. Dynamic programming is a natural technique to choose for solving stochastic dynamic problems. However, the point to be made is not that dynamic programming is the most appropriate technique for solving all resource problems, merely that it can be used for solving many resource problems.

Although, there are many potential applications of dynamic programming in agriculture and natural resource industries, the obvious question is then why it is not being used more as a management tool? One reason may be institutional in the case of natural resource industries. Land, forest and fishery resources are often national or social resources. Policy, framed at the government level, often defines the parameters within which private resource users can operate. In such a planning environment, dynamic programming results cannot be used as an operational tool. However, they can be an important source of advice to government.

In the case of agriculture there do not appear to be institutional constraints of this type to the same extent. Prerequisites for applying dynamic programming which may be lacking are managers' understanding of the technique, relevant data, computer software, and computing power. This study considered dynamic programming as a management tool to assist reclaimed mine soil managers' for revegetation planning. It is hoped that the present application will open a door for dynamic programming in the agriculture and natural resources management.

MODEL DEVELOPMENT

This chapter presents the submodels used in developing a comprehensive physically based SDOM planning model for revegetation of reclaimed mine soils. The PGGM submodel considers the physical relationships between plant growth and environmental factors and was used to generate long-term biomass yield for tall fescue. The generated long-term biomass yield was used as input to the probability model. The final section presents the mathematical formulation of SDOM for strip mine revegetation which essentially gives the optimum combination of mine soil characteristics for successful revegetation at a given level of probability of revegetation success. The following sections give a detailed outline of the models.

Development of a Perennial Grass Growth Model (PGGM)

One of the important submodels required to satisfy the major goal of this study was the PGGM. In reclaimed mined areas it is desirable to establish a complete ground cover as rapidly as possible after mining to minimize erosion. The preferred plants for control of early erosion are grasses and legumes. These plants are also beneficial for: wild and domesticated animal forage, hay production, increasing the organic matter content of soils, and controlling acid-water formation. Because grasses and legumes transpire large quantities of water, they reduce the amount of water that percolates down through the root zone of mine soil profiles, resulting in reduced acid-water formation. Vegetation also increases mine soil infiltration and permeability which reduces surface runoff and consequently erosion and peak runoff rates and has an overall beneficial effect on surface mine reclamation.

This section presents the fundamental logic and the necessary improvements and modifications of the PGGM originally developed by Smith and Loewer (1983). The original model considered a rainfall factor to reflect the random effect of rainfall on the growth rate of crops. Their method involves comparision of actual daily rainfall and actual accumulated daily rainfall with normal daily rainfall and normal accumulated daily rainfall. This approach indirectly considers differences in soils, water movement in soils, water utilization by plants, soil surface evaporation and plant transpiration. This logic is limited when evaluating situations where specific soil parameters should be considered as in the case of mine soils. Thus, the present study incorporates a valid water balance model to estimate a soil moisture factor on a daily basis considering the physics of soil-plant-water relationship. In developing such a complex relationship between plant growth and soil moisture stress a sigmoidal relationship was hypothesized and is presented in the following section. A computer program was developed in FORTRAN programming language which is named as VPIGRO and the listing of computer codes are presented in appendix B. VPIGRO model was tested and adopted for predicting vegetation growth on reclaimed mine soils.

Plant Available Soil Moisture (PASM) Model

The amount of plant available soil moisture (ASM) is a function of several complex processes including infiltration, evapotranspiration and drainage. ASM at a particular location can be predicted using meteorological data, plant, and soil properties. Richardson and Ritchie (1973) developed a model to predict the ASM on a daily basis using initial soil moisture, soil properties, plant characteristics, and climatic data as input variates. The Richardson and Ritchie (1973) model was used in this study to generate the daily ASM and subsequently used as input to the PGGM to reflect an environmentally altered plant growth regime. The reason for selecting this PASM model was that it appeared to be one of the best models, it has been used in other parts of the country and because of some evidence of its applicability under Virginia conditions (Rojiani et al., 1982). To measure the effect of soil moisture stress on potential plant growth it was hypothesized that a sigmoidal relationship exists between dry matter yield and ASM. Under this assumption plant growth increases slowly with the increase in ASM up to a certain point, after which there will be a rapid increase in plant growth with further increase in ASM up to a point where it reaches the maximum plant growth.

The ASM is a function of root depth and the soil water transmission characteristics. For an established perennial grass crop (e.g., tall fescue) soil moisture could be a limiting factor when the average soil moisture falls below a critical level (i.e., below 50% of maximum ASM). Established perennial grass roots can penetrate the entire soil depth to a depth of 4 meters. The maximum ASM was measured as the moisture content between 33 Kpa and 1,500 Kpa tensiometer pressure. The maximum ASM was used as an input parameter and was measured in the laboratory for five combinations of sandstone (SS) and siltstone (SiS): 2:1 SS/SiS, 1:1 SS/SiS, 1:2 SS/SiS (Roberts, 1986).

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

$$\mathrm{SMF} = \mathrm{SMAC} * 2, \quad \text{if} \quad 0.25 \leq \mathrm{SMAC} < 0.50 \qquad [36]$$

$$\mathrm{SMF} = \frac{\mathrm{SMAC}}{2}, \quad \text{if} \quad \mathrm{SMAC} < 0.25 \qquad [37]$$

$$\mathrm{SMF} = 1.0, \qquad \text{if} \quad \mathrm{SMAC} \geq 0.50 \qquad [38]$$

where, SMF = soil moisture stress factor; and SMAC = percent of maximum plant available soil moisture.

Mathematical-Logic Flow

The mathematical-logic was programmed to predict dry matter yield for each chronological day as follows:

1. The PASM model was used to calculate a daily soil moisture factor (SMF);
2. Equations (33), (34), and (35) were used to calculate a photoperiod factor (PF);
3. The product of SMF and PF multiplied by R and Q_3 to alter the crop parameters to reflect the environmentally altered growth regime;
4. Equations (30a), (30b), (31a) and (31b) were then solved by separating variables and integrating to get y;
5. Equation (32) was used to calculate leaf area factor (LAF);
6. LAF was multiplied by y to obtain the actual dry matter yield (Y);
7. The Y's were accumulated to obtain accumulated dry matter (ADM) which was used in equation (32) for the next day;
8. Steps (1) to (7) were repeated for the whole growing season (i.e. 183 days) and continued to simulate dry matter yield for all years of input data.

A flow chart of the mathematical-logic flow is shown in Fig. 1.

The input parameters to the model are the crop parameters, T_1, T_2, T_3, R , Q_3 , A, B, and C and the environmental parameters T_1, T_2, and DL.

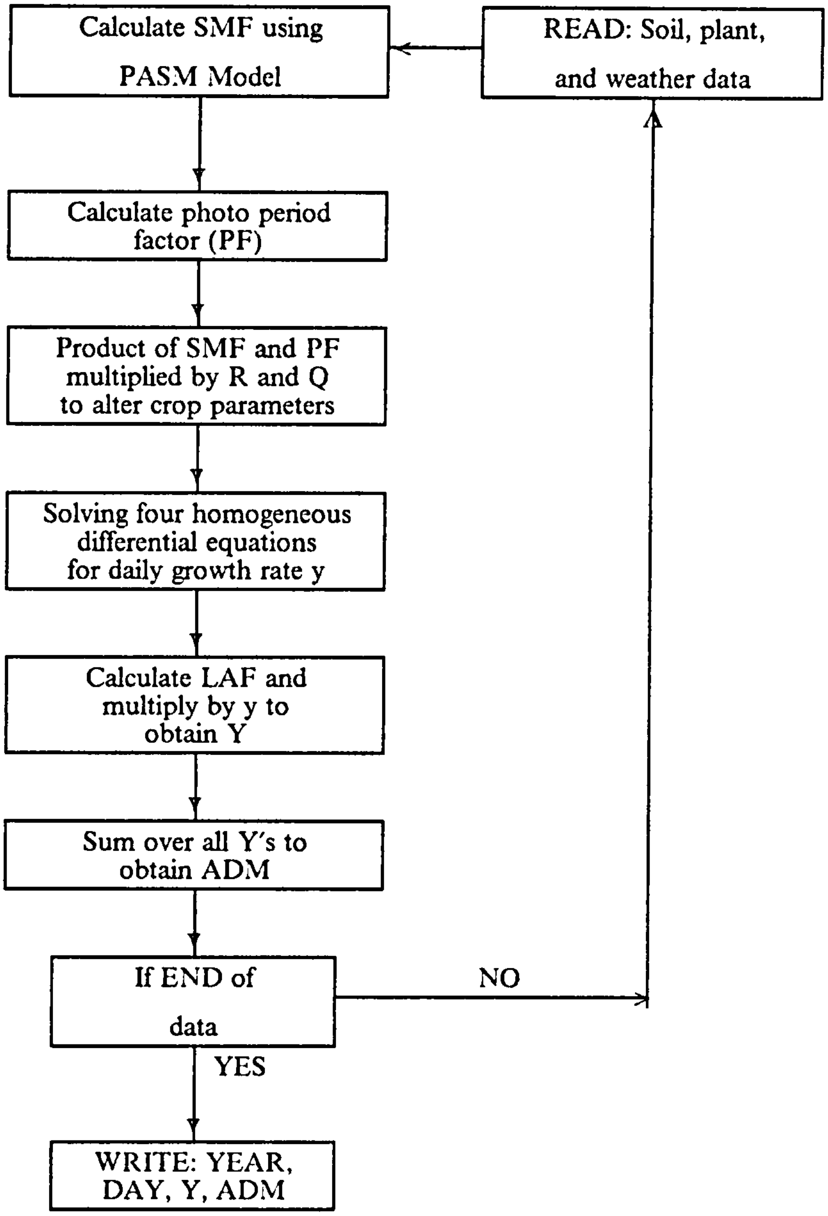

Figure 1. Flow chart of the mathematical-logic flow

Preliminary Statistical Analysis of Biomass Yield

The data generated using PGGM is used as input to a probability model. In order to gain some insight into the probability model that would accurately represent the dry matter yield in a given year for a specified soil depth, soil material, and environmental regime, a preliminary statistical analysis was considered. This consisted primarily of the determination of mean, maximum, minimum, standard deviation, coefficient of variation and serial correlation of dry matter yields.

Figures 2 and 3 show the daily growth rate in kg/ha/day and cumulative growth in kg/ha, respectively, for the calander year 1970. The daily growth rate curve (Fig. 2) shows that the growth rate increases slowly in the begining of the growing season and reached a maximum daily growth rate after about 80 days and then starts to decrease as the plant matures. The cumulative growth curve (Fig. 3) shows a typical accumulated growth of tall fescue grass.

Typical plots of the dry matter yields for each year are shown in Figs. 4 to 6. The three plots shown are for 2.54 cm, 7.62 cm, and 12.7 cm of ASM. These plots revealed that the dry matter yields for the 50 year period (1930-79) were a stochastic process and that the dry matter yield of any given year can be modeled as a stochastic (random) variate. Fig. 7 shows the plot of mean dry matter yield versus ASM . This plot shows that the mean dry matter yield increased with the increase in ASM and the mean dry matter yield almost reached its maximum value at about 11.43 cm of ASM. Figs. 8 and 9 show the standard deviation σ and coefficient of variation C_v of the dry matter yields against ASM. Both the σ and C_v values were higher at lower values of ASM, then decreased with the increase in ASM, and finally reached a constant value around 11.43 cm of ASM. The trends in standard deviation and coefficient of variation show that the probability of revegetation success increases with the increase in ASM up to 11.43 cm ASM depth but beyound 11.43 cm of ASM, there is little improvement in vegetation effort. This phenomenon can be explained easily by considering a known environmental input, such as soil depth, to a controlled soil-plant-water system. If the soil depth is increased continuously, a point will be reached after which the plant can not use the additional ASM effectively, and the excess ASM will be lost as deep drainage or evaporate.

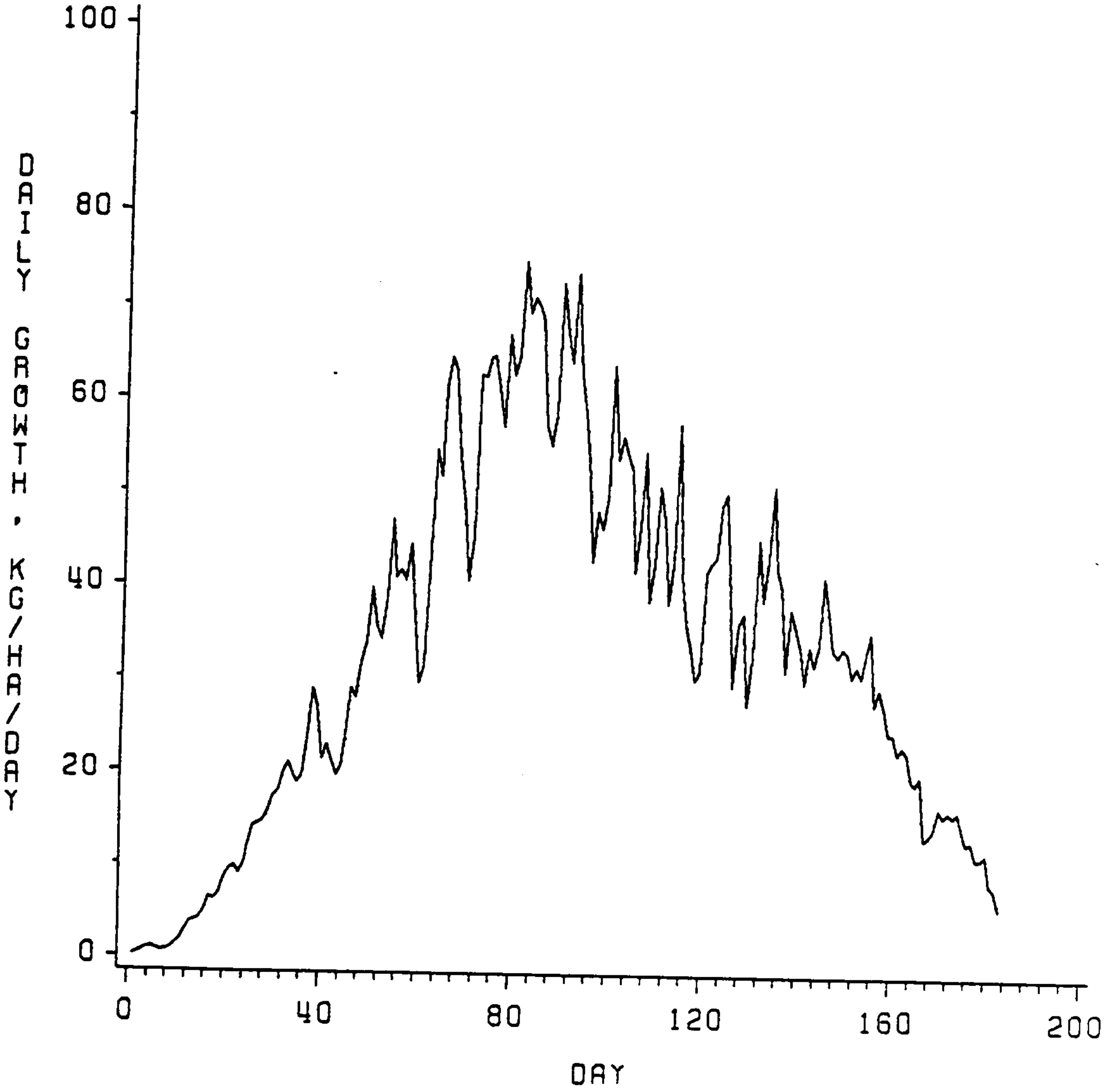

Figure 2. Tall fescue daily growth rate in kg/ha/day for year 1970.

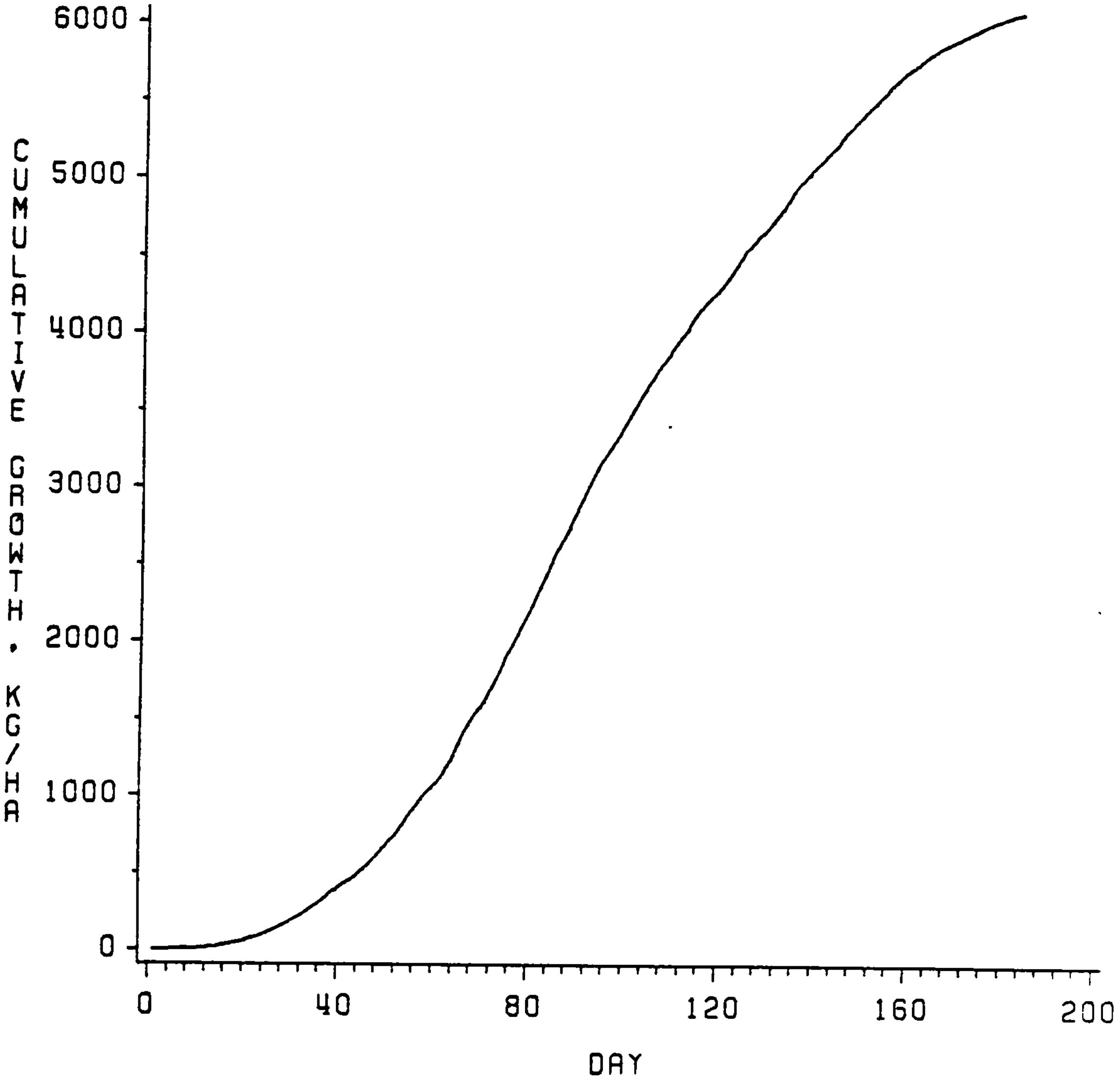

Figure 3. Tall fescue cumulative growth curve in kg/ha for year 1970.

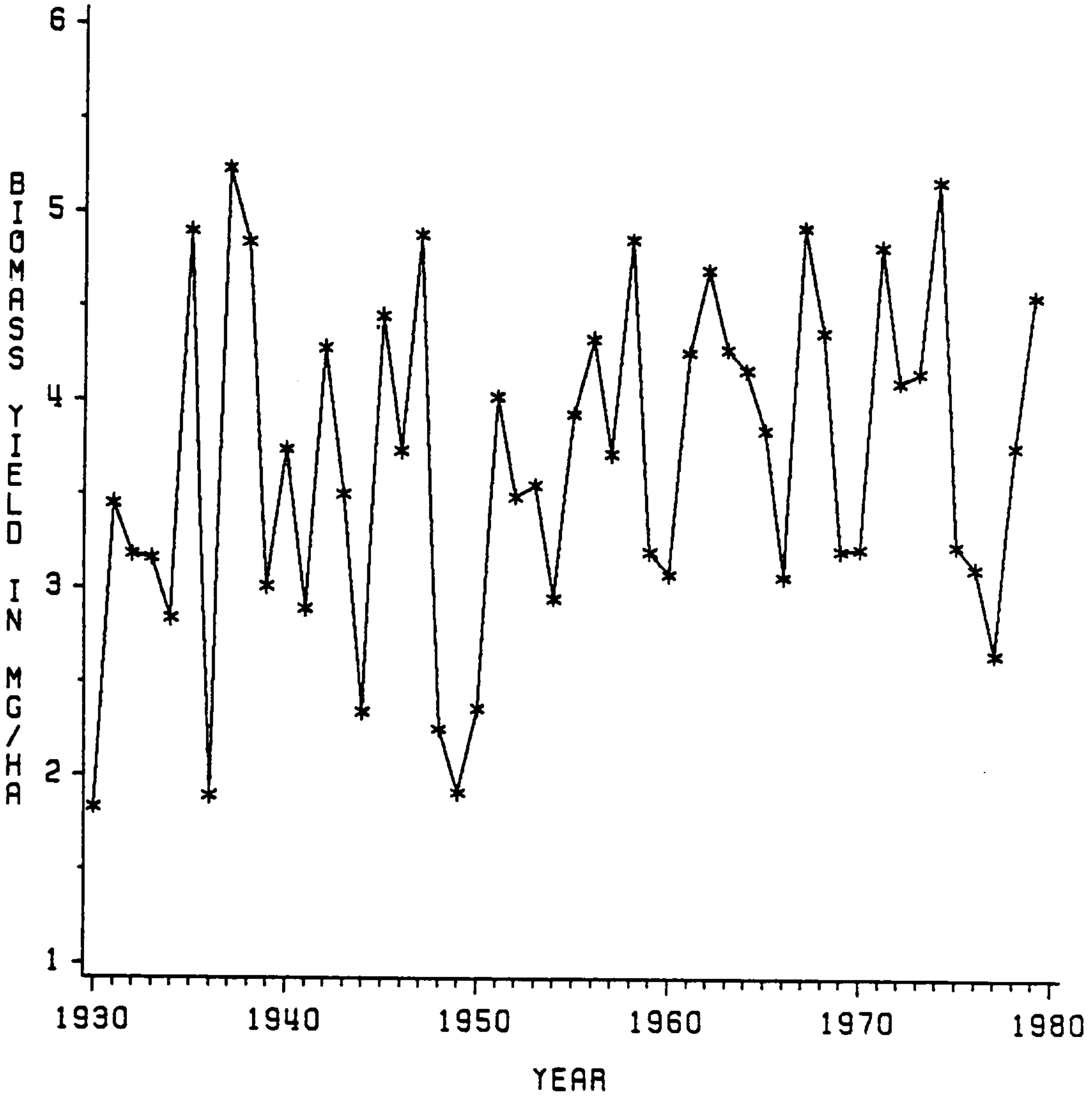

Figure 4. Simulated biomass yields for years 1930-1980 with 2.54 cm ASM.

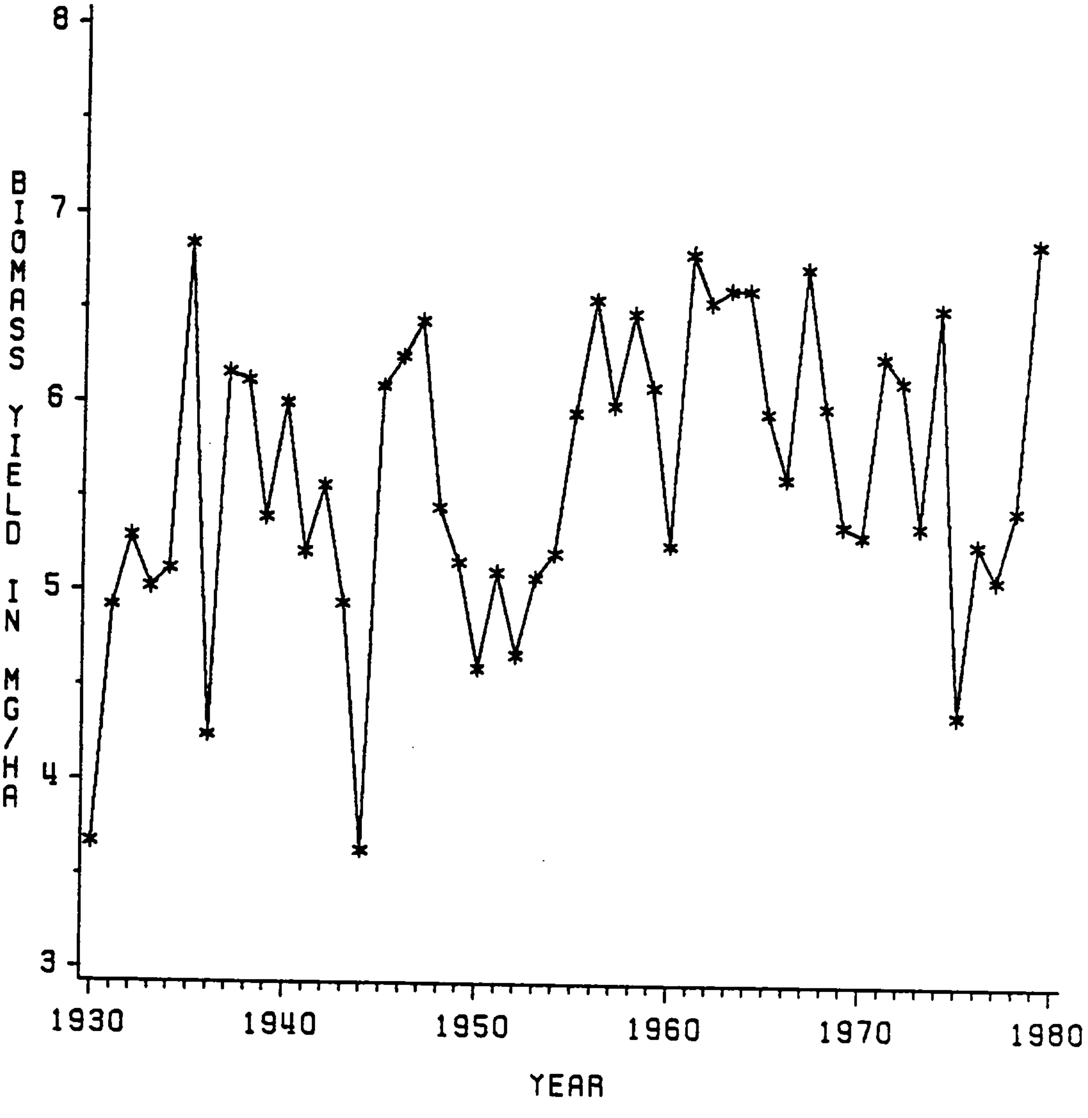

Figure 5. Simulated biomass yields for years 1930-1980 with 7.62 cm ASM.

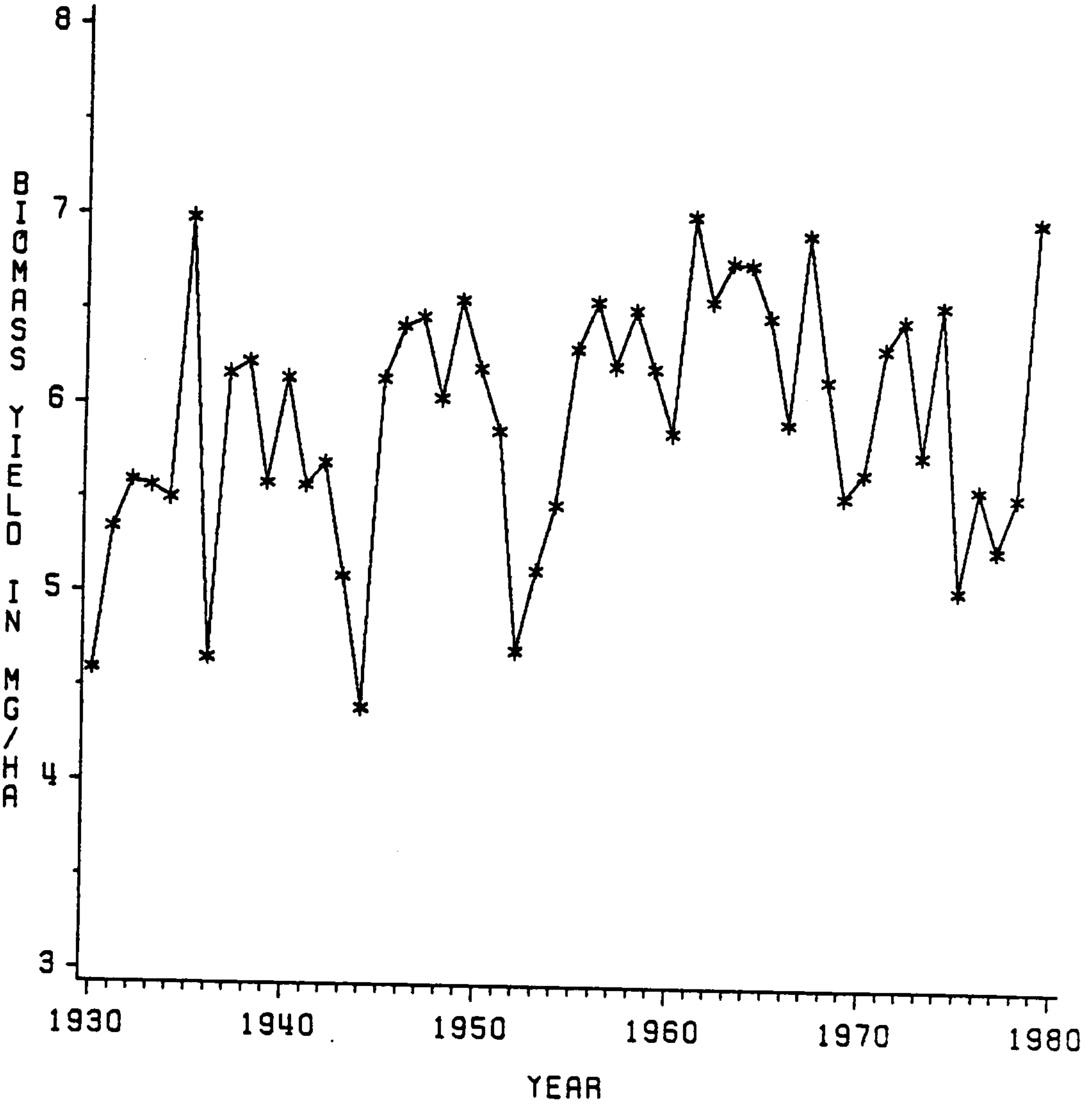

Figure 6. Simulated biomass yields for years 1930-1980 with 12.7 cm ASM.

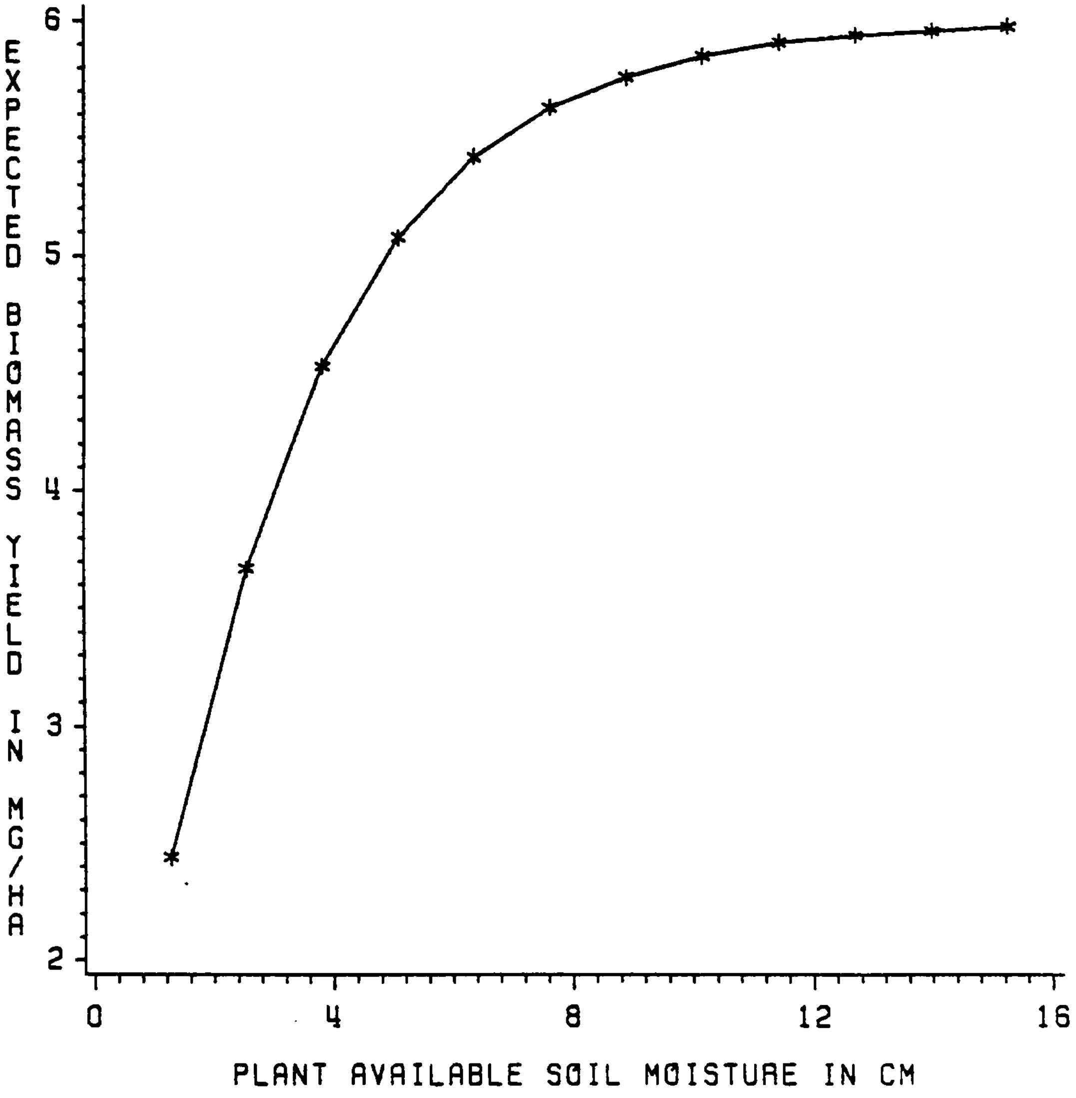

Figure 7. Expected biomass yields versus plant available soil moisture.

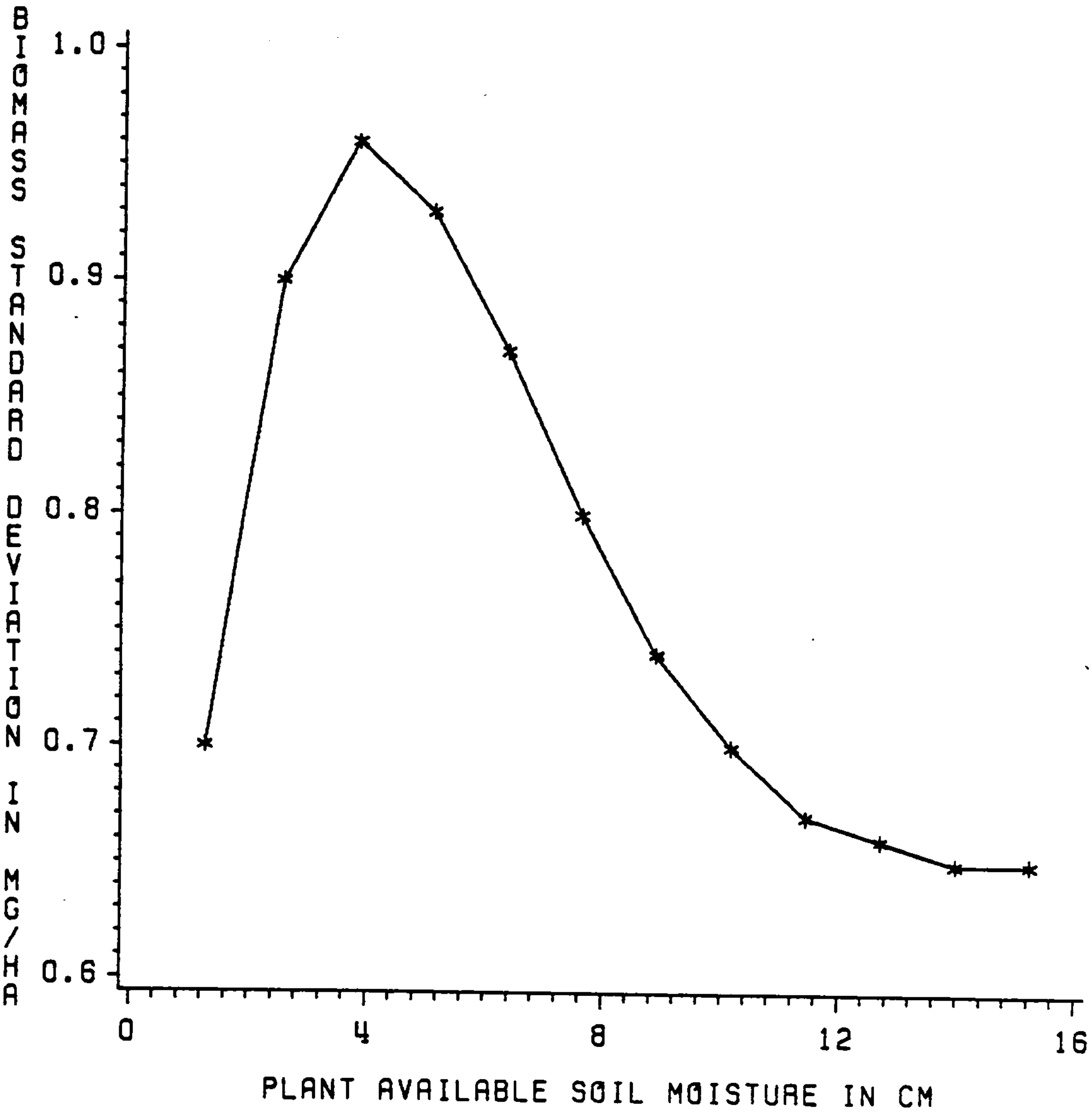

Figure 8. Biomass standard deviation versus plant available soil moisture.

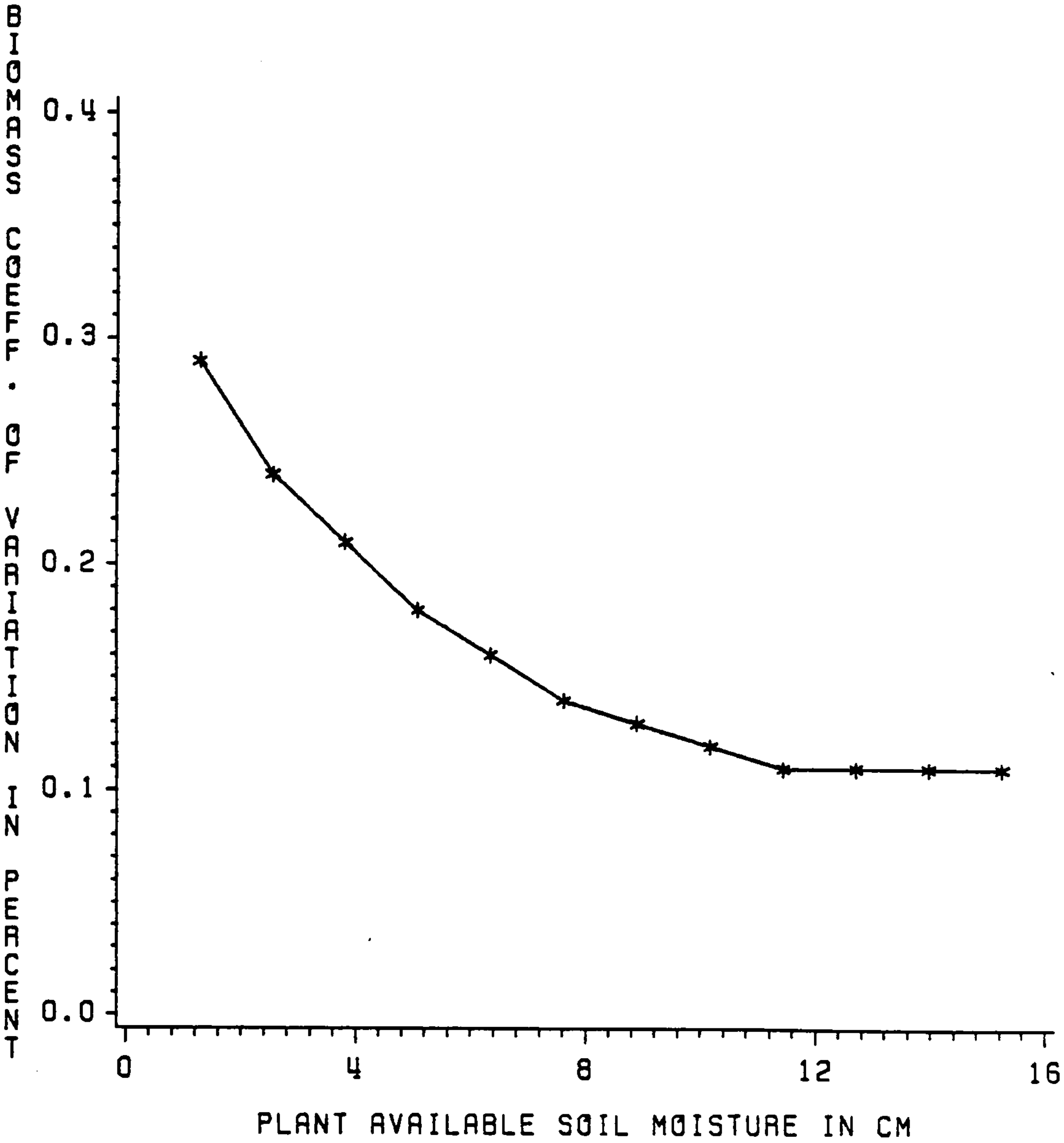

Figure 9. Biomass coefficient of variation versus plant available soil moisture.

Serial Correlation Analysis of Biomass Yield

It is expected that the dry matter yield in a given year will depend 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 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. A higher correlation could be due to soils with high ASM or successive years of similar precipitation and other climatic factors. To determine this correlation, auto-correlation coefficients can be computed. The auto-correlation coefficient (or serial correlation coefficient) measures the correlation between successive observations at an interval of k. It gives the correlation between dry matter yields y_i and y_{i+k}, where k is the lag in years. It is defined as:

$$\gamma_k = \frac{\sum_{i=1}^{n-k} (y_i - \bar{y}) \ (y_{i+k} - \bar{y})}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \qquad [39]$$

where, γ_k = auto-correlation coefficient at lag k; n is the total number of years; $\bar{y}$ is the over all mean, $\bar{y} = \sum_{i=1}^{n} y_i/n$; and y_i is the dry matter yield on year i.

Correlograms for 2.54 cm, 7.62 cm, and 12.7 cm of ASM are shown in Figs. 10 to 12. These correlogram plots show that the correlation between successive years of dry matter yields is not significant statistically. This further confirms that dry matter yields follow a stochastic process and therefore, dry matter yield in a given year can be treated as an independent stochastic variate.

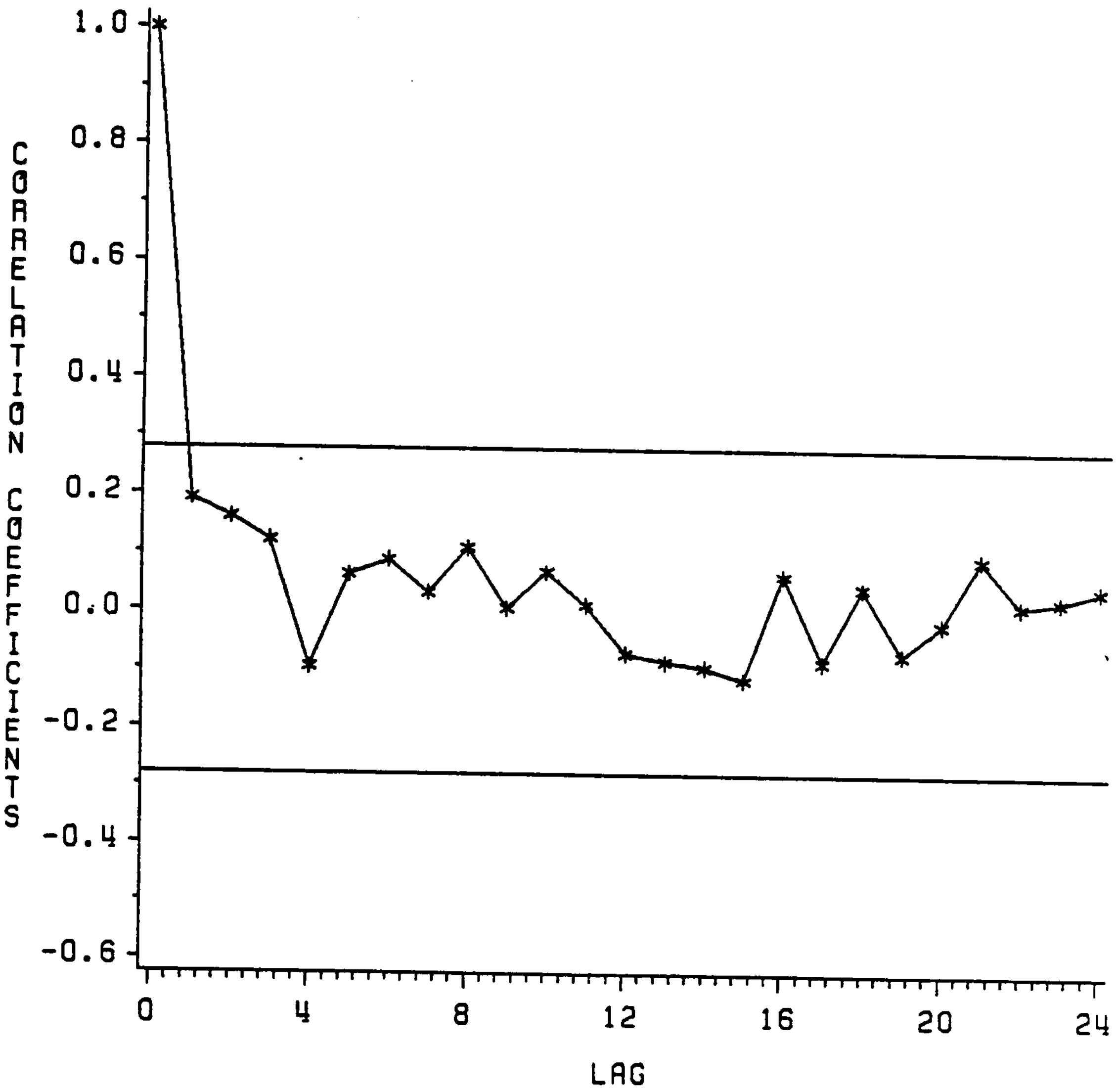

Figure 10. Correlogram plot for 2.54 cm ASM.

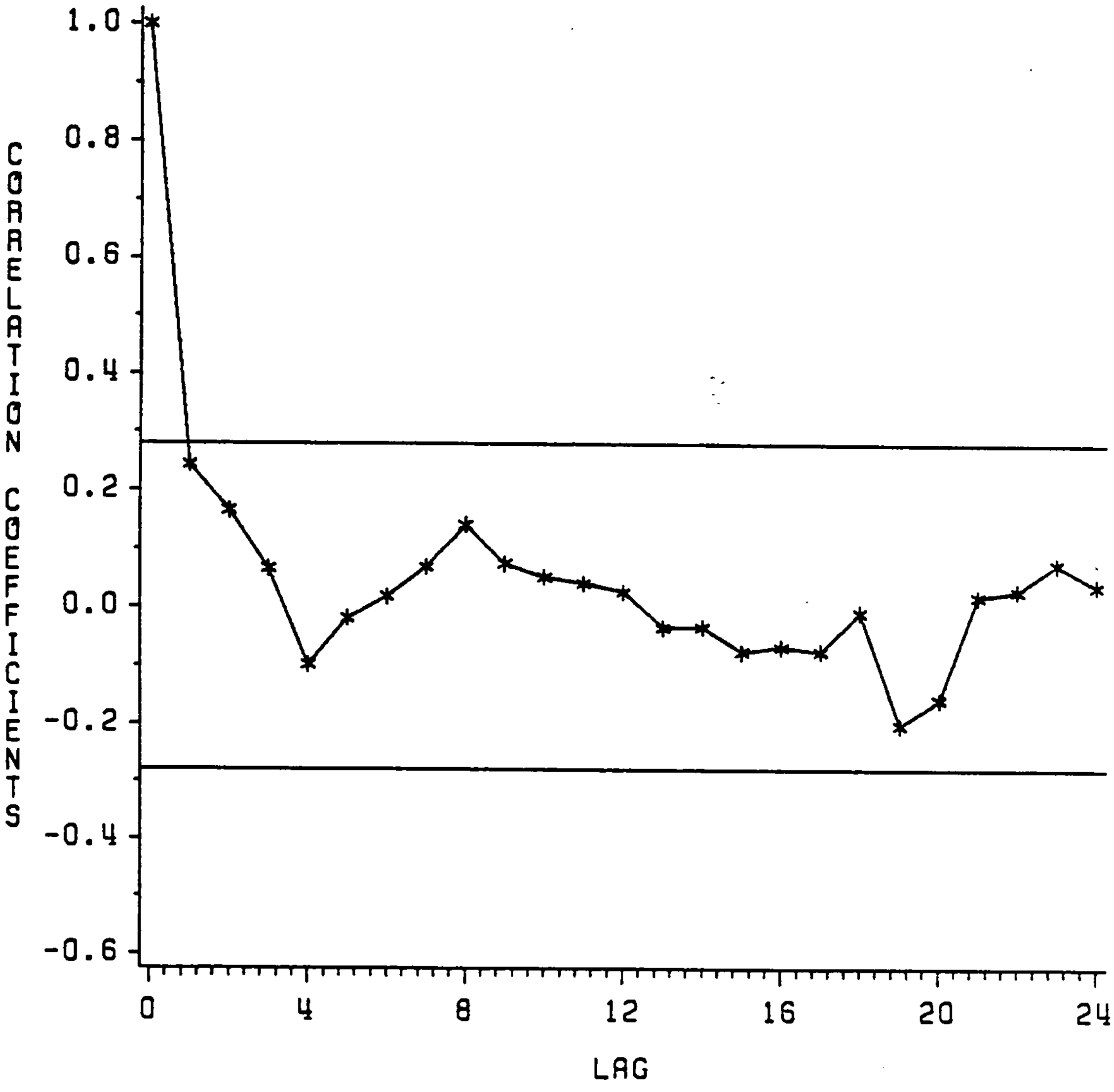

Figure 11. Correlogram plot for 7.62 cm ASM.

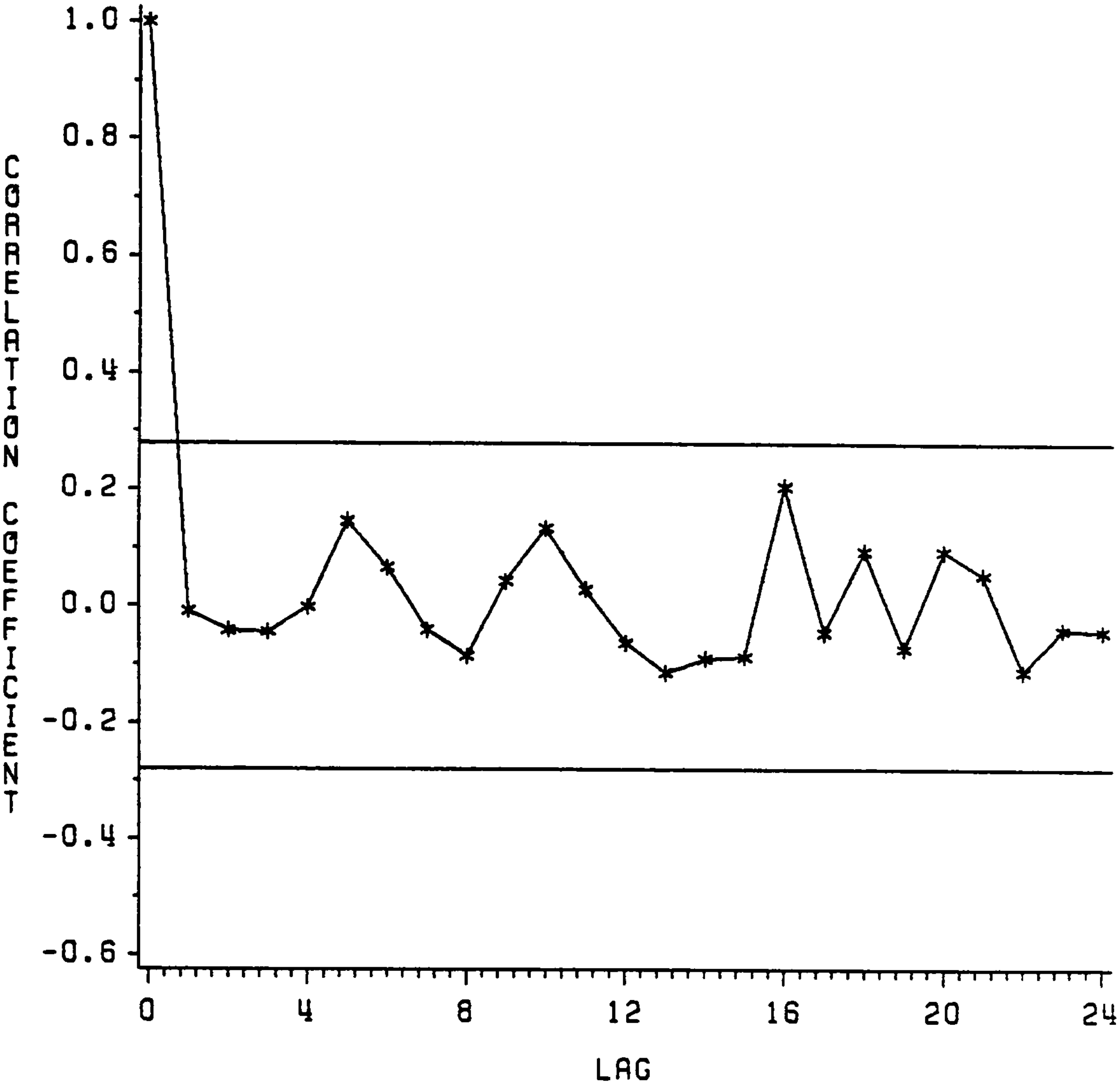

Figure 12. Correlogram plot for 12.7 cm ASM.

The Probability Model of Revegetation Success Events

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:

$$S_i = \{y_i > y_{ref}\} \qquad [40]$$

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:

$$P_{S_i} = P(S_i) = P(y_i > y_{ref}) = P \qquad [41]$$

The probability of revegetation failure in a given year i can be written as:

$$P_{F_i} = 1 - P_{S_i} = P(F_i) = P(y_i < y_{ref}) = 1 - P \qquad [42]$$

In general, events of interest in mine soil reclamation are as follows:

1. Event A: the occurrence of successful revegetation in all 5 years of the bond release period. This requires success in revegetation 100% of the time under consideration.
2. Event B: the occurrence of revegetation success in at least the last 4 years of the 5 year bond release period. This event permits the first year either to be a success or failure, but the last four years must be successful.
3. Event C: successful revegetation in at least the last 3 years of the 5 year bond release period. This allows the first two years either to be success, failure, or a combination of two other combinations, but the last 3 years must be a success.
4. Event D: successful revegetation in at least the last 2 years of the 5 year bond release period. This allows the first 3 years either to be success, failure, or any possible combinations, but the last 2 years must be a success.

5. Event E: successful revegetation in at least the last year of the 5 year bond release period. Under SMCRA, this is the event considered to evaluate the success or failure of a revegetation plan. Note that for event E, during the first year vegetation is established and then five year bond release period begins. Establishment of vegetation could possibly take one or more years and then five year period would start.

The probability of revegetation success of event A can be expressed as:

$$P(A) = P\{y_1 > y_{ref} \cap y_2 > y_{ref} \cap y_3 > y_{ref} \cap y_4 > y_{ref} \cap y_5 > y_{ref}\} \qquad [43]$$

where $\cap$ represents the "intersection of" or the occurrence of revegetation success of all 5 years of bond release period. Therefore, P(A) can be written as:

$$P(A) = P(S_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) \qquad [44]$$

Since, the events S_1, S_2, S_3, S_4, and S_5 are independent and identically distributed, equation (15) can be written as:

$$P(A) = P(S_1) \cdot \; P(S_2) \cdot \; P(S_3) \cdot \; P(S_4) \cdot \; P(S_5) = P^5 \qquad [45]$$

where $P(S_1) = P(S_2), \ldots, P(S_5) = P$

The probability of revegetation success of event B can be expressed as:

$$P(B) = P(S_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) + P(F_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) = P^5 + P^4 \; (1 - P) \qquad [46]$$

The probability of revegetation success of event C can be expressed as

$$P(C) = P(S_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) + P(S_1 \cap F_2 \cap S_3 \cap S_4 \cap S_5)$$

$$+ P(F_1 \cap F_2 \cap S_3 \cap S_4 \cap S_5) + P(F_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5)$$

$$= P^5 + 2\,P^4\,(1 - P) + P^3\,(1 - P)^2 \qquad [47]$$

The probability of revegetation success of event D can be expressed as

$$P(D) = P(S_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) + P(S_1 \cap S_2 \cap F_3 \cap S_4 \cap S_5)$$

$$+ P(S_1 \cap F_2 \cap S_3 \cap S_4 \cap S_5) + P(F_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5)$$

$$+ P(S_1 \cap F_2 \cap F_3 \cap S_4 \cap S_5) + P(F_1 \cap F_2 \cap S_3 \cap S_4 \cap S_5)$$

$$+ P(F_1 \cap F_2 \cap F_3 \cap S_4 \cap S_5)$$

$$= P^5 + 3P^4(1-P) + 2P^3(1-P)^2 + P^2(1-P)^3 \qquad [48]$$

The probability of revegetation success of event E can be expressed as:

$$P(E) = P(S_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) + P(S_1 \cap S_2 \cap S_3 \cap F_4 \cap S_5)$$

$$+ P(S_1 \cap S_2 \cap F_3 \cap S_4 \cap S_5) + P(S_1 \cap F_2 \cap S_3 \cap S_4 \cap S_5)$$

$$+ P(F_1 \cap S_2 \cap S_3 \cap S_4 \cap S_5) + P(S_1 \cap S_2 \cap F_3 \cap F_4 \cap S_5)$$

$$+ P(F_1 \cap F_2 \cap S_3 \cap S_4 \cap S_5) + P(S_1 \cap F_2 \cap F_3 \cap S_4 \cap S_5)$$

$$+ P(F_1 \cap S_2 \cap S_3 \cap F_4 \cap S_5) + P(F_1 \cap S_2 \cap F_3 \cap S_4 \cap S_5)$$

$$+ P(S_1 \cap F_2 \cap S_3 \cap F_4 \cap S_5) + P(S_1 \cap F_2 \cap F_3 \cap F_4 \cap S_5)$$

$$+ P(F_1 \cap F_2 \cap F_3 \cap S_4 \cap S_5) + P(F_1 \cap S_2 \cap F_3 \cap F_4 \cap S_5)$$

$$+ P(F_1 \cap F_2 \cap S_3 \cap F_4 \cap S_5) + P(F_1 \cap F_2 \cap F_3 \cap F_4 \cap S_5)$$

$$= P^5 + 4P^4(1-P) + 6P^3(1-P)^2 + 4P^2(1-P)^3 + P(1-P)^4 \qquad [49]$$

Determination of the Probability Distribution of Biomass Yield

Distribution functions for the dry matter yield at a given ASM depth were obtained from an analysis of the data generated by the PGGM. Using crop characteristics, soil properties and meteorological data, the PASM, and the PGGM, the dry matter yield for the whole range of ASM depths were computed for a n year period. This data was then used as input for the probability distribution analysis.

A Kolmogorov-Smirnov (K-S) goodness-of-fit statistical test was considered for each ASM depth. K-S test procedure involves a comparison between the observed cumulative frequency and an assumed theoretical distribution function. The theoretical distribution is accepted if the discrepancy between the observed and theoretical values is small with respect to what is normally expected for a given sample size (Ang and Tang, 1975).

The theoretical distributions considered are the normal, lognormal, gamma, beta, two parameter Weibull, and the three parameter Weibull distributions. The parameters of the theoretical distributions were estimated from the sample statistics. For the three parameter Weibull distribution, a maximum likelihood estimation procedure was used. The data was ordered and then a stepwise cumulative probability distribution, $PP_n(d)$, was computed and the maximum difference between the observed distribution and the theoretical distribution $F_d(d)$ was obtained from:

$$D_n^\alpha = \max_d \mid F_d(d) - PP_n(d) \mid \qquad [50]$$

This difference was compared with the critical value, D_n^α, where α is the significance level. The critical value D_n^α for a sample size of 50 is 0.19 for a significance level of 5% and 0.23 for a significance level of 1% (Hoel, 1962). From this analysis, normal distribution gave the best fit at 5% significance level and was used in the SDOM. Figs. 13 and 14 show the frequency distribution plot and frequency distribution with the theoretical normal distribution of tall fescue biomass yields for years 1930-1980 with 2.54 cm ASM, respectively.

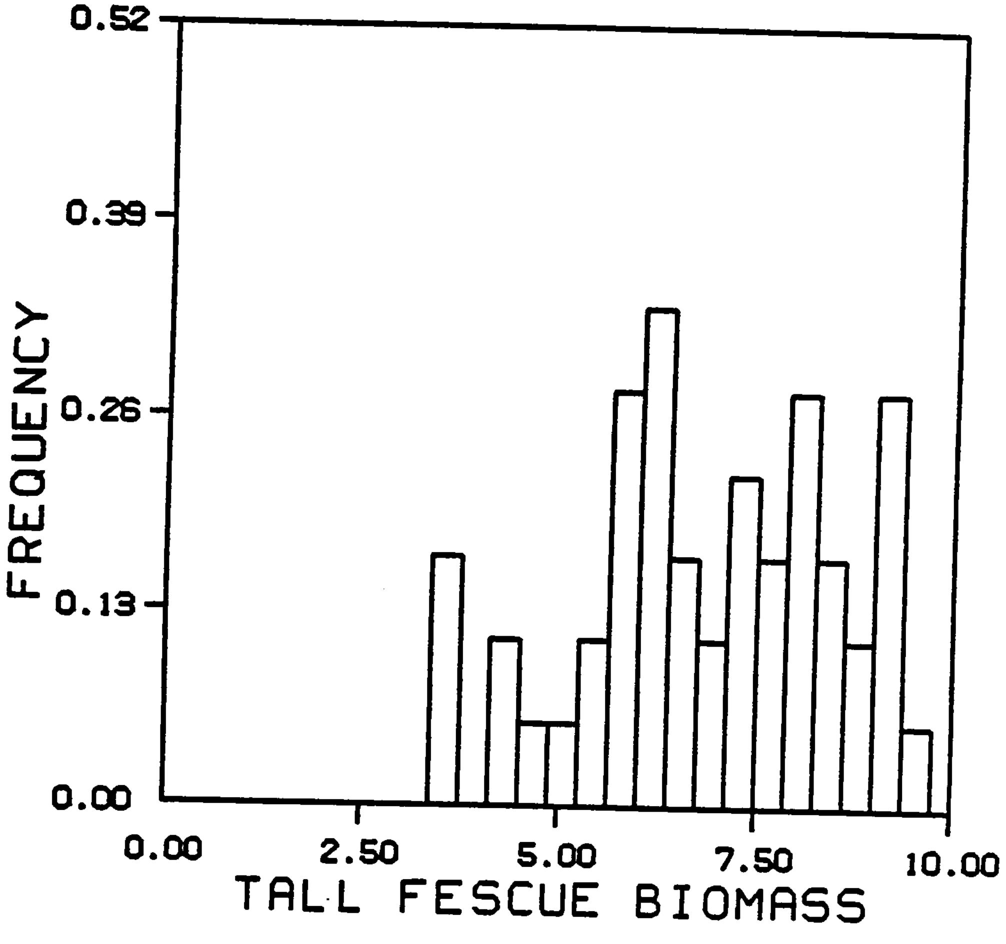

Figure 13. Frequency distribution of tall fescue biomass yields for years 1930-1980 with 2.54 cm ASM.

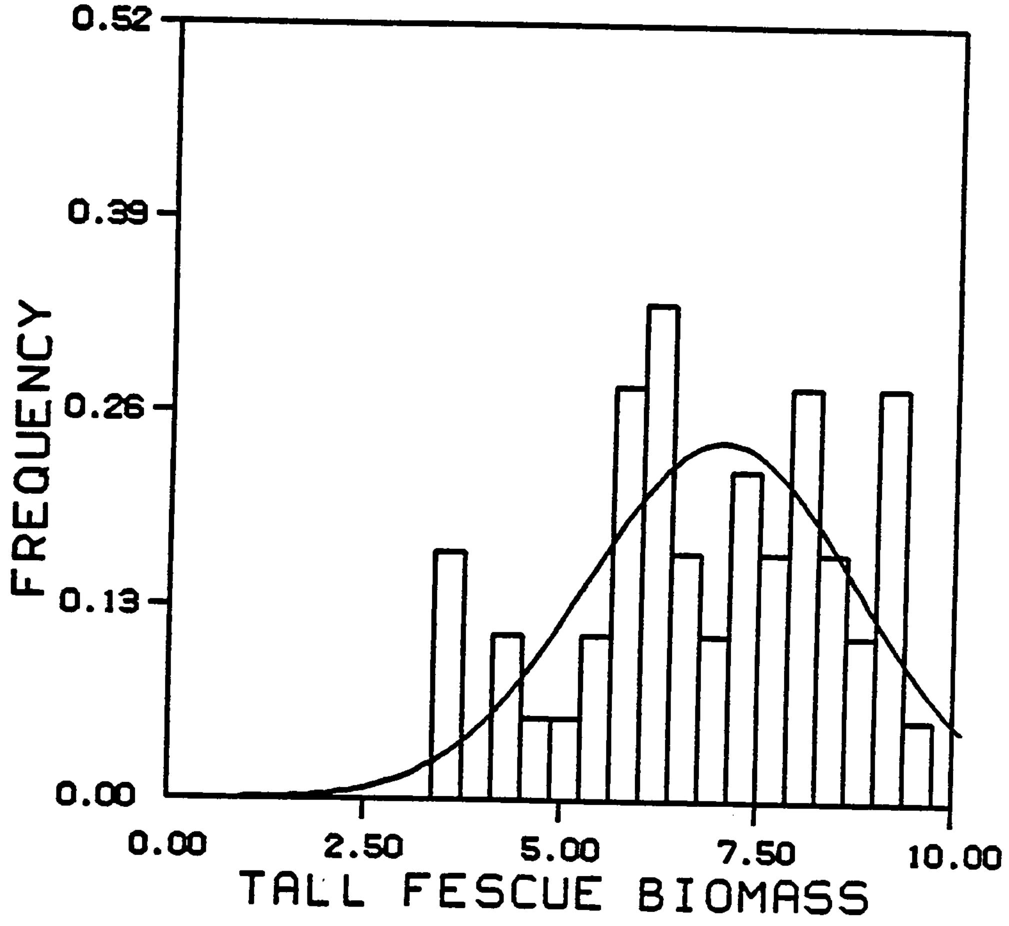

Figure 14. Frequency distribution of tall fescue biomass yields for years 1930-1980 with 2.54 cm ASM and theoretical normal distributio

Table 1. Chi-square test results for tall fescue biomass yields.

Interval	Observed Frequency N	Theoretical Frequency E	(N-E)**2/E
less then 5.141	7	5.63	0.33
5.141 to 5.517	4	7.34	1.52
5.517 to 5.893	12	10.48	0.22
5.893 to 6.269	10	10.94	0.08
6.269 to 6.644	11	8.35	0.84
greater than 6.644	6	7.26	0.22
Totals =	50	50.00	3.21

Number of class intervals = 6
Chi-square test statistics= 3.21
Chi-square (3.00)0.95 = 7.81

Table 1, shows that the chi-square test statistics (3.21) which is less then the table value of chi-square (7.81). Therefore, we can not reject the hypothesis that the tall fescue biomass yields follow a normal distribution.

Nonlinear Regression Analysis of Biomass Yield Versus ASM

The plot between mean dry matter yield versus ASM depth (Fig. 5) shows a nonlinear relationship. A linear relationship may be used to describe the general trend between each pair of values. Prediction on such linear relationships may overestimate (in certain ranges of the variables) or underestimate (in other ranges of the variables) the expected dry matter yield. The nonlinear regression models studied included the quadratic, cubic, exponential and lognormal. The nonlinear model which gave high R^2 (coefficient of determination) and small C_p statistics (measure of total squared error) values were selected. The lognormal model met the above criteria and the lognormal regression model can be expressed as:

$$E\ (y\,/\,ASM) = \alpha + \beta \ln ASM \qquad [51]$$

where α and β are the regression constants determined from the data.

Mathematical Formulation of SDOM for Strip Mine Revegetation

The problem objective is to find the optimum combination of soil depth and soil mixture, which will achieve successful vegetation for reclaimed mine soils, under non-irrigated condition and considering that weather is the only random element of the system. Considering the soil water balance as a homogeneous process within each day of the growing season, a general expression was developed for computing the daily plant available soil moisture without irrigation. The model considered a mixture of legume and grass crop for vegetation purposes. The dry matter production and/or percentage cover of vegetation was computed as a function of actual soil moisture, photoperiod, daylength, and temperature regime. The objective function is to find the optimum depth of ASM which will support a successful vegetation stand at the end of the 5-year period of performance bond release. 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 years 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 factors that may 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/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 can be represented as a stagewise process as shown in Fig. 15. In Fig. 15, the vector X is the decision vector which represents combinations of soil depth and soil mixture ratio. 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 , $i = 1, 2, \ldots, 5$, is the random weather input vector to the system in the ith year or period and r_i, $i = 1, 2, \ldots, 5$ is the cost in dollars for the 1st to ith 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_o is the initial condition of vegetation, that is, at the beginning of the first year. Y_i, $i = 1, 2, \ldots, 5$ is the vegetation yield in terms of dry matter or percentage cover at the end of the ith year and is a function of decision vector X and the initial vegetation conditions Y_o and Y_{i-1}.

Fig. 15 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. 15, can be simplified into an equivalent single stage decision problem plus a 5-stage Markovian transition process as shown in Fig. 16.

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).

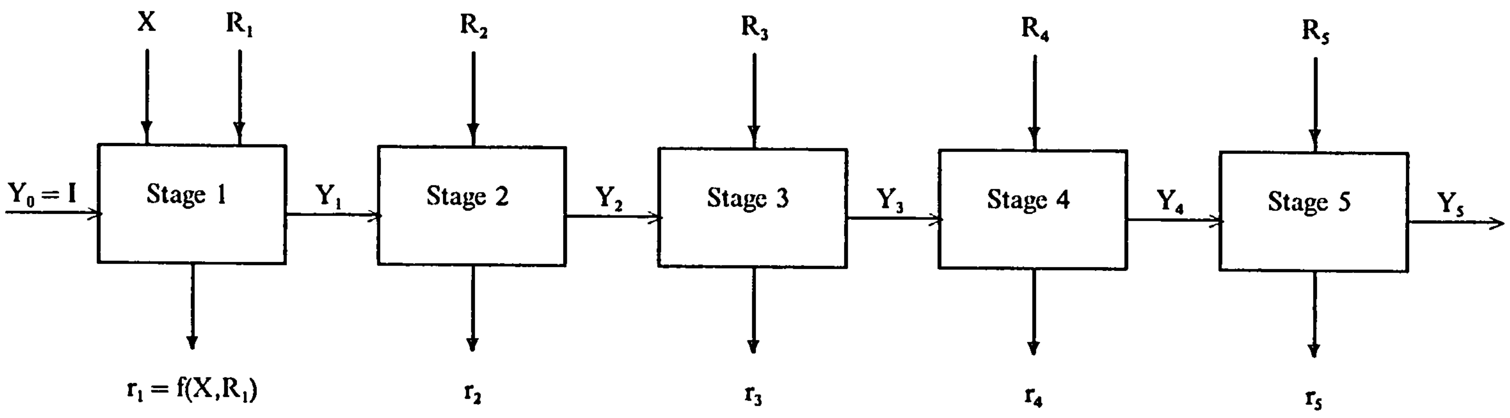

Figure 15. Stagewise representation of SDOM.

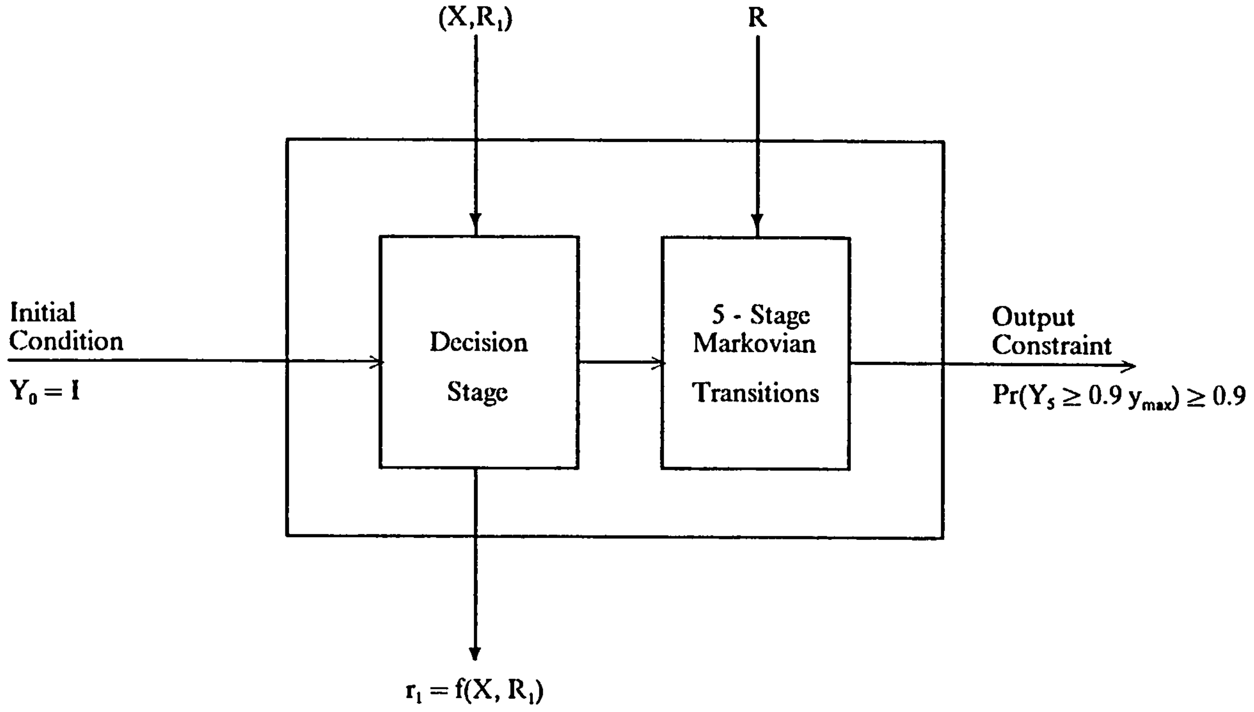

Figure 16. Single stage markovian decision problem.

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.

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

$$d^* = \min_{d \in D}\{d\} \qquad [52]$$

subject to :

$$\text{For event A}, \qquad P^5 \geq 0.9 \qquad [53]$$

$$\text{For event B}, \qquad P^5 + P^4\ (1 - P) \geq 0.9 \qquad [54]$$

$$\text{For event C}, \qquad P^5 + 2P^4\ (1 - P) + P^3(1 - P)^2 \geq 0.9 \qquad [55]$$

$$\text{For event D}, P^5 + 3\,P^4\,(1 - P) + 2\,P^3\,(1 - P)^2 + P^2\,(1 - P)^3 \geq 0.9 \qquad [56]$$

$$\text{For event E}, P^5 + 4\,P^4\,(1 - P) + 6\,P^3\,(1 - P)^2 + 4\,P^2\,(1 - - P)^3 + P\,(1 - P)^4 \geq 0.9 \qquad [57]$$

$$P_{S_i} = \Pr(y_i > y_{ref}) = P \qquad [58]$$

$$P = \Pr\ \{Z_k \geq \frac{y_{ref} - \bar{y}_k}{\sigma_k}\} \qquad [59]$$

$$\bar{y}_k = \alpha\ +\ \beta\ \ell n\ d_k \qquad [60]$$

$$\sigma_k = \sigma_{i-1} + (\bar{y}_k - \bar{y}_{i-1})* \frac{\sigma_{i+1} - \sigma_{i-1}}{\bar{y}_{i+1} - \bar{y}_{i-1}} \qquad [61]$$

$$0.0 \leq \Pr(Z_k) \leq 1.0 \qquad [62]$$

$$\sum_{\text{all } k} \Pr(Z_k) = 1.0 \qquad [63]$$

$$d_1 \le d_k \le d_{n+1} \qquad [64]$$

$$Z_k \sim N(0, 1) \qquad [65]$$

where $i = 1, 2, \ldots, k-1, k, k+1, \ldots, n+1$; n is the number of depth intervals used in PGGM; $\alpha, \beta, \bar{y}_i$, and σ_i values were estimated from n years of generated dry matter yield; Z_k is defined as standardized normal variate with $\mu_Z = 0$ and $\sigma_Z = 1.0$.

SDOM computer codes were developed in FORTRAN programming language to optimize the above mathematical problem. The SDOM is presented in appendix B.

Model Assumptions

1. The PGGM considers that the chemical properties of the mine soils are corrected before the starting year of bond release period.
2. The PGGM considers only tall fescue grass because of its drought resistance genetical characteristics and importance in erosion control.
3. A sigmoidal relationship was hypothesized to consider the effect of soil water stress on plant growth.
4. The PASM model is applicable only to homogeneous and isotropic soil media.
5. The PASM model considers that the roots are established over the whole soil depth before the starting year of bond release period.
6. The PASM model considers that for an established tall fescue grass, soil moisture could be a limiting factor when the average soil moisture falls below 50% of maximum ASM.
7. The maximum quantity of accumulated dry matter that provides enough leaf area for maximum growth was assumed to be 6196 kg/ha (after Smith and Loewer, 1983).
8. The optimum growth rate of tall fescue grass was assumed to be 6.5 kg/ha/h (This parameter was determined in consultation with Dr. Lee Daniels and Roberts (1986) field observations.

9. The minimum air temperature (t_1) below which growth does not occur, the maximum air temperature (t_3) above which growth does not occur and the optimum air temperature (t_2) where the growth rate is optimum were assumed to be 4.4°C, 18.3°C, and 32.2°C, respectively (after Salisbury and Ross, 1969).
10. It is assumed that the dry matter yield follows a stochastic process and dry matter yield in a given year is an independent stochastic variate.
11. In defining the event of revegetation success it is assumed that the dry matter yield of that year exceeds the reference area's dry matter yield which is assumed to be equal to 4.0 Mg/ha.
12. This research was performed for non-irrigated plant growth conditions because it is required by the SMCRA that the plant growth during the bond release period should be under natural conditions.
13. In the formulation of SDOM it is assumed that the only stochastic input to the system is weather.
14. The SDOM assumes that the distribution of dry matter yield is well defined by the first and second moments only.

Model Input Parameters

The required model input parameters were collected from both direct field observations available from literature and personal contact with experts in the field of mine soil reclamation. The observed values were compared with experts understanding and finally a reasonable parameter value was fixed for the purpose of this analysis. Table 2 presents the important model input parameters with their representative values and sources.

Table 2. Model input parameters.

PGGM inputs

Parameters	Tall fescue *
T_1 (°C)	4.4
T_2 (°C)	18.3
T_3 (°C)	32.2
R (kg/ha – hr)	6.5
Q_1 (kg/ha)	2065.0
Q_2 (kg/ha)	3019.0
Q_3 (kg/ha)	6196.0
A (hr)	14.8
B (hr)	11.8
C	0.1

* All parameters were determined in consultation with Dr. Lee Daniels.

PASM model inputs

Parameters	Value	Source
UL (mm)	Max ASM	Roberts (1986)
U (mm)	6.0	Richardson & Ritchie (1973)
SALPHA (mm per day$^{1/2}$)	0.10	Richardson & Ritchie (1973)
ELEV (ft)	2600	HISARS
SWINIT	0.5 UL	Roberts (1986)
TMAX, TMIN	Daily values	HISARS
ARN	Daily values	HISARS
PEN	Daily values	HISARS
DL	Daily values	HISARS

COMPARISON OF MODEL PREDICTIONS AND OBSERVED DATA

Weather, Soil, and Tall Fescue Biomass Data

To demonstrate the usefulness of the SDOM, data from Wise County, Virginia, was used because a good deal of revegetation research in reclaimed mine soils has been completed or is in progress in this area. Virginia Tech has been actively involved in revegetation efforts during the last few years, but a great deal of additional research is needed in this area. The necessary data required for the application of SDOM are: (a) long-term daily weather data for precipitation, maximum and minimum temperatures, daylength hours, vapor pressure, solar radiation and pan evaporation; (b) soil properties of mine soils including bulk density, percent of coarse fragments, soil moisture-suction head relationships for both fine soil particles (< 2 mm in diameter) and coarse fragments (> 2 mm in diameter), plant root depth and total soil depth for all soil materials studied; and (c) tall fescue biomass yield data.

Daily weather data at Pennington Gap and Marion weather stations in Virginia is available from 1930 - 1987 from the Hydrologic Information Storage and Retrieval System (HISARS) (Virginia Water Resources Research Center) and was used in this study. Historical weather data was adequate for the present study and is assumed characteristic of the mining region in south west Virginia.

Some studies were done to characterize the physical properties of mine soils by Younos and Shanholtz (1980), Bell (1982), Daniels et al. (1983), Roberts (1986). Younos and Shanholtz (1980)

Table 3. **Plant available soil moisture by depth and rock mixture (Roberts, 1986).**

Rock mix	Plant available soil moisture Less than 2 mm soil fraction (kg/kg)	 Over whole soil depth (mm)	Whole soil bulk density (kg/m^3)	Coarse fraction (%)
Sandstone	0.089	76.94	1900.	65
2:1 Mixture	0.107	81.94	1900.	69
1:1 Mixture	0.110	78.79	1900.	71
1:2 Mixture	0.117	78.03	1900.	73
Siltstone	0.125	77.19	1900.	75

Equations used:

$$\underset{(kg/m^3)}{\text{Fine soil}} = \underset{(kg/m^3)}{\text{Whole soil B.D.}} * (1.0 - \underset{(\%)}{\text{Coarse fraction}})$$

$$\underset{(kg/m^3)}{\text{ASM}} = \underset{(kg/m^3)}{\text{Fine soil}} * \underset{(kg/kg)}{\text{Available water}}$$

$$\underset{(cm)}{\text{TASM}} = (\underset{(kg/m^3)}{\text{ASM}} * X)/(10)$$

where:
B.D. is the Bulk density;
ASM is the plant available soil moisture;
TASM is the total plant available soil moisture;
X is the soil depth in meters.

Table 4. Annual standing tall fescue biomass production (Roberts ,1986)

Year	Sandstone	2:1 Mixture	1:1 Mixture	1:2 Mixture	Siltstone
	Rock mixture				
	.... Mg/ha				
1982	6.3a**	6.0a	6.0a	4.4b	3.7b
1983	6.5bc	9.3a	7.6b	6.4bc	5.2c
1984	5.7a	4.1a	5.2a	6.3a	4.4a
1985	5.7a*	4.1a*	5.2a*	6.3a*	4.4a*
1986	3.4ab	3.9ab	2.9b	4.4a	4.2ab
Max.	6.5	9.3	7.6	6.4	5.2
Min.	3.4	3.9	2.9	4.4	3.7
Mean	5.520	5.480	5.380	5.560	4.380
Std.	1.237	2.300	1.697	1.059	0.540
C.V.	0.224	0.419	0.315	0.190	0.123

* Means estimated from visual examination

**Means followed by different letters within columns by year are significantly different, $\alpha = 0.05$ (Fisher's LSD).

determined hydraulic properties such as water contents at 1/3 to 15 bar pressure, water holding capacity, water content at saturation and saturated conductivity of three pre-mining horizons and that of post-mining disturbed soil. Bell (1982) determined the physical properties for mine soils at different depths including: coarse fragment content, particle size distribution of materials, moisture retention data and plant available water. Roberts (1986) determined particle size distribution, water retention and water availability for both rock mix experiment treatments and surface amendment experiment treatments. These field and laboratory data, and personnel experiences of the mine soil reclamation expert (Lee Daniels) at Virginia-Tech were used to characterize mine soil physical properties required by the models used in this study. Plant available soil moisture values by soil depth and rock mixture that are used in this study are shown in Table 3.

Roberts et al. (1988) published tall fescue biomass standing data for a period of five years (1982 - 1984 and 1986 - 1987), for five different mine soil materials 130 cm deep (Table 4). Although, 5 years of biomass data is inadequate to establish a direct mathematical relationship for prediction purposes, it was the best source of available data. This study considers a dynamic simulation approach using analytical expressions to predict biomass yield and predicted yields are then compared statistically with Robert's (1988) observed biomass standing to justify the applicability of the model. The following section presents the procedures used to test the dynamic simulation model.

Model Testing

Parts of the PGGM were based on existing models that have been undergone considerable testing and have proved to be quite robust. For example, (a) the nonspecific crop growth computations have been used and tested by Smith and Loewer (1983), Brown (1982), Neels (1981), Ewen (1980), and Benger et al. (1980); (b) the evapotranspiration computations of Richardson and Ritchie (1973) and the soil water balance budgets for the area have been tested by Rojiani et al. (1982).

Numerous statistical tests have been suggested in the literature as appropriate for testing simulation models (Steel and Torrie, 1960; Mood and Graybill, 1963; Naylor and Finger, 1967; Shannon, 1975; Ang and Tang, 1975; Haan, 1977; Dent and Blackie, 1979; Law and Kelton, 1983). These included both subjective and objective approaches as well as parametric and non-parametric hypothesis testing using statistical procedures. In this study, predicted dry matter yields were paired with field observations and statistics for each soil material of the total set and compared with the following tests:

1. means by paired, two-sided tests;
2. variance by F-tests;
3. frequency distributions by two-sided Kalmogorov-Smirnov tests;
4. first-order autocorrelation by two-sided Z-tests;
5. linear regression test.

Each test was applied to specific characteristics of the model. For example, (1) the mean test compared the expected dry matter yield prediction and observed expected dry matter yield; (2) the variance test compared the overall variability of model and field data; (3) the Kalmogorov-Smirnov test procedure compared the observed cumulative frequency and the predicted distribution function; (4) the first order autocorrelation test compared variability of sequential observations; and (5) finally, linear regression analysis determined a- and b- statistics (intercept and slope), with standard errors and R^2 values. A simulation model that perfectly explains the field data would result in a regression line that passes through the origin (intercept, $a=0$) with a slope of 1 (i.e., $b=1$). A F-ratio was calculated for simultaneously testing $a=0$ and $b=1$. In terms of overall model accuracy, the F-ratio test was probably the most comprehensive of the set, but it provided little information about specific deficiencies of the model. To perform the above mentioned statistical tests SAS procedures (SAS User's Guide: Statistics, 1982) were used.

The appropriate significance level to use with the statistical tests of model validity is problematic. The main concern of a modeler is to avoid accepting as valid an invalid model (Type II error, Steel and Torrie, 1960). The probability of such an error can only be determined if certain population parameters are known. They are generally unknown, but using a higher percentage significance level than the conventional 5% does reduce the probability of such an error. The 15% significance level was arbitrarily chosen as appropriate for the tests. The 5% level was used for the simultaneous F-test of the regression equation because the F-ratio depend on the standard error of the estimate of the regression equation and is therefore very conservative (Mood and Graybill, 1963).

RESULTS AND DISCUSSION

Statistical Analysis of Weather and Biomass Data

To characterize the climatology of Southwest Virginia, a statistical analysis was performed on the weather data for 1930 - 1987 obtained from HISARS (Virginia Water Resources Research Center, 1986), collected at Pennington Gap and Marion weather stations. These data show that during the growing season (April to September) the maximum and the minimum rainfall amounts recorded were 870 and 362 mm, respectively. Table 5 presents monthly rainfall statistics which includes maximum, minimum, mean, and standard deviation. The maximum and the minimum monthly mean rainfall occurred in July and September and the amounts are 130 and 77 mm, respectively. The maximum and the minimum standard deviation of monthly rainfall occurred in May and July, respectively.

Table 6 presents monthly pan evaporation statistics which includes maximum, minimum, mean, and standard deviation. These data show that during the growing season the maximum and the minimum pan evaporation values recorded were 832 and 695 mm, respectively. The maximum and the minimum monthly mean pan evaporation occurred in August and April and the amounts are 170 and 61 mm, respectively. The maximum and the minimum standard deviation of monthly pan evaporation occurred in August and April, respectively. The potential evapotranspiration (PET) demand was estimated by multiplying the pan evaporation with the product of a pan coefficient and a crop coefficients. The product of pan coefficients and crop coefficients are 0.67, 0.67, 0.63, 0.69, 0.70 and 0.72 respectively for April, May, June, July, August, and September. The maximum and the minimum PET during the growing season were estimated as 567 and 473 mm,

Table 5. Monthly rainfall statistics at Pennington Gap, Virginia.

	Monthly rainfall statistics, cm											
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max.	31.3	29.7	35.3	26.6	19.2	22.5	26.6	23.0	19.5	19.3	22.0	23.1
Min.	0.2	2.2	3.9	0.7	0.7	3.5	3.3	2.8	1.1	0.1	1.9	1.5
Mean	11.9	11.8	13.5	10.5	10.6	10.5	13.0	10.4	7.7	7.2	9.5	10.7
Std.	6.5	5.6	6.1	4.6	4.8	4.1	4.7	4.4	4.3	4.1	4.7	4.6

Table 6. Monthly pan evaporation statistics at Marion, Virginia.

	Monthly pan evaporation statistics, cm					
Year	Apr	May	Jun	Jul	Aug	Sep
Max.	6.6	12.3	15.7	17.4	18.0	13.2
Min.	5.4	10.2	13.1	14.6	15.1	11.1
Mean	6.1	11.6	14.8	16.4	17.0	12.4
Std.	0.2	0.4	0.5	0.6	0.6	0.4

respectively. The maximum and the minimum monthly mean PET occurred in August and April and the amounts were estimated as 117.3 and 40.9 mm, respectively.

The above mentioned monthly rainfall and PET statistics demonstrate that in a very good year there will be sufficient moisture available to meet evapotranspiration demand if the total amount of rainfall is uniformly distributed during the growing season. However, in a very dry year plants may experience a severe soil moisture stress between rains.

Table 7 presents the number of monthly rainy days statistics such as maximum, minimum, mean and standard deviation. Table 7 shows that the maximum, the minimum and the mean monthly rainy days during the growing season varies between 15 to 19, 2 to 6 and 7 to 11 days respectively. These statistics show that in a very good year one will expect rain at least 1 out of 2 days, at least 1 out of 4 days in an average year, and 1 out of 15 days in a very dry year. Therefore, it is possible that in above average years, sufficient moisture may be available to meet successful revegetation growth and ground cover, but in below average years there is a possibility of not having sufficient moisture to meet successful revegetation and ground cover between rainy days. The standard deviation of monthly rainy days remains almost a constant value of 3 days/month. This means that the variation in rainy days is not significantly different from month to month during the growing season.

Table 8 presents the statistics for monthly maximum and minimum temperatures. During the growing season, the maximum and the minimum temperatures vary from 20.1 to 29.7 °C and 4.9 to 16.3 °C, respectively. The extreme high and the extreme low temperatures of 33.3 °C and 1.7 °C occurred in July and April, respectively. The occurrence of low temperatures in May will delay warming of the soil which will result in delayed plant growth. The extreme high temperatures in July might kill the plants due to high soil moisture stress. Under optimum moisture condition the minimum temperature below which tall fescue grass does not grow is about 4.4 °C, and the maximum temperature above which tall fescue growth ceases is 32.2 °C The optimum temperature for tall fescue growth is about 18.3 °C. The standard deviation for monthly maximum temperature was highest in April and was lowest in August, respectively. The high variation in maximum temperature in the beginning of the growing season means that there is a high probability of having

Table 7. Monthly rainy days statistics at Pennington Gap, Virginia.

Year	Number of monthly rainy days statistics											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max.	19	23	18	15	17	17	18	19	16	12	16	17
Min.	2	2	4	2	6	4	3	5	3	1	3	3
Mean	11	10	12	10	11	10	11	10	7	7	9	10
Std.	4	4	3	3	3	3	3	3	3	2	3	3

Table 8. Monthly maximum and minimum temperature statistics at Pennington Gap, Virginia.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Monthly maximum temperature statistics											
Max	56.0	64.0	67.1	78.0	84.1	89.1	92.0	90.5	86.4	76.9	65.9	57.9
Min	32.3	37.4	42.0	57.2	69.1	74.6	80.2	80.2	75.1	65.3	47.1	37.6
Mean	44.9	48.8	57.2	68.3	76.6	83.1	85.5	84.9	80.8	71.1	57.7	47.9
Std	5.1	5.5	5.5	4.3	3.1	2.9	2.6	2.3	2.7	2.9	4.1	4.7
	Monthly minimum temperature statistics											
Max	41.1	35.8	40.5	53.6	55.7	69.0	65.4	73.0	72.8	51.2	43.4	35.0
Min	12.7	16.0	17.7	35.0	43.1	51.5	56.7	55.2	47.2	32.7	26.0	15.8
Mean	24.6	25.9	32.5	40.9	49.3	57.5	61.3	60.6	53.7	41.1	32.1	25.9
Std	6.5	4.6	3.9	3.1	2.7	2.9	1.9	2.7	3.9	3.7	3.8	4.2

temperatures lower than the optimum. Table 9 present the environmental regime during 1930-79 at Pennington Gap, Virginia.

Table 4 shows tall fescue standing biomass statistics for five mine soil materials found at Wise County, Virginia (Roberts, 1986). First year (1982) tall fescue standing biomass was highest (6.3 Mg/ha) in the SS treatment and decreased as SiS content increased. Although standing biomass on the SiS treatment was again lowest in 1983 (5.2 Mg/ha), the SS and 1:2 SS/SiS treatments supported similar production levels. Biomass production in 1984 and 1986 was highest on the 1:2 SS/SiS treatment. Treatments with higher SiS contents supported production in the fifth year that equaled or exceeded high SS treatments. Spoil type effects were most noticeable in the second year of the experiment (1983) when maximum production occurred. The lower biomass production on high SiS spoils is attributed to initially high pH (pH 7.5) and to detrimental physical properties such as rockiness, low ASM, and restricted rooting volume (Roberts, 1986). These results show that spoil type has an important influence on the first 2 years of fescue growth. Parent material effects diminish once the spoil surface is stabilized by litter layer developments, organic matter accumulation, and leaching of soluble salts (Roberts, 1986). In all treatments a complete ground cover was observed for all five growing seasons. Annual biomass standing of tall fescue was compared at 5% significance level by Fisher's protected least significant difference comparison (Ott, 1984). Statistical tests found that annual biomass standing in first year (1982) for the SS, 2:1 SS/SiS and 1:1 SS/SiS were statistically different than 1:2 SS/SiS and SiS at the 5% significance level. But in third year (1984) biomass standing for all five treatments were not statistically different at 5% significance level. Roberts (1986) also reported that the pedogenic changes over time and stabilization of mine soil surface properties reduced parent material affects on biomass production. These limited experimental results suggest that it is possible to stabilize chemical properties of mine soils within a reasonable time to support successful vegetation. Thus, the assumption of favorable chemical environment as considered in this study could be defended based on Roberts (1986) observations. For the years 1982-1986 tall fescue biomass yield was simulated using VPIGRO to make a comparision with the observed biomass data and is presented in Table 10.

Table 9. Environmental regime from 1930-79 at Pennington Gap, Virginia.

Year	Rain (cm)	Temperature indices (in number of days)						
		n_1	n_2	n_3	n_4	n_5	n_6	n_7
1930	43.07	123	0	0	15	45	16	12
1931	57.32	150	0	0	14	19	38	20
1932	52.98	142	0	0	13	28	31	13
1933	46.10	146	0	0	14	23	28	11
1934	48.84	154	1	0	12	17	44	14
1935	67.84	165	1	0	14	4	21	20
1936	64.31	130	1	0	17	36	37	16
1937	60.88	164	0	0	15	4	22	17
1938	79.68	166	0	0	12	5	36	14
1939	54.13	148	0	0	20	15	40	17
1940	62.23	147	1	0	26	10	32	18
1941	61.41	151	0	0	12	20	41	9
1942	83.74	158	0	0	22	3	36	14
1943	54.83	137	1	0	24	22	39	17
1944	50.77	133	2	0	14	36	25	17
1945	75.84	149	0	0	24	10	7	21
1946	56.51	166	0	0	14	3	14	9
1947	61.74	159	0	0	18	6	32	12
1948	50.87	157	0	0	9	17	26	8
1949	40.28	166	1	0	15	2	17	15
1950	36.17	162	3	0	21	0	4	14
1951	60.83	152	0	0	22	9	8	18
1952	52.20	130	1	0	16	37	17	13
1953	60.22	129	0	0	21	33	18	18
1954	43.91	140	0	0	20	23	11	17
1955	48.41	162	0	0	13	8	14	9
1956	78.58	155	0	0	28	0	7	23
1957	68.48	160	0	0	16	7	4	14
1958	81.94	170	0	0	12	1	28	14
1959	58.75	161	0	0	20	2	32	14
1960	53.64	156	0	0	27	0	12	17
1961	54.91	149	0	0	34	0	10	25
1962	67.56	160	0	0	23	0	15	21
1963	57.15	158	0	0	24	1	10	16
1964	68.58	171	0	0	12	0	14	9
1965	47.21	173	0	0	9	1	18	7
1966	69.97	150	0	0	24	9	16	18
1967	63.90	162	0	0	21	0	18	6
1968	62.68	154	0	0	17	12	30	5
1969	50.54	151	0	0	19	13	31	3
1970	69.31	151	0	0	18	14	28	7

Table 9. continued...

1971	81.25	153	0	0	30	0	13	5
1972	68.14	160	0	0	19	4	28	12
1973	67.48	150	0	0	24	9	37	12
1974	82.82	164	0	0	19	0	16	9
1975	60.75	137	0	0	21	25	10	8
1976	46.93	139	0	0	31	13	6	4
1977	86.96	150	0	0	13	20	18	4
1978	68.35	150	0	0	17	16	13	7
1979	65.76	164	0	0	19	0	24	9

T_1 = Minimum air temperature for crop growth;
T_2 = Optimum air temperature for plant growth;
T_3 = Maximum air temperature for plant growth;
T_{max} = Maximum air temperature;
T_{min} = Minimum air temperature;
n_1 = Number of days $T_{min} \geq T_1$ and $T_{max} \leq T_3$;
n_2 = Number of days $T_{max} < T_1$;
n_3 = Number of days $T_{min} > T_3$;
n_4 = Number of days $T_{min} < T_1$ and $T_{max} < T_3$;
n_5 = Number of days $T_{min} > T_1$ and $T_{max} > T_3$;
n_6 = Number of days $T_{min} \geq T_2$;
n_7 = Number of days $T_{max} \leq T_2$;
Rain = Total rainfall during the growing season, cm;
R_{normal} = Normal rainfall for the growing season was 61.11 cm.

Table 10. Tall fescue biomass simulation using VPIGRO

Year	Rock mixture				
	Sandstone	2:1 Mixture	1:1 Mixture	1:2 Mixture	Siltstone
	.... Mg/ha				
1982	6.094	6.094	6.094	6.094	6.094
1983	5.432	5.441	5.436	5.434	5.433
1984	5.676	5.727	5.698	5.692	5.682
1985	5.802	5.805	5.804	5.803	5.802
1986	4.700	4.758	4.722	4.714	4.703
Max.	6.094	6.094	6.094	6.094	6.094
Min.	4.700	4.758	4.722	4.714	4.703
Mean	5.540	5.565	5.550	5.547	5.542
Std.	0.527	0.507	0.519	0.522	0.526
C.V.	0.095	0.091	0.093	0.094	0.095

Comparison of Model Predictions and Observed Data

The results of the hypothesis testing using regression analysis are presented in Table 11. The separate t-statistics presented in Table 11 indicates that both the slope and the intercept parameters fail to reject the null hypothesis. Use of the F-statistics to jointly test the null hypothesis ($a=0$; $b=1$) also fail to reject the null hypothesis at 5% level of significance. Therefore, both the t-test and the F-test support the hypothesis that the simulated biomass yields are reasonable predictions. In statistical terms, predicted data can be used to represent the observed data.

Statistical Analysis of Long-Term Simulated Biomass Yield

Table 12 shows the long-term (1930-79) tall fescue biomass yield for 12 representative ASM depths ranging from 1.27 to 15.24 cm. Table 12 also presents the statistics for the long-term tall fescue biomass yield which includes maximum, minimum, mean, standard deviation and coefficient of variations. Maximum, minimum and mean biomass yields ranged from 3.93 to 7.03, 1.13 to 4.59, and 2.44 to 5.98 Mg/ha, respectively. Maximum, minimum and mean biomass yields increased with an increase in ASM and reached their maximum values at about 11.43 cm ASM depth. Minimum biomass yields at 1.27, 2.54, 3.81, and 5.08 cm ASM depths occurred in years 1949, 1930, 1930 and 1944, respectively. Minimum biomass yield for the ASM depth greater than 5.08 cm occurred in 1944. Rainfall records from the study area show that the total rainfall during the growing season in years 1930, 1944 and 1949 were 43.08, 50.77 and 40.28 cm, respectively. The long-term records also revealed that 1930, 1944 and 1949 were the driest years observed during the period 1930-87. Temperature records show that in years 1930, 1944 and 1949, the total number of days with favorable temperature were 123, 133 and 166 days, respectively.

Maximum biomass yields with 1.27, 2.54, 3.81, 5.08, 6.35, 7.62, 8.89, 10.16, 11.43, 12.70, 13.97 and 15.24 cm ASM depths occurred in years 1967, 1937, 1974, 1935, 1935, 1979, 1979, 1979, 1961,

Table 11. Regression analysis testing of tall fescue five years observed data against VPIGRO simulated biomass.

Soil type	a	b	SE(a)	SE(b)	$t_0(a)$	$t_0(b)$	$t_{.95}(3)$
Sandstone	-5.34	1.96	4.14	0.75	-1.29	1.28	2.35
2:1 Mixture	2.66	0.51	14.52	2.60	0.18	-0.19	2.35
1:1 Mixture	-5.22	1.91	8.51	1.53	-0.61	0.59	2.35
1:2 Mixture	2.85	0.49	6.32	1.14	0.45	-0.45	2.35
Siltstone	5.91	-0.27	3.17	0.57	1.86	-2.23	2.35

a = intercept of the regression line;
b = slope of the regression line;
SE(a) = standard error of a;
SE(b) = standard error of b;
$t_0(a)$ = t-statistics of a;
$t_0(b)$ = t-statistics of b;
$t_{.95}(3)$ = table value of t-statistics.

Since $t_0(a)$ and $t_0(b)$ are less than $t_{.95}(3)$ for all cases, we conclude not to reject hypothesis (H_0:a = 0&b = 1) at the 5% significance level.

Table 12. Long-term tall fescue biomass simulation using VPIGRO

Year	Tall fescue biomass (Mg/ha) for plant available soil moisture (cm)											
	1.27	2.54	3.81	5.08	6.35	7.62	8.89	10.1	11.4	12.7	13.9	15.2
1930	1.19	1.83	2.50	3.05	3.37	3.67	3.97	4.25	4.48	4.59	4.63	4.67
1931	2.43	3.45	3.84	4.28	4.63	4.92	5.12	5.22	5.29	5.34	5.36	5.37
1932	2.11	3.18	4.01	4.68	5.05	5.29	5.43	5.51	5.56	5.59	5.61	5.63
1933	2.02	3.16	3.69	4.17	4.61	5.02	5.25	5.41	5.51	5.56	5.58	5.59
1934	1.94	2.84	3.66	4.26	4.82	5.12	5.33	5.44	5.49	5.50	5.50	5.51
1935	3.33	4.90	5.84	6.41	6.71	6.84	6.91	6.94	6.96	6.98	6.98	6.99
1936	1.17	1.89	2.63	3.33	3.84	4.24	4.43	4.55	4.63	4.65	4.65	4.65
1937	3.63	5.23	5.86	6.07	6.14	6.16	6.16	6.16	6.17	6.16	6.16	6.17
1938	3.29	4.84	5.60	5.90	6.04	6.12	6.16	6.19	6.21	6.22	6.22	6.22
1939	1.99	3.01	4.24	4.95	5.24	5.39	5.49	5.54	5.56	5.58	5.60	5.61
1940	2.69	3.74	4.78	5.43	5.80	6.00	6.07	6.11	6.14	6.14	6.14	6.14
1941	1.97	2.89	3.50	4.15	4.77	5.21	5.42	5.50	5.55	5.57	5.59	5.60
1942	2.92	4.28	4.92	5.31	5.49	5.56	5.62	5.64	5.68	5.69	5.71	5.74
1943	1.80	3.50	4.32	4.65	4.82	4.94	5.02	5.05	5.08	5.09	5.10	5.10
1944	1.63	2.34	2.65	2.95	3.37	3.63	3.85	4.03	4.22	4.39	4.52	4.59
1945	3.02	4.45	5.41	5.87	6.04	6.09	6.11	6.13	6.14	6.14	6.14	6.14
1946	2.48	3.73	4.84	5.63	6.05	6.25	6.36	6.41	6.42	6.42	6.42	6.42
1947	2.99	4.88	5.98	6.29	6.41	6.44	6.46	6.47	6.47	6.47	6.47	6.47
1948	1.32	2.25	3.39	4.31	4.95	5.45	5.73	5.89	5.98	6.04	6.06	6.07
1949	1.13	1.91	2.56	3.37	4.31	5.16	5.74	6.19	6.43	6.56	6.63	6.67
1950	1.48	2.36	3.20	3.78	4.20	4.60	5.04	5.46	5.85	6.20	6.42	6.59
1951	2.83	4.02	4.49	4.71	4.91	5.11	5.33	5.52	5.70	5.87	5.95	6.01
1952	2.18	3.49	4.29	4.54	4.63	4.67	4.69	4.70	4.70	4.70	4.70	4.70
1953	2.32	3.55	4.49	4.87	5.01	5.08	5.11	5.13	5.13	5.13	5.13	5.13
1954	2.15	2.95	3.82	4.56	4.99	5.21	5.33	5.42	5.47	5.48	5.49	5.50
1955	2.27	3.93	5.14	5.61	5.82	5.96	6.07	6.18	6.26	6.31	6.34	6.37
1956	2.83	4.33	5.73	6.34	6.51	6.56	6.56	6.56	6.56	6.56	6.56	6.56
1957	2.31	3.72	4.69	5.40	5.80	6.00	6.12	6.18	6.20	6.22	6.23	6.23
1958	3.54	4.86	5.79	6.27	6.45	6.49	6.51	6.52	6.52	6.52	6.52	6.52
1959	1.98	3.20	4.53	5.43	5.89	6.10	6.18	6.21	6.21	6.21	6.21	6.21
1960	1.94	3.08	3.99	4.54	4.93	5.26	5.56	5.72	5.83	5.87	5.91	5.97
1961	2.67	4.26	5.24	6.00	6.57	6.81	6.95	7.01	7.02	7.02	7.02	7.02
1962	2.90	4.70	5.64	6.24	6.47	6.55	6.57	6.57	6.57	6.57	6.57	6.57
1963	2.77	4.28	5.56	6.18	6.49	6.62	6.68	6.72	6.76	6.78	6.78	6.80
1964	2.77	4.17	5.13	5.94	6.36	6.62	6.71	6.74	6.76	6.77	6.77	6.77
1965	2.81	3.85	4.81	5.38	5.71	5.97	6.13	6.27	6.40	6.49	6.55	6.60
1966	1.88	3.07	4.00	4.70	5.36	5.62	5.79	5.88	5.93	5.93	5.93	5.93
1967	3.93	4.93	5.72	6.29	6.58	6.74	6.83	6.88	6.91	6.93	6.94	6.96
1968	3.21	4.37	4.97	5.48	5.80	6.00	6.10	6.14	6.16	6.16	6.16	6.16
1969	1.88	3.21	4.37	4.95	5.22	5.37	5.45	5.49	5.52	5.54	5.56	5.57
1970	1.87	3.22	4.31	4.81	5.12	5.32	5.51	5.59	5.64	5.67	5.69	5.70

Table 12. continued...

1971	3.79	4.83	5.52	5.94	6.17	6.27	6.32	6.33	6.33	6.33	6.33	6.33
1972	2.64	4.11	4.97	5.52	5.91	6.14	6.30	6.39	6.44	6.48	6.50	6.51
1973	2.83	4.16	4.80	5.01	5.23	5.37	5.50	5.59	5.74	5.77	5.79	5.84
1974	3.37	5.18	6.05	6.36	6.49	6.53	6.55	6.56	6.56	6.56	6.56	6.56
1975	2.70	3.24	3.58	3.86	4.12	4.37	4.60	4.80	4.95	5.05	5.13	5.19
1976	1.80	3.12	4.00	4.60	5.04	5.28	5.42	5.48	5.55	5.59	5.62	5.67
1977	2.08	2.66	3.62	4.48	4.88	5.09	5.21	5.25	5.27	5.27	5.27	5.27
1978	2.06	3.77	4.64	5.13	5.37	5.46	5.51	5.52	5.54	5.55	5.55	5.56
1979	3.32	4.57	5.45	6.22	6.67	6.88	6.97	7.01	7.01	7.01	7.01	7.01
Tall fescue biomass statistics												
Max.	3.93	5.23	6.05	6.41	6.71	6.88	6.97	7.01	7.02	7.03	7.02	7.02
Min.	1.13	1.83	2.50	2.95	3.37	3.63	3.85	4.03	4.22	4.39	4.52	4.59
Mean	2.44	3.67	4.53	5.08	5.42	5.63	5.76	5.85	5.91	5.94	5.96	5.98
Std.	0.70	0.90	0.96	0.93	0.87	0.80	0.74	0.70	0.67	0.66	0.65	0.65
C.V.	0.29	0.24	0.21	0.18	0.16	0.14	0.13	0.12	0.11	0.11	0.11	0.11

1961, 1961 and 1961, respectively. Rainfall data show that during the growing season total rainfall in years 1935, 1937, 1961, 1967, and 1979 were 67.84, 60.88, 54.91, 63.90 and 65.76 cm, respectively. The long-term records revealed that years 1935, 1937, 1961, 1967, and 1979 were the wetest years observed during the period of record. Temperature records show that in years 1935, 1937, 1961, 1967 and 1979 the total number of days with favorable plant growth temperature regime were 165, 164, 149, 162 and 164 days respectively. Temperature and rainfall records combined show that years 1935, 1937, 1961, 1967 and 1979 were the most favourable years for crop growth and VPIGRO also predicted the maximum biomass yield for these years despite some variability from year to year due to the stochasticity of rainfall and temperature regime. Standard deviation and the coefficient variation varied between 0.65 to 0.96 Mg/ha and 11 to 29 percent, respectively. The coefficient of variation at 1.27 cm ASM depth was the highest and decreased with the increase in ASM depth and reached a constant minimum value at about 11.43 cm ASM depth.

Non-Linear Relationship between Biomass Yield and PASM

Before establishing the relationship between biomass yield and ASM depth it was necessary to find the range of ASM depths between which the equation relating biomass yield and ASM is nonlinear. From theoretical consideration it was hypothesized that

$$y = a + b\,x + cx^2 \qquad \text{if } x < x_o \qquad [66]$$

$$y = p \qquad \text{if } x > x_o \qquad [67]$$

That is, for values of ASM, $x \leq x_o$, equation (49) is nonlinear and for values of ASM, $x > x_o$, the equation (50) is a horizontal line.

The curve must be continuous (the two sections must meet at x_o) and the curve must be smooth (the first derivatives with respect to x are the same at x_o). These conditions imply that

$$x_o = -b/2c \qquad [68]$$

$$p = a - b^2/4c \qquad [69]$$

The segmented equation includes only three parameters; however, the equation is nonlinear with respect to these parameters. A computer program was written with the SAS procedure NLIN (SAS User's Guide: Statistics, 1982) to conditionally execute different sections of code for the two parts of the model, depending on whether x is less than x_o. The computer program is presented in the Appendix C. Using this program x_o was found and its value is about 11.43 cm. Then a statistical test was performed using nonlinear regression procedures. The lognormal model gave high R^2 and small C_p statistics and was selected for further analysis.

Optimum Soil Depth for each Soil Material

Using the developed SDOM, the optimum soil depth required for successful revegetation for all five events of interest were estimated and are presented in Table 13. Table 13 shows that the optimum soil depth for all events of interest was lowest for 2:1 SS/SiS and was highest for SS. The optimum soil depths required for the event A were 137.3, 129.0, 134.1, 135.4 and 136.9 cm for SS, 2:1 SS/SiS, 1:1 SS/SiS, 1:2 SS/SiS, and SiS respectively. Event A and event E required the maximum and minimum soil depths respectively for all soil materials. The maximum difference in optimum soil depths between SS and 2:1 SS/SiS mixtures is 8.3 mm. Although the absolute difference in soil depth seems small, in terms of total saving in reclamation cost per unit area based on the present cost of overhauling ($35.0/ m^3) is $2900.0/ha. This is a significant savings in mine soil reclamation effort.

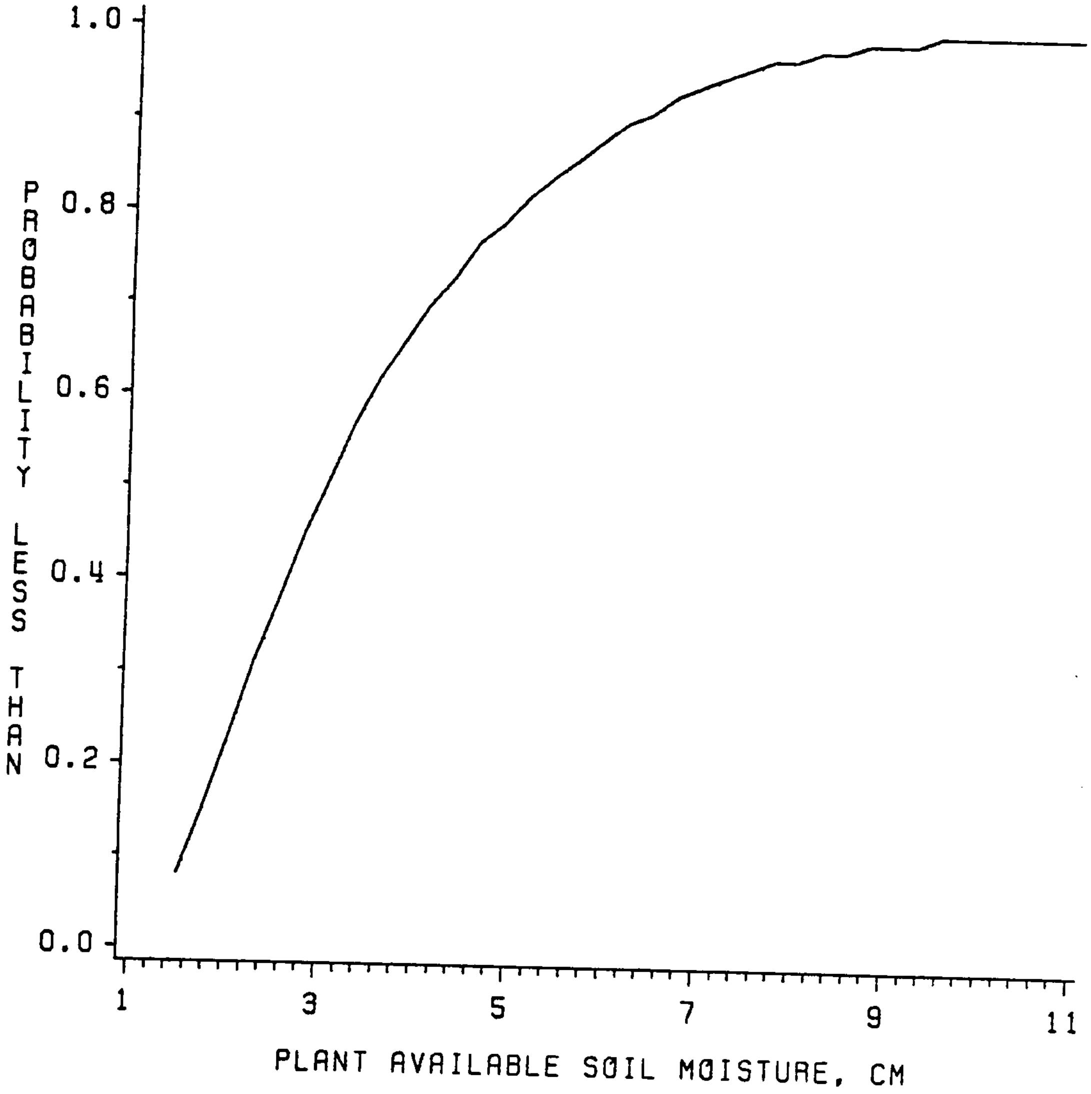

Figure 17. Relationship between ASM and the probability of revegetation success for the event E.

Fig. 17 shows the relationship between ASM and probability of revegetation success for the event E. This figure allows determination of the required ASM for a given probability of revegetation success for the study area. For example, an ASM depth of 6.09 cm is required to satisfy at most 90% probability of revegetation success at all times. Once the ASM is determined, the actual soil depth can be calculated for the selected soil mixture using the procedure outlined in Table 3. Fig. 18 presents the relationship between ASM and actual soil depth for a 2:1 SS/SiS soil mixture. Fig. 18 shows that 96.7 cm actual soil depth of 2:1 SS/SiS soil mixture gives 6.09 cm ASM. Similarly, the required actual soil depth for 1:0, 1:1, 1:2 and 0:1 SS/SiS soil mixture for 6.09 ASM were calculated as 103.0 cm, 100.6 cm, 101.6 cm, and 102.7 cm, respectively. Note that once the model predicts the required ASM depth for an area and specific crop miners can construct a soil using this ASM. Miners could select any soil mixture and provide the actual soil depth required to meet the predicted ASM.

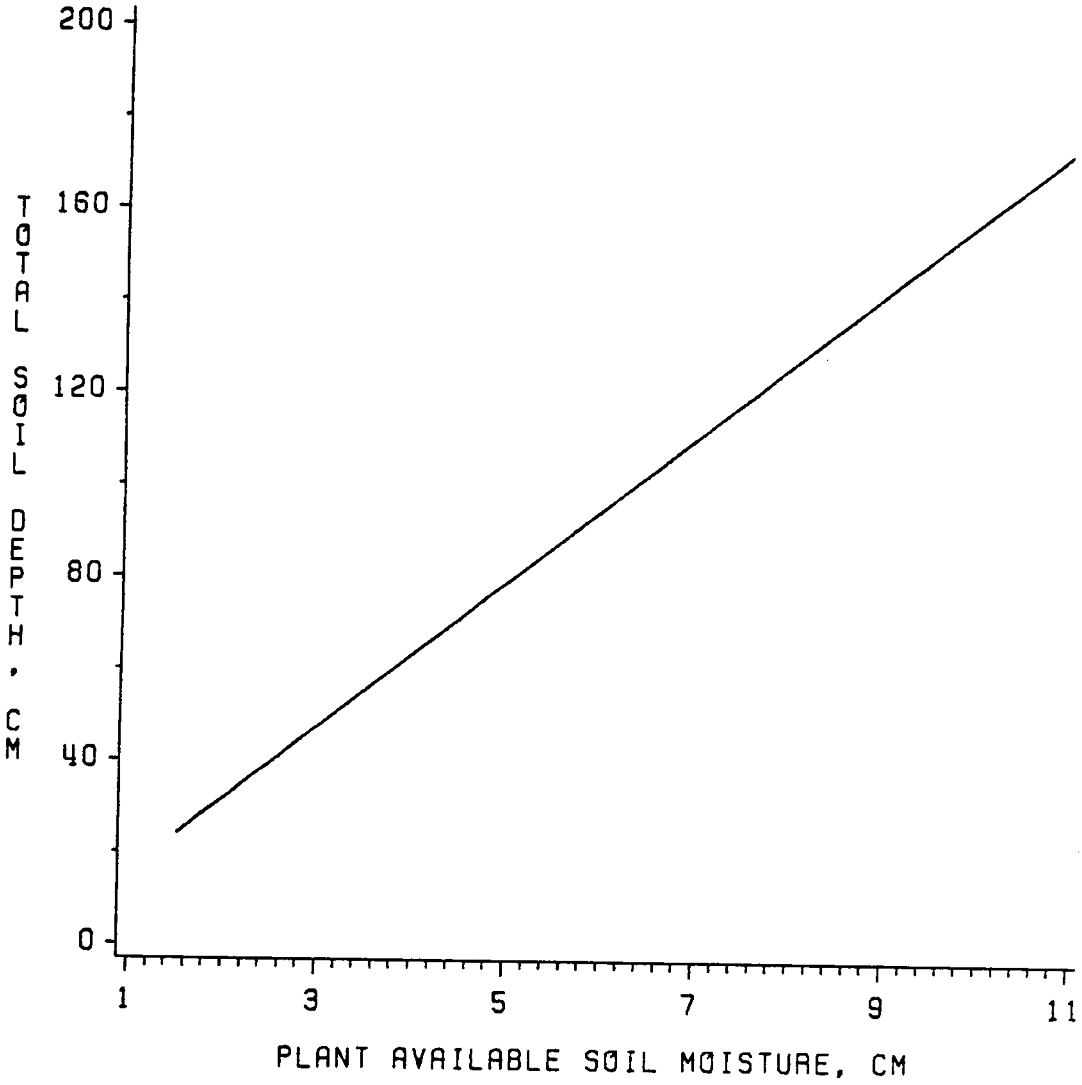

Figure 18. Relationship between ASM and actual soil depth for 2:1 SS/SiS mine soil mixture.

Table 13. Optimum soil depth for five soil mixture at 90% probability of revegetation success.

							Soil depth, cm				
							S/SiS ratio				
ASM	Yield	P(A)	P(B)	P(C)	P(D)	P(E)	1:0	2:1	1:1	1:2	0:1
(cm)	(Mg/ha)	<		percent		>					
1.5	3.05	0.00	0.00	0.00	0.01	0.12	25.7	24.2	25.1	25.4	25.7
1.8	3.27	0.00	0.00	0.01	0.03	0.19	30.0	28.2	29.3	29.6	29.9
2.0	3.47	0.00	0.01	0.02	0.06	0.27	34.3	32.2	33.5	33.9	34.2
2.3	3.63	0.00	0.01	0.04	0.10	0.34	38.6	36.3	37.7	38.1	38.5
2.5	3.79	0.01	0.03	0.07	0.14	0.41	42.9	40.3	41.9	42.3	42.8
2.8	3.92	0.02	0.05	0.10	0.19	0.47	47.2	44.3	46.1	46.6	47.1
3.0	4.05	0.04	0.07	0.14	0.24	0.52	51.5	48.4	50.3	50.8	51.3
3.3	4.16	0.06	0.10	0.18	0.29	0.57	55.8	52.4	54.5	55.0	55.6
3.6	4.27	0.09	0.14	0.23	0.34	0.61	60.1	56.4	58.7	59.2	59.9
3.8	4.37	0.12	0.18	0.28	0.39	0.65	64.4	60.5	62.9	63.5	64.2
4.1	4.46	0.15	0.22	0.32	0.44	0.68	68.7	64.5	67.1	67.7	68.4
4.3	4.55	0.19	0.26	0.37	0.48	0.72	73.0	68.5	71.2	71.9	72.7
4.6	4.63	0.23	0.31	0.41	0.53	0.74	77.2	72.5	75.4	76.2	77.0
4.8	4.71	0.27	0.35	0.46	0.57	0.77	81.5	76.6	79.6	80.4	81.3
5.1	4.78	0.32	0.40	0.50	0.61	0.79	85.8	80.6	83.8	84.6	85.6
5.3	4.85	0.36	0.44	0.54	0.65	0.82	90.1	84.6	88.0	88.9	89.8
5.6	4.92	0.41	0.49	0.58	0.68	0.84	94.4	88.7	92.2	93.1	94.1
5.8	4.98	0.45	0.53	0.62	0.71	0.85	98.7	92.7	96.4	97.3	98.4
6.1	5.04	0.49	0.57	0.65	0.74	0.87	103.0	96.7	100.6	101.6	102.7
6.3	5.10	0.53	0.61	0.69	0.77	0.88	107.3	100.8	104.8	105.8	106.9
6.6	5.16	0.58	0.65	0.72	0.80	0.90	111.6	104.8	109.0	110.0	111.2
6.9	5.21	0.62	0.68	0.75	0.82	0.91	115.9	108.8	113.1	114.3	115.5
7.1	5.26	0.66	0.72	0.78	0.84	0.92	120.2	112.8	117.3	118.5	119.8
7.4	5.31	0.70	0.75	0.80	0.86	0.93	124.5	116.9	121.5	122.7	124.1
7.6	5.36	0.73	0.78	0.83	0.88	0.94	128.7	120.9	125.7	127.0	128.3
7.9	5.41	0.76	0.80	0.85	0.89	0.95	133.0	124.9	129.9	131.2	132.6
8.1	5.45	0.79	0.83	0.87	0.91	0.95	137.3	129.0	134.1	135.4	136.9
8.4	5.50	0.82	0.86	0.89	0.92	0.96	141.6	133.0	138.3	139.7	141.2
8.6	5.54	0.85	0.88	0.91	0.94	0.97	145.9	137.0	142.5	143.9	145.4
8.9	5.58	0.88	0.90	0.92	0.95	0.97	150.2	141.1	146.7	148.1	149.7
9.1	5.62	0.90	0.92	0.94	0.96	0.98	154.5	145.1	150.9	152.3	154.0
9.4	5.66	0.92	0.93	0.95	0.97	0.98	158.8	149.1	155.1	156.6	158.3
9.7	5.70	0.93	0.95	0.96	0.97	0.99	163.1	153.1	159.2	160.8	162.6
9.9	5.74	0.95	0.96	0.97	0.98	0.99	167.4	157.2	163.4	165.0	166.8
10.2	5.77	0.96	0.97	0.98	0.98	0.99	171.7	161.2	167.6	169.3	171.1
10.4	5.81	0.97	0.98	0.98	0.99	0.99	176.0	165.2	171.8	173.5	175.4
10.7	5.84	0.98	0.98	0.99	0.99	1.00	180.2	169.3	176.0	177.7	179.7
10.9	5.88	0.98	0.99	0.99	0.99	1.00	184.5	173.3	180.2	182.0	183.9
11.2	5.91	0.99	0.99	0.99	1.00	1.00	188.8	177.3	184.4	186.2	188.2
11.4	5.94	0.99	0.99	1.00	1.00	1.00	193.1	181.4	188.6	190.4	192.5
11.7	5.97	0.99	1.00	1.00	1.00	1.00	197.4	185.4	192.8	194.7	196.8

Sensitivity Analysis of SDOM Input Variables on Output

Sensitivity analysis show how sensitive a model is to various input parameters and also tells which parameters are the most important. This study considered a sensitivity analysis of the model output on the following input parameters:

1. the optimum rate of production of dry matter yield (R);
2. the quantity of accumulated dry matter that provides enough leaf area to support optimum growth (Q_3);
3. the minimum air temperature below which crop growth does not occur (T_1) ;
4. the maximum air temperature above which crop growth does not occur (T_3) ;
5. the optimum air temperature at which the growth rate of each crop is optimum (T_2);
6. and, the initial soil moisture (ISM) content.

For the purpose of testing the sensitivity of the above mentioned input parameters on the optimum ASM, the SDOM was run 156 times by increasing and decreasing the parameter values by a predetermined percentage. Table 14 presents the sensitivity analysis results. These results show that when R was decreased by 10%, the optimum ASM depth was increased by 37.8%. However, when R was increased by 10%, the optimum ASM depth was decreased by only 27.3%. Thus, the optimum ASM depth is more sensitive to a reduction in R than an increase. Choosing a lower R will result in a higher optimum ASM depth and will provide higher confidence for the revegetation success in long run. But a higher confidence in vegetation success will cost more in reclamation effort. On the other hand, choosing a higher R will result in a lower optimum ASM depth and lower confidence in vegetation success, but a lower cost in reclamation effort. This analysis definitely shows the importance of the input crop parameter R on the selection of the optimum ASM depth, vegetation success, and the cost of reclamation effort.

Table 14 shows that when Q_3 was decreased and increased by 10%, the optimum ASM depth was decreased and increased by 12.1%. Thus, the optimum ASM depth is equally sensitive for both the higher and the lower values of Q_3. This linear effect of higher and lower values of Q_3 may be explained by Eq. 32 if the second term effect is considered to be negligible. Choosing a higher Q_3 will result in a higher optimum ASM depth, higher confidence in the success of revegetation and higher reclamation costs. On the other hand, choosing a lower Q_3 will result in a lower optimum ASM depth, lower confidence in vegetation success, and lower reclamation cost.

Table 14 shows that when T_1 was increased by 10%, the optimum ASM depth was increased by 4.5%. However, when T_1 was decreased by 10%, the optimum ASM depth was decreased by 1.5%. The effect of T_1 on ASM depth was not significant because when T_1 was increased or decreased by 10%, there was no significant change in total favourable plant growth hours. Table 14 shows that when T_2 was decreased and increased by 10%, the optimum ASM depth was increased and decreased by 37.8% and 27.3%, respectively. Similarly, when T_3 was decreased and increased by 2.5%, the optimum ASM depth was increased and decreased by 34.8% and 19.6%, respectively. This significant effect of T_3 on ASM depth was due to a significant change in total favourable plant growth hours. The effect of R and T_2 on ASM depth were equal because these two parameters have an one-to-one relationship (Eq. 30a).

Finally, Table 14 shows that when initial soil moisture (ISM) was decreased by 50%, the optimum ASM depth was increased by 19.7%. However, with the increase in ISM by 50%, the optimum ASM depth remained unchanged. This is because of the assumption that plant stress occurs only after the moisture content falls below 50% of the maximum soil storage capacity.

In general, this analysis shows the effect of input parameters on the optimum ASM depth. These results suggest that R , T_2, and T_3 are the most sensitive input parameters and the values for these parameters should be obtained from experimental data.

Table 14. Sensitivity analysis of SDOM input parameters on optimum ASM depth.

Parameter			Result	
	Value	% change	Optimum ASM (cm)	% change
R (Mg/ha-hr)	5.85	-10	9.1	37.8
	6.50	0	6.6	0.0
	7.15	+10	4.8	27.3
Q_3 (Mg/ha)	5576.4	-10	5.8	12.1
	6196.0	0	6.6	0.0
	6815.6	+10	7.4	12.1
T_1 (°C)	3.96	-10	6.5	1.5
	4.4	0	6.6	0.0
	4.84	+10	6.9	4.5
T_2 (°C)	16.47	-10	9.1	37.8
	18.3	0	6.6	0.0
	20.13	+10	4.8	27.3
T_3 (°C)	31.4	-2.5	8.9	34.8
	32.2	0	6.6	0.0
	33.0	+2.5	5.3	19.6
ISM (%)	25.0	-50	7.9	19.7
	50.0	0	6.6	0.0
	75.0	+50	6.6	0.0

SUMMARY AND CONCLUSIONS

Summary and Conclusions

The principal objective of this study was to develop a comprehensive physically based stochastic dynamic optimization model to assist planners in making decisions concerning mine soil depths and soil mixture ratios required to achieve successful revegetation at different probability levels of success for the release of performance bonds, subject to an uncertain weather regime. To accomplish the above objective a perennial grass growth model was selected and modified for predicting vegetation growth in reclaimed mine soils. The model is based on continuous relationships between plant growth, air temperature, day length, leaf area, photoperiod and plant-soil-moisture stresses. A plant available soil moisture model was adopted to estimate daily soil moisture for mine soils. The SCS runoff curve number procedure was incorporated into the plant available soil moisture model to partition infiltration and runoff. Potential evaporation was estimated from pan evaporation data. Daily soil evaporation and plant evaporation were estimated separately using a two stage drying process suggested by Ritchie (1972). A sigmoidal relationship was used to estimate the effect of water stress on biomass yield.

A general probability model was developed to calculate the occurrence of successful revegetation in 5-years of the bond release period at a given probability level of success. The probability model consists of five different events of interest in mine soil reclamation planning. These five events of interest are: (i) the occurrence of successful revegetation in all years of the bond release period; (ii) revegetation success in at least the last 4 years of the 5 years bond release period; (iii) successful revegetation in at least the last 3 years of the 5 years bond release period; (iv) successful revegetation in at least the last 2 years of the 5 years bond release period; and, (v) successful revegetation in at least the last year of the 5 years bond release period which is actually required by the SMCRA. It should be noted that the SMCRA has the provision that the miners are allowed to establish a good vegetation cover and plant rooting system before starting the five year bond release period. The initial vegetation establishment process which is designated as Phase I of the reclamation effort could possibly take one or more years and then Phase II period, that is, the five year bond release period begins. Phase I of the vegetation process is the most critical period and might require reseeding, fertilization and/or chemical treatment of the soil materials. Once Phase I activities are completed, Phase II starts and the reclaimed area is left alone without any interferance from miners or government agencies. Therefore, the fate of reclamation effort during Phase II depends on the weather patterns and initial conditions established during Phase I. This research clearly defines Phases I and II of a reclamation plan and presents a solid mathematical formulation for minimizing reclamation problems.

A general nonlinear relationship between mean dry matter yield and ASM depth was developed. The developed SDOM was used to find the optimum combination of soil depth and soil mixture ratios that met the successful vegetation standard under non-irrigated conditions with weather as the only random element of the system.

To demonstrate the usefulness of the SDOM, data from Wise County, Virginia, were used. Application of the developed model found that a 2:1 SS/SiS soil mixture required the minimum soil depth for all events of revegetation success studied. These results are also supported by field data obtained by Roberts et al. (1986).

In conclusion, the developed model allows the planners to make optimum decisions concerning mine soil characteristics under uncertain weather conditions. Through optimum decisions, a significant amount of economic saving is possible in mine soil reclamation and environmental preservation. The developed model can be used by miners, SMCRA, and research scientists for finding the relationship between probability of revegetation success and ASM. Once the relationship has been established for an area and a given crop, one can evaluate the success or failure of other reclamation plans using the same vegetation without rerunning the model. The developed model should help to reduce reclamation costs by better defining soil mixture and the depths of topsoil required to achieve revegetation success.

Model users should be aware of the following limitations of the model:

1. The model is applicable only for homogeneous and isotropic soil media.
2. The model is highly sensitive to the R and T_2, and T_3 parameters. Users should obtain good estimates of these parameters.
3. The model should not suitable for the Phase I revegetation problem without major modifications.

RECOMMENDATIONS FOR FURTHER RESEARCH

1. The developed model was validated only for the one soil depth for which field experimental data was available. It is recommended that more field data be gathered to verify the model over a range of soil depths. Additional verification is required to demonstrate the use of the developed model as a versatile planning tool.
2. The developed SDOM model assumes that the chemical properties of the mine soils are corrected before the starting year of bond release period. In reality, neutralization of negative chemical effects may take more time, therefore, in such cases it will be necessary to include the effect of chemical properties in the PGGM. One way to consider the effect of chemical properties in the PGGM would be to incorporate a chemical factor in biomass yield.
3. This study assumed that Ritchies′ PASM model gives reasonable estimates of daily soil moisture levels. Although, the assumption of uniform distribution of soil water in the root zone is a conservative assumption, it may be possible to improve the soil moisture prediction by considering a complex soil moisture redistribution process under unsaturated conditions. Therefore, it is recommended that an unsaturated moisture redistribution function be incorporated into the PASM model.
4. This study assumed a sigmoidal relationship between soil moisture deficit and biomass yield reduction in absence of a verified function. It is recommended that a long-term monitoring system for soil moisture and biomass yield be established to develop a valid functional relationship between soil moisture deficit and biomass yield reduction.

5. The developed SDOM was applied to a specific area in Virginia. The model should be applied to other areas before it is used for reclamation planning in other regions.

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APPENDICES

Appendix A: List of Principal Symbols

a = domain of saturation associated with concave portion of curve, and

a_k = plant sensitivity parameter;

A = daylength when the crop begins to store carbohydrates;

ADM = the accumulated dry matter which is the sum of daily growth rates;

B = daylength when the portion of carbohydrates going into storage reaches a constant value;

b = domain of saturation associated with convex portion of curve.

b_k = plant sensitivity factor to water deficits;

C = maximum effect of photoperiod as a proportion of the optimum growth rate;

C = capillary rise from lower levels;

C_1, C_2, and C_3 are coefficients;

CS = crop sensitivity factor to water deficit;

$D(\theta)$ = diffusion coefficient,

d = depth of available water in the root zone at time t;

d_f = depth of available water in the root zone at the end of the field test;

DL = day length, hours;

$\frac{dy}{d\theta}$ = growth rate of a plant, kg/ha/h;

E = evaporation or condensation;

ET = actual evapotranspiration;

ETP = potential evapotranspiration;

h = saturated thickness of aquifer or confined aquifer thickness (L),

H = water table elevation or piezometric head, referred to an established datum (L),

K = hydraulic conductivity (L/T),

L = net lateral subsurface outflow;

LAF = leaf area factor;

m = shape factor of the curve,

P = precipitation;

P = probability of revegetation success in a given year i;

PF = photoperiod factor;

q = total amount of water received by the plant per unit area;

Q = percolation.

Q = net groundwater withdrawl (L^3/T),

Q_3 = the maximum quantity of accumulated dry matter that provides enough leaf area for maximum growth;

R = surface runoff;

R = the optimum growth rate;

S = storage coefficient for confined case or effective porosity for unconfined case (dimensionless),

SD = stress day factor;

S_s = sink term used to simulate evapotranspiration,

S = saturation,

S_r = residual saturation,

SM_t = soil moisture volume at time t;

SM_{t-1} = soil moisture volume at previous time;

T = transpiration;

t = time dimension (T),

t = air temperature, °F;

t_1 = minimum air temperature below which growth does not occur;

t_3 = maximum air temperature above which growth does not occur;

t_2 = optimum air temperature where the growth rate of each crop is optimum;

T_a = actual transpiration;

T_p = potential transpiration;

T_{max} = maximum air temperature;

T_{min} = minimum air temperature;

β_k = plant sensitivity factor;

θ = the elapsed time from sunrise, hours;

θ = soil moisture content,

θ_k = available soil moisture during period k;

λ_k = crop sensitivity factor to water stress;

ψ = capillary pressure (suction) head,

ψ_i = capillary pressure head at inflection point,

x,y = space dimensions (L), and

y_i = dry matter yield in year i;

$Y_M(q_M)$ = maximum yield that can be obtained with the maximum quantity of water;

y_{ref} = dry matter yield in kg/ha/year for the reference area;

Z = depth.

Z_k = standardized normal variate with zero mean and standard deviation equals one;

Appendix B: Variable Glossary

NAME	TYPE	MAIN USE	DEFINITION
A	R	VARIABLE	Daylength (after the summer solstice) when the crop begins to store carbohydrates, hrs
ADM	R	ARRAY	Accumulated dry matter yield, kg/ha
ARN	R	ARRAY	Daily raiffall, cm
B	R	VARIABLE	Daylength when the portion of carbohydrates going into storage reaches a constant value, hrs
C	R	VARIABLE	Maximum effect of photoperiod of the optimum growth rate ($0.0 \geq C \leq 1.0$)
D	R	VARIABLE	Soil depth, cm
DELY	R	ARRAY	Hourly rate of biomass production, Mg/ha-hr
DL	R	ARRAY	Day length, hrs
DSAND	R	VARIABLE	Soil depth for 1:0 S/SiS mixture, cm
D21MIX	R	VARIABLE	Soil depth for 2:1 S/SiS mixture, cm
D11MIX	R	VARIABLE	Soil depth for 1:1 S/SiS mixture, cm
D12MIX	R	VARIABLE	Soil depth for 1:2 S/SiS mixture, cm
DSILT	R	VARIABLE	Soil depth for 0:1 S/SiS mixture, cm
F	R	VARIABLE	Weight given to current conditions in determining the soil moisture factor ($0.0 \geq F \leq 1.0$)
LAF	R	ARRAY	Leaf area factor
LDAY	R	VARIABLE	Last day of the growing season, (give value 183)
N	I	VARIABLE	Number of days over which the soil moisture that occurs on a given day can be effectively used by the crop, days
NYEARS	I	VARIABLE	Number of years to simulate
P	R	VARIABLE	Probability of revegetation success in a given year, percentage
PA	R	VARIABLE	Probability of revegetation success in all 5 years of the bond release period, percentage
PB	R	VARIABLE	Probability of revegetation success in at least the last 4 years of the 5 year bond release period, percentage
PC	R	VARIABLE	Probability of revegetation success in at least the last 3 years of the 5 year bond release period, percentage

PD	R	VARIABLE	Probability of revegetation success in at least the last 2 years of the 5 year bond release period, percentage
PE	R	VARIABLE	Probability of revegetation success in at least the last year of the 5 year bond release period, percentage
PEN	R	ARRAY	Daily pen evaporation, cm
PF	R	ARRAY	Photoperiod factor
Q1	R	VARIABLE	Min. quantity of ADM which provides enough leaf area for full growth rate in an optimum temp. regime, Mg/ha
Q2	R	VARIABLE	Max. quantity of ADM which provides enough leaf area for full growth rate in an optimum temp. regime, Mg/ha
Q3	R	VARIABLE	Max. quantity of ADM when growth terminates, Mg/ha
R	R	VARIABLE	Optimum growth rate, Mg/ha-hr
SDAY	I	VARIABLE	Starting day of the growing season, (Give value 1)
SMAC	R	ARRAY	Soil moisture from actual daily rainfall, cm
SMF	R	ARRAY	Soil moisture factor, fraction
SMFPF	R	ARRAY	Product of SMF and PF factors
STD1	R	VARIABLE	Biomass standard deviation for 1.27 cm plant available soil moisture, Mg/ha
STD2	R	VARIABLE	Biomass standard deviation for 2.54 cm plant available soil moisture, Mg/ha
STD3	R	VARIABLE	Biomass standard deviation for 3.81 cm plant available soil moisture, Mg/ha
STD4	R	VARIABLE	Biomass standard deviation for 5.08 cm plant available soil moisture, Mg/ha
STD5	R	VARIABLE	Biomass standard deviation for 6.35 cm plant available soil moisture, Mg/ha
STD6	R	VARIABLE	Biomass standard deviation for 7.62 cm plant available soil moisture, Mg/ha
STD7	R	VARIABLE	Biomass standard deviation for 8.89 cm plant available soil moisture, Mg/ha
STD8	R	VARIABLE	Biomass standard deviation for 10.1 cm plant available soil moisture, Mg/ha
STD9	R	VARIABLE	Biomass standard deviation for 11.4 cm plant available soil moisture, Mg/ha
STD10	R	VARIABLE	Biomass standard deviation for 12.7 cm plant available soil moisture, Mg/ha
T	R	VARIABLE	Air temperature for a diurnal period, degree C

T1	R	VARIABLE	Min. air temp. below which growth does not occur, degree C
T2	R	VARIABLE	Optimum air temp. where the growth rate of each crop is optimum, degree C
T3	R	VARIABLE	Max. air temp. above which growth does not occur, degree C
TMAX	R	ARRAY	Maximum daily temperature, degree C
TMIN	R	ARRAY	Minimum daily temperature, degree C
V1	R	VARIABLE	Expected biomass yield for 1.27 cm plant available soil moisture, Mg/ha
V2	R	VARIABLE	Expected biomass yield for 2.54 cm plant available soil moisture, Mg/ha
V3	R	VARIABLE	Expected biomass yield for 3.81 cm plant available soil moisture, Mg/ha
V4	R	VARIABLE	Expected biomass yield for 5.08 cm plant available soil moisture, Mg/ha
V5	R	VARIABLE	Expected biomass yield for 6.35 cm plant available soil moisture, Mg/ha
V6	R	VARIABLE	Expected biomass yield for 7.62 cm plant available soil moisture, Mg/ha
V7	R	VARIABLE	Expected biomass yield for 8.89 cm plant available soil moisture, Mg/ha
V8	R	VARIABLE	Expected biomass yield for 10.1 cm plant available soil moisture, Mg/ha
V9	R	VARIABLE	Expected biomass yield for 11.4 cm plant available soil moisture, Mg/ha
V10	R	VARIABLE	Expected biomass yield for 12.7 cm plant available soil moisture, Mg/ha
Y	R	VARIABLE	Estimate biomass yield for soil depth D cm, Mg/ha
YREF	R	VARIABLE	Biomass yield for the reference area, Mg/ha-yr

Appendix C: SDOM MODEL

```
C..==================================================================
C             SDOM model was developed by Golam Mustafa
c               Department of Agricultural Engineering
c         Virginia Polytechnic Institute & State University
c                    Blacksburg, Virginia, 24061
c                          November, 1988.
c..==================================================================
C.....PROGRAM TO CALCULATE THE PROBABILITY OF REVEGETATION SUCCESS
C.....FOR FIVE DIFFERENT SOIL MATERIALS CONSTRUCTED FROM SANDSTONE AND
C.....SILTSTONE ROCKS AVAILABLE AT THE COAL MINED AREAS OF SW VIRGINIA.
C.....
C.....THIS PROGRAM COMPUTES THE PROBABILITIES AT DIFFERENT SOIL DEPTHS
C.....FOR FIVE EVENTS OF REVEGETATION SUCCESS.
C.....EVENT A: ALL 5 YRS' ARE SUCCESS;
C.....EVENT B: AT LEAST LAST 4 YRS ARE SUCCESS;
C.....EVENT C: AT LEAST LAST 3 YRS ARE SUCCESS;
C.....EVENT D: AT LEAST LAST 2 YRS ARE SUCCESS;
C.....EVENT E: AT LEAST LAST YEAR A SUCCESS;
C.....LET P BE THE PROBABILITY OF SUCCESS AT SOIL DEPTH D;
C.....A SUCCESSFUL EVENT IS DEFINED AS ( YIELD >= 0.9 * REFERENCE YIELD);
C.....
      REAL Z,P
      YREF=4.0
      V1=2.44
      V2=3.67
      V3=4.53
      V4=5.08
      V5=5.42
      V6=5.63
      V7=5.76
      V8=5.85
      V9=5.91
      V10=5.94
      STD1=0.70
      STD2=0.90
      STD3=0.96
      STD4=0.93
      STD5=0.87
      STD6=0.80
      STD7=0.74
      STD8=0.70
      STD9=0.67
      STD10=0.66
      STD11=0.65
      D=0.6
      WRITE(6,105)
 105  FORMAT(1X,'PASW','YIELD','P','P(A)','P(B)','P(C)','P(D)','SAND',
     *'MIX21','MIX11','MIX12','SILT')
  99  Y=3.734+3.746*LOG10(D)
      IF(Y .GE. V1 .AND. Y .LT. V2) GO TO 10
      IF(Y .GE. V2 .AND. Y .LT. V3) GO TO 20
```

Appendix C: continue...

```
      IF(Y .GE. V3 .AND. Y .LT. V4) GO TO 30
      IF(Y .GE. V4 .AND. Y .LT. V5) GO TO 40
      IF(Y .GE. V5 .AND. Y .LT. V6) GO TO 50
      IF(Y .GE. V6 .AND. Y .LT. V7) GO TO 60
      IF(Y .GE. V7 .AND. Y .LT. V8) GO TO 70
      IF(Y .GE. V8 .AND. Y .LT. V9) GO TO 80
      IF(Y .GE. V9 .AND. Y .LT. V10) GO TO 90
      IF(Y .GT. V10) GO TO 100
 10   DSTD=ABS(STD1-STD2)
      STD=STD1+DSTD/(V2-V1)*(Y-V1)
      Z=(YREF-Y)/STD
      GO TO 333
 20   DSTD=ABS(STD2-STD3)
      STD=STD2+DSTD/(V3-V2)*(Y-V2)
      Z=(YREF-Y)/STD
      GO TO 333
 30   DSTD=ABS(STD3-STD4)
      STD=STD3-DSTD/(V4-V3)*(Y-V3)
      Z=(YREF-Y)/STD
      GO TO 333
 40   DSTD=ABS(STD4-STD5)
      STD=STD4-DSTD/(V5-V4)*(Y-V4)
      Z=(YREF-Y)/STD
      GO TO 333
 50   DSTD=ABS(STD5-STD6)
      STD=STD5-DSTD/(V6-V5)*(Y-V5)
      Z=(YREF-Y)/STD
      GO TO 333
 60   DSTD=ABS(STD6-STD7)
      STD=STD6-DSTD/(V7-V6)*(Y-V6)
      Z=(YREF-Y)/STD
      GO TO 333
 70   DSTD=ABS(STD7-STD8)
      STD=STD7-DSTD/(V8-V7)*(Y-V7)
      Z=(YREF-Y)/STD
      GO TO 333
 80   DSTD=ABS(STD8-STD9)
      STD=STD8-DSTD/(V9-V8)*(Y-V8)
      Z=(YREF-Y)/STD
      GO TO 333
 90   DSTD=ABS(STD9-STD10)
      STD=STD9-DSTD/(V10-V9)*(Y-V9)
      Z=(YREF-Y)/STD
      GO TO 333
100   STD=STD11
      Z=(YREF-Y)/STD
 333  CALL MDNOR(Z,P)
      P=1-P
```

Appendix C: continue...

```
C
       P1=P**5
       P2=(P**4)*(1.-P)
       P3=(P**3)*((1.-P)**2)
       P4=(P**2)*((1.-P)**3)
       P5=P*((1.-P)**4)
       PA=P1
       PB=P1+P2
       PC=P1+2.*P2+P3
       PD=P1+3.*P2+2.*P3+P4
       PE=P1+2.*P2+P3
       PF=P1+3.*P2+2.*P3+P4
       PG=P1+4.*P2+3.*P3+2.*P4+P5
C.....CALCULATE ACTUAL SOIL DEPTH FOR EACH MATERIALS AND PRINT OUTPUT
       DSAND=D*2540.0/59.185
       D21MIX=D*2540.0/63.023
       D11MIX=D*2540.0/60.610
       D12MIX=D*2540.0/60.021
       DSILT=D*2540.0/59.375
       WRITE(6,101) D,Y,P,PA,PB,PC,PD,DSAND,D21MIX,D11MIX,D12MIX,DSILT
       WRITE(6,*)
 101   FORMAT(2X,F4.1,6F6.2,5F6.1)
       D=D+0.1
       IF(D .GT. 5.0) GO TO 222
       GO TO 99
 222   STOP
       END
```

Appendix C: Plant Growth Model (VPIGRO V1.0)

```
C..===================================================================
c                 VPIGRO V1.0 was developed by GOLAM MUSTAFA
C                   Department of Agricultural Engineering
C              Virginia Polytechnic Institute & State University
c                         Blacksburg, Virginia, 24061
c                               November, 1988.
c..===================================================================
C  THIS PROGRAM SIMULATES PERENNIAL GRASS GROWTH ON A DAILY BASIS
C..===================================================================
C....................................................................
C..  THIS PROGRAM USES SOIL MOISTURE FACTOR (SMF) COMPUTED FROM RITCHIE'S
C..  WATER BALANCE MODEL
C..........................................................
C......        LIST OF VARIABLES
C...........................................................
C..... SMAC = SOIL MOISTURE FROM ACTUAL DAILY RAINFALL, INCHES
C..... TMAX   = MAXIMUM DAILY TEMPERATURE, DEGREE F
C..... TMIN   = MINIMUM DAILY TEMPERATURE, DEGREE F
C..... DL     = DAY LENGTH, HOURS
C..... Y      = DRY MATTER YIELD, KG/HA/DAY
C..... ADM    = ACCUMULATED DRY MATTER YIELD, KG/HA
C..... LAF    = LEAF AREA FACTOR
C..... SMF    = SOIL MOISTURE FACTOR
C..... PF     = PHOTOPERIOD FACTOR
C..... SMFPF  = SMF*PF
C..... R      = OPTIMUM GROWTH RATE
C..... Q1     = MIN. QUANTITY OF ADM WHICH PROVIDES ENOUGH LEAF AREA
C......            TO SUPPORT THE FULL DAILY GROWTH RATE IN AN OPTIMUM
C.......           TEMPERATURE REGIME
C..... Q2     = MAX. QUANTITY OF ADM WHICH PROVIDES ENOUGH LEAF AREA
C......            TO SUPPORT THE FULL DAILY GROWTH RATE IN AN OPTIMUM
C.......           TEMPERATURE REGIME
C..... Q3     = MAX. QUANTITY OF ADM WHEN GROWTH TERMINATES
C..... N      = NUMBER OF DAYS OVER WHICH THE SOIL MOISTURE THAT OCCURS
C.......           ON A GIVEN DAY CAN BE EFFECTIVELY USED BY THE CROP
C.......
C..... F      = WEIGHT GIVEN TO CURRENT CONDITIONS IN DETERMINING THE
C......              SOIL MOISTURE FACTOR ( 0.0 >= F =<1.0)
C..... A      = DAYLENGTH (AFTER THE SUMMER SOLSTICE) WHEN THE CROP
C.....              BEGINS TO STORE CARBOHYDRATES
C..... B      = DAYLENGTH WHEN THE PORTION OF CARBOHYDRATES GOING INTO
C.....               STORAGE REACHES A CONSTANT VALUE, HOURS
C..... C      = MAXIMUM EFFECT OF PHOTOPERIOD OF THE OPTIMUM GROWTH RATE
C.......             (0.0 >= C <= 1.0)
C..... NYEARS = NUMBER OF YEARS TO SIMULATE
C..... SDAY   = STARTING DAY (GIVE VALUE 1)
C..... LDAY   = LAST DAY (GIVE VALUE 183)
C.....................................................................
C.....................................................................
      COMMON /BLOCK1/NYEARS,SDAY,LDAY
      COMMON /BLOCK2/Q1,Q2,Q3
```

Appendix C: continued...

```
      COMMON /BLOCK3/A,B,C
      COMMON /BLOCK4/R,T1,T2,T3
      COMMON /BLOCK5/N,F
      DIMENSION SMAC(50,183),
     *SMF(50,183),PF(183),SMFPF(50,183),LAF(50,183),
     *ADM(50,183),TMAX(50,183),TMIN(50,183),TAVE(50,183),DL(183),
     *Y(50,183),ARN(50,183),PEN(50,183),YY(50,183),NOSTR(50),MIDSTR(50),
     *SEVSTR(50)
      REAL LAF,ADM,ARN,PEN
      INTEGER NYEARS,SDAY,LDAY,SEVSTR,MIDSTR,NOSTR
C
      READ(1,101)NYEARS,SDAY,LDAY
      READ(1,102) R,Q1,Q2,Q3
      READ(1,103) N,F,A,B,C
      READ(1,104)T1,T2,T3
C
      READ(5,444) (DL(I),I=1,183)
 444  FORMAT(2X,F4.1)
      DO 10 I=1,NYEARS
      DO 20 J=SDAY,LDAY
      READ(3,555)SMAC(I,J)

      READ(4,777) MO,KDAY,KYR,TMAX(I,J),TMIN(I,J),ARN(I,J),PEN(I,J)
101   FORMAT(I2,2X,I3,2X,I3)
102   FORMAT(F3.1,2X,F6.1,2X,F6.1,2X,F6.1)
103   FORMAT(I2,2X,F4.2,2X,F4.1,2X,F4.1,2X,F4.1)
104   FORMAT(F4.1,2X,F4.1,2X,F4.1)
555   FORMAT(2X,F10.2)
777   FORMAT(6X,3I2,F8.0,F10.0,15X,F5.3,20X,F10.3)
  20  CONTINUE
  10  CONTINUE
C ......................................................
C ... CALL SUBROUTINE PHOTO TO CALCULATE PHOTOPERIOD FACTOR (PF)
C.......................................................
      CALL PHOTO(PF,DL)
      DO 30 II=1,NYEARS
      DO 40 JJ=SDAY,LDAY
      IF(SMAC(II,JJ) .GE. .50) NOSTR(II)=NOSTR(II)+1
      IF(SMAC(II,JJ) .GE. .25 .AND. SMAC(II,JJ) .LT. 0.50)
     *MIDSTR(II)=MIDSTR(II)+1
      IF(SMAC(II,JJ) .LT. .25) SEVSTR(II)=SEVSTR(II)+1
      IF(SMAC(II,JJ) .GE. .25 .AND. SMAC(II,JJ) .LT. 0.50)
     $SMF(II,JJ)=SMAC(II,JJ)*2.0
      IF( SMAC(II,JJ) .LT. 0.25) SMF(II,JJ)=SMAC(II,JJ)/2.0
      IF( SMAC(II,JJ) .GE. 0.50) SMF(II,JJ)=1.0
C
      SMFPF(II,JJ) = SMF(II,JJ)*PF(JJ)
   40 CONTINUE
   30 CONTINUE
```

Appendix C: continued...

```
C.......................................................
C.... CALL SUBROUTINE TEMP TO SIMULATE DAILY PLANT GROWTH
C.......................................................
      CALL TEMP(TMAX,TMIN,DL,Y,YY)
      DO 50 I1=1,NYEARS
      TYY=0.0
      DO 60 J1=SDAY,LDAY
      TYY=TYY+Y(I1,J1)*SMFPF(I1,J1)
      ADM(I1,J1)=TYY
   60 CONTINUE
   50 CONTINUE
C..............................................................
C.... CALL SUBROUTINE LAFACTOR TO ESTIMATE LEAF AREA FACTOR (LAF)
C..............................................................
      CALL LAFACTOR (LAF,ADM)
      WRITE(6,678)
      DO 70 I2=1,NYEARS
      TYY=0.0
      DO 80 J2=SDAY,LDAY
      Y(I2,J2)=Y(I2,J2)*LAF(I2,J2)*SMFPF(I2,J2)
      TYY=TYY+Y(I2,J2)
      IF(J2 .EQ. LDAY) KYR=1929+I2
   80 CONTINUE
      WRITE(6,888) KYR,TYY,NOSTR(I2),MIDSTR(I2),SEVSTR(I2)
  888 FORMAT(4X,I4,5X,F10.2,3I12)
  678 FORMAT(4X,'YEAR',9X,'YIELD',7X,'NO STRESS',2X,'MOD STRESS',2X,
     *'SEV STRESS')
   70 CONTINUE
      STOP
      END
C.......................................................
C.....SUBROUTINE PHOTO TO ESTIMATES PHOTOPERIOD FACTOR (PF)
C.......................................................
      SUBROUTINE PHOTO(PF,DL)
      COMMON/BLOCK1/NYEARS,SDAY,LDAY
      COMMON/BLOCK3/A,B,C
      DIMENSION PF(183),DL(183)
      INTEGER NYEARS,SDAY,LDAY
      DO 10 I=SDAY,LDAY
      PF(I)=1.0 + (C - 1.0)/(B - A) * (DL(I) -A)
      IF(DL(I) .GE. A) PF(I)=1.0
      IF(DL(I) .LE. B) PF(I)=C
   10 CONTINUE
      RETURN
      END
C...............................................................
C.... SUBROUTINE TEMP SIMULATES DAILY PLANT GROWTH (Y IN KG/HA/DAY)
C...............................................................
      SUBROUTINE TEMP(TMAX,TMIN,DL,Y,YY)
```

Appendix C: continued...

```
      COMMON/BLOCK1/NYEARS,SDAY,LDAY
      COMMON/BLOCK4/R,T1,T2,T3
      DIMENSION Y(50,183),DELY(1500),DL(183),TMAX(50,183),TMIN(50,183),
     $YY(50,183)
      INTEGER NYEARS,SDAY,LDAY
      DO 111 NY=1,NYEARS
      TYY=0.0
      DO 222 ND=SDAY,LDAY
      KK=0
      KK1=0
      TOTY=0.0
      KOUNT=IFIX(DL(ND)*100)
      H=0.01
      DO 10 I=1,KOUNT
      KK=KK+1
      DELT=FLOAT(I)/100.
      IF (DELT .GE. (DL(ND)/2.) .AND. DELT .LE. DL(ND)) GO TO 4
      T=TMIN(NY,ND)-4.*(TMIN(NY,ND)-TMAX(NY,ND))/(DL(ND))*DELT+
     $4.*(TMIN(NY,ND)-TMAX(NY,ND))/(DL(ND)**2)*(DELT**2)
      IF(T .GT. T1 .AND. T .LT. T2) GO TO 31
      IF(T .GE. T2 .AND. T .LT. T3) GO TO 32
      IF(T .LE. T1 .OR. T .GE. T3) DELY(I)=0.0
      GO TO 99
  31  DELY(I)=R/((T1-T2)**2)*(T1*(T1-2*T2)+2.*T2*T-T**2)
      GO TO 99
  32  DELY(I)=R/((T3-T2)**2)*(T3*(T3-2*T2)+2.*T2*T-T**2)
      GO TO 99
  4   T=(TMIN(NY,ND)+TMAX(NY,ND))/2.+2.*(TMAX(NY,ND)-TMIN(NY,ND))/
     *DL(ND)*DELT+2.*(TMIN(NY,ND)-TMAX(NY,ND))/(DL(ND)**2)*(DELT**2)
      IF(T .GT. T1 .AND. T .LT. T2) GO TO 41
      IF(T .GE. T2 .AND. T .LT. T3) GO TO 42
      IF(T .LE. T1 .OR. T .GE. T3) DELY(I)=0.0
      GO TO 99
  41  DELY(I)=R/((T1-T2)**2)*(T1*(T1-2*T2)+2.*T2*T-T**2)
      GO TO 99
  42  DELY(I)=R/((T3-T2)**2)*(T3*(T3-2*T2)+2.*T2*T-T**2)
  99  IF(DELY(I) .GT. 0.0) KK1=KK1+1
      IF(KK1 .EQ. 1)TOTY=TOTY+H/2.*DELY(I)
      IF(KK .EQ. KOUNT)TOTY=TOTY+H/2.*DELY(I)
      IF(KK .NE. KOUNT .OR. KK .NE. 1)TOTY=TOTY+H*DELY(I)
  10  CONTINUE
```

```
      Y(NY,ND)=TOTY
      TYY=TYY+Y(NY,ND)
      YY(NY,ND)=TYY
 222  CONTINUE
 111  CONTINUE
      RETURN
      END
C.............................................................
C...  SUBROUTINE LAFACTOR ESTIMATES LEAF AREA FACTOR (LAF)
C.............................................................
      SUBROUTINE LAFACTOR (LAF,ADM)
      COMMON/BLOCK1/NYEARS,SDAY,LDAY
      COMMON/BLOCK2/Q1,Q2,Q3
      DIMENSION LAF(50,183),ADM(50,183)
      REAL LAF,ADM
      INTEGER NYEARS,SDAY,LDAY
      DO 10 I=1,NYEARS
      DO 20 J=SDAY,LDAY
      LAF(I,J)=0.001+(2.*(1.-0.001)/Q3)*ADM(I,J)-((1.-0.001)/(Q3**2))*
     $(ADM(I,J)**2)
      IF(ADM(I,J) .GE. Q3) LAF(I,J)=1.0
  20  CONTINUE
  10  CONTINUE
      RETURN
      END
```

Appendix C: Soil Moisture Model

```
C..==============================================================
C        The following soil moisture model codes were adopted
C        from Rojiani et al. (1982).
C
C**********************************************************************************************
C........THIS PROGRAM COMPUTES DAILY SOIL MOISTURE USING RITCHIE'S
C........  WATER BALANCE MODEL
C************************************************************************************************
      DIMENSION SWAT(366),DAY(366)
      DIMENSION ALAI(367,4),XMR(366,4),NAME(20),XMS(4),SUMES1(4),
     1 SUMES2(4),T(4),SW(4),ETMO(4),ETYR(4),EPMO(4),EPYR(4),ESMO(4),
     2 ESYR(4),EIMO(4),EIYR(4),RMO(4),RYR(4),TIMO(4),TIYR(4),QMO(4),
     3 QYR(4),DRMO(4),DRYR(4),EOMO(4),PP(4),RS(4),PS(4),S(4),RAIN(4),
     4 TR(4),OP(4),PI(4),XMI(4),TI(4),RAIN2(4),Q(4),HO(4),EO(4),ES(4),
     5 EP(4),ET(4),EI(4),EM(4),DR(4),EOYR(4),PANCOF(12)
      DATA PANCOF/.53,.50,.60,.67,.67,.63,.69,.70,.72,.80,.91,.86/
      DO 9765 I=1,366
      SWAT(I)=0.0
      XI=I
      DAY(I)=XI
9765  CONTINUE
      XMAX=366.
      YMAX=300.
C********READ THE NUMBER OF YEARS TO BE SIMULATED AND THE NUMBER OF
C******** SEGMENTS WITHIN THE WATERSHED.
      READ(1,1000) NYRS,NC
1000  FORMAT(16I5)
      DO 1 I=1,NC
      XMS(I)=0.
      SUMES1(I)=0.
      SUMES2(I)=0.
      T(I)=0.
1     CONTINUE
      NYR=0
      KKK = 0
C******** READ SOIL PARAMETERS AND WATERSHED ELEVATION.
      READ(1,1001) MO1,KD1,KYR1,UL,U,     SALPHA,ELEV
      CONA = 3.5
1001  FORMAT(3I3,1X,7F10.0)
      PLL=0.25*UL
C******* READ INITIAL SOIL WATER IN MM.
      READ(1,1002)(SW(I),I=1,NC)
      SWINIT=SW(1)
1002  FORMAT(8F10.0)
C     WRITE(6,2001) UL,PLL,U,CONA
 2001 FORMAT(10X,'THE SOIL PARAMETERS ARE---',//,20X,'UPPER LIMIT =',F5.
     10,'MM',/,20X,'LOWER LIMIT FOR POT. EVAP. =',F5.0,'MM',/,20X,'THE U
     2PPER LIMIT FOR STAGE I SOIL EVAPORATION IS',F5.1,/,20X,'THE STAGE
     3II SOIL EVAPORATION EQUATION IS--',/,25X,'SUMES = ',F4.1,'T**0.5',
     4//)
```

Appendix C: continue...

```
C     WRITE(6,2002) ELEV,SALPHA
2002  FORMAT(//,10X,'ELEVATION = ',F6.0,/,10X,'SOIL ALBEDO = ',F5.2)
2     CONTINUE
      JDAY = 0
      JZZ = 7
      XRAIN = 0.0
      XWATER = 0.0
      CCODE = 0
      SUM4 = 0.0
      SUM5 = 0.0
      DO 102 I=1,NC
      ETMO(I)=0.
      ETYR(I)=0.
      EPMO(I)=0.
      EPYR(I)=0.
      ESMO(I)=0.
      ESYR(I)=0.
      EIMO(I)=0.
      EIYR(I)=0.
      RMO(I)=0.
      RYR(I)=0.
      TIMO(I)=0.
      TIYR(I)=0.
      QMO(I)=0.
      QYR(I)=0.
      DRMO(I)=0.
      DRYR(I)=0.
      EOMO(I)=0.
      EOYR(I)=0.
102   CONTINUE
      IF(KKK.EQ.1)SW(1)=SWINIT
      IF(KKK .EQ. 1) GO TO 5015
      READ(1,1003)(NAME(I),I=1,20)
1003  FORMAT(20A4)
C     WRITE(6,2003)(NAME(I),I=1,20)
2003  FORMAT('1',20A4)
C******READ PLANT POPULATION FOR EACH SEGMENT
      READ(1,1002)(PP(I),I=1,NC)
C******* READ ROW SPACING FOR EACH SEGMENT
      READ(1,1002)(RS(I),I=1,NC)
      DO 3 I=1,NC
C     WRITE(6,2004) I,PP(I),RS(I)
2004  FORMAT(//,10X,'SEGMENT NO. ',I4,/,10X,'PLANT POPULATION = ',F8.0,
     1 'PLANT/ACRE',/,10X,'ROW SPACING =',F5.0,'INCHES')
C******* PS = PLANT SPACING WITHIN ROW (FT)
      PS(I) = (43560.*12./RS(I))/PP(I)
      S(I)=PS(I)*12./RS(I)
3     CONTINUE
      READ(1,1001) IDAY
      DO 9 I=1,NC
      READ(1,1001) NLAI
```

Appendix C: continue...

```
C     WRITE(6,2005) I
2005  FORMAT('1',10X,'LEAF AREA INDEX FOR SEGMENT ',I4,/,20X,'DAY',10X,
     1 'LAI',/)
      KT=0
      READ(1,1004) ND,XLAI
1004  FORMAT(I5,F5.0)
C     WRITE(6,2006) ND,XLAI
2006  FORMAT(20X,I3,10X,F7.2)
      ALAI(ND,I)=XLAI
      KT=KT+1
      IF(ALAI(ND,I) .NE. 0.) GO TO 5
      DO 4 J=1,ND
4     ALAI(J,I)=0.
5     ND1=ND
      READ(1,1004) ND,XLAI
C     WRITE(6,2006) ND,XLAI
      ALAI(ND,I)=XLAI
      KT=KT+1
      DELTA=(ALAI(ND,I)-ALAI(ND1,I))/(ND-ND1)
      NP1=ND1+1
      DO 6 J=NP1,ND
6     ALAI(J,I)=ALAI(J-1,I)+DELTA
      IF(KT-NLAI)5,7,7
7     NDP1=ND+1
      DO 8 J=NDP1,367
8     ALAI(J,I)=0.
9     CONTINUE
      DO 15 I=1,NC
      READ(1,1001) NML
C     WRITE(6,2007) I
2007  FORMAT('1',10X,'MULCH RATE FOR SEGMENT',I4,/,20X,'DAY',10X,'KG/HA'
     1 )
      KT=0
      READ(1,1004) ND,XNML
C     WRITE(6,2006)ND,XNML
      XMR(ND,I)=XNML
      KT=KT+1
      IF(XMR(ND,I) .NE. 0.) GO TO 11
      DO 10 J=1,ND
10    XMR(J,I) =0.
11    ND1=ND
      READ(1,1004) ND,XNML
C     WRITE(6,2006) ND,XNML
      XMR(ND,I) = XNML
      KT=KT+1
```

```
      DELTA=(XMR(ND,I)-XMR(ND1,I))/(ND-ND1)
      NP1=ND1+1
      DO 12 J=NP1,ND
12    XMR(J,I)=XMR(J-1,I)+DELTA
      IF(KT-NML) 11,13,13
13    NDP1=ND+1
      DO 14 J=NDP1,366
14    XMR(J,I)=0.
15    CONTINUE
16    READ(1,1001) NDAYS
5015  CONTINUE
      KKK = 1
C     WRITE(6,2003)(NAME(I),I=1,20)
C     WRITE(6,2000)
 2000 FORMAT(1H1,         18X,'NET    LEAF',8X,'MULCH',32X,'POT.     PLA
     1NT    SOIL     INTCEP   TOTAL  SOIL    SOIL',/,18X,'RAD.    AREA  TR
     2AN  RATE   RAIN INTCEP RUNOFF DRAINAGE    EVAP.    EVAP.    EVAP.
     3  EVAP.    EVAP.  WATER  WATER',/,1X,'MO DAY YR JDAY (MM/DAY) INDE
     4X RAD. (KG/HA) (MM)  (MM)   (MM)    (MM)   (MM/DAY) (MM/DAY) (MM/D
     5AY) (MM/DAY) (MM/DAY) (MM)    (%)',/)
100   READ(2,1005,END=999) MO,KDAY,KYR,TMAX,TMIN,RN,RAD,PANEVA
1005  FORMAT(6X,3I2,F8.0,F10.0,15X,F5.0,10X,2F10.0)
      PANPET=PANCOF(MO)*PANEVA
      IF(MO .EQ. 1 .AND. KDAY .EQ. 1) GO TO 9009
      IF(MO .EQ. 12 .AND. KDAY .EQ. 31) GO TO 9009
      GO TO 9010
C9009 WRITE(6,9011) SW(1)
9009  DUMMY=0.0
9011  FORMAT(10X,'SOIL WATER EQUALS',F10.2,/)
9010  CONTINUE
      JDAY = JDAY + 1
      SUM5 = SUM5 + RN
      XRAIN = XRAIN + RN
      IF(RN .EQ. 0.00) GO TO 4011
C     WRITE(6,4010) JDAY,RN
4010  FORMAT(40X,I10,F10.2)
4011  CONTINUE
      IF(CCODE .EQ. 1 ) GO TO 4002
      IF(JZZ .EQ. 7) GO TO 4000
      GO TO 4001
4000  JZZ = 0
C     WRITE(6,4008) JDAY
4008  FORMAT(20X,I10)
      WATER = 0.0
4002  IF(RN .GT. 0.0) GO TO 4003
      CCODE = 0
      XWATER = XWATER + WATER
      SUM4 = SUM4 + WATER
      RN = RN + WATER
```

Appendix C: continue...

```
C     WRITE(6,4004) JDAY,WATER
4004  FORMAT(10X,I10,F10.2)
      GO TO 4001
4003  CCODE = 1
4001  CONTINUE
      JZZ = JZZ + 1
      DO 161 IJ=1,NC
161   RAIN(IJ)=RN
101   IDAY=IDAY+1
      IF(MO .LE. MO1) GO TO 1021
C     WRITE(6,2010)
2010  FORMAT(/,1X,'MONTHLY TOTALS')
      DO 1020 I = 1,NC
C     WRITE(6,2011)RMO(I),TIMO(I),QMO(I),DRMO(I),EOMO(I),EPMO(I),ESMO(I)
C    1,EIMO(I),ETMO(I)
      ETMO(I) = ETMO(I) / 25.4
      DRMO(I) = DRMO(I)/25.4
C     WRITE(6,4006)MO1,XRAIN,XWATER,ETMO(I),KYR,DRMO(I)
4006  FORMAT(10X,'MONTH=',I3,' MONTHLY RAIN=',F10.2,' MONTHLY ADDIT. WAT
     1ER=',F10.2,' MONTHLY ET=',F10.2,'YEAR=',I4,' DRAIN=',F10.2,/)
      XRAIN = 0.0
      XWATER = 0.0
      ETMO(I)=0.
      EPMO(I)=0.
      ESMO(I)=0.
      EIMO(I)=0.
      RMO(I)=0.
      TIMO(I)=0.
      QMO(I)=0.
      DRMO(I)=0.
      EOMO(I)=0.
1020  CONTINUE
C     WRITE(6,2000)
1021  CONTINUE
      DO 22 I=1,NC
      CALL TRAD(S,ALAI,IDAY,TR,OP,I)
      CALL INTCEP(ALAI,IDAY,RAIN,TR,PI,XMR,XMI,XMS,TI,I)
      PI(I)=PI(I)/25.4
      XMI(I)=XMI(I)/25.4
      RAIN2(I)=RAIN(I)-PI(I)-XMI(I)
      IF(RAIN2(I))17,17,18
17    Q(I)=0.
      GO TO 21
18    CN = 34./(1.34 - (SW(I)/UL))
      SS=(1000.-10.*CN)/CN
      QQ=RAIN2(I)-0.2*SS
```

Appendix C: continue...

```
      IF(QQ)19,19,20
19    Q(I)=0.
      GO TO 21
20    Q(I)=(QQ**2)/(RAIN2(I)+0.8*SS)
21    RAIN2(I)=RAIN2(I)-Q(I)
22    CONTINUE
C***** CONVERT FROM INCHES TO MM.
      DO 23 I=1,NC
      RAIN(I)=RAIN(I)*25.4
      RAIN2(I)=RAIN2(I)*25.4
      Q(I)=Q(I)*25.4
      PI(I)=PI(I)*25.4
      XMI(I)=XMI(I)*25.4
23    CONTINUE
      CALL POTEVA(RAD,TMAX,TMIN,ELEV,IDAY,HO,EO,D,    DELTA,GAMMA,SALPHA,
     1 TR,NC,PANPET)
      CALL EVAP(EO,ALAI,IDAY,U,SUMES1,SUMES2,RAIN2,CONA,T,ES,EP,ET,HO,
     1 D,  DELTA,GAMMA,TR,PI,XMS,XMR,EI,EM,NC)
      CALL SOLWAT(ALAI,EO,EP,ES,ET,SW,RAIN2,IDAY,UL,PLL,DR,PI,EM,NC)
C     WRITE(6,2008)
2008  FORMAT(/)
      DO 24 I=1,NC
      SWAT(IDAY)=SW(I)
      XDAY=IDAY
      DAY(IDAY)=XDAY
      PERC=(SW(I)/UL)
C     WRITE(8,9998)IDAY,PERC
9998  FORMAT(I10,F10.1)
      SWINS=SW(I)/25.4
      WRITE(9,9999)PERC
9999  FORMAT(2X,F10.2)
C     WRITE (6,2009) MO, KDAY, KYR, IDAY, HO(I), ALAI(IDAY,I),TR(I),
C    1XMR(IDAY,I),RAIN(I), TI(I), Q(I), DR(I), EO(I), EP(I), ES(I),
C    2EI(I), ET(I), SW(I), PERC
2009  FORMAT(2I3,I4,I5,F6.1,F8.2,F7.2,F7.0,2F6.2,F7.1,2F8.1,4F9.2,2F8.1)
      ETMO(I)=ETMO(I)+ET(I)
      ETYR(I)=ETYR(I)+ET(I)
      EPMO(I)=EPMO(I)+EP(I)
      EPYR(I)=EPYR(I)+EP(I)
      ESMO(I)=ESMO(I)+ES(I)
      ESYR(I)=ESYR(I)+ES(I)
      EIMO(I)=EIMO(I)+EI(I)
      EIYR(I)=EIYR(I)+EI(I)
      RMO(I)=RMO(I)+RAIN(I)
      RYR(I)=RYR(I)+RAIN(I)
      TIMO(I)=TIMO(I)+TI(I)
      TIYR(I)=TIYR(I)+TI(I)
      QMO(I)=QMO(I)+Q(I)
```

```
      QYR(I)=QYR(I)+Q(I)
      DRMO(I)=DRMO(I)+DR(I)
      DRYR(I)=DRYR(I)+DR(I)
      EOMO(I)=EOMO(I)+EO(I)
      EOYR(I)=EOYR(I)+EO(I)
24    CONTINUE
      MO1=MO
      IF(IDAY .EQ. NDAYS) GO TO 25
      GO TO 100
25    DUMMY=0.0
C25   WRITE(6,2010)
      DO 26 I=1,NC
      ETMO(I) = ETMO(I) / 25.4
      DRMO(I) = DRMO(I)/25.4
C     WRITE(6,4006)MO1,XRAIN,XWATER,ETMO(I),KYR,DRMO(I)
C     WRITE(6,2011) RMO(I),TIMO(I),QMO(I),DRMO(I),EOMO(I),EPMO(I),
C    1 ESMO(I),EIMO(I),ETMO(I)
2011  FORMAT(22X,F28.2,F6.2,F7.1,2F8.1,4F9.1)
26    CONTINUE
      DO 27 I=1,NC
C     WRITE(6,2012) I,RYR(I),QYR(I),ETYR(I),DRYR(I)
2012  FORMAT(//,55X,'ANNUAL WATER BUDGET FOR SEGMENT',I4,/,55X,'RAINFALL
     1-------------',F6.1,' MM.',/,55X,'RUNOFF--------------',F6.1,' MM.'
     2,/,55X,'EVAPORATION----------',F6.1,' MM.',/,55X,'DRAINAGE---------
     3---',F6.1,' MM.')
27    CONTINUE
C     WRITE(6,4005) SUM4,SUM5
4005  FORMAT(10X,'ADDITIONAL WATER =',F10.2,'     RAINFALL =',F10.2)
C     CALL PRINT(XMAX,YMAX,DAY,SWAT,NDAYS)
      NYR=NYR+1
      MO1 = 1
      IDAY = 0
      IF(NYR .LT. NYRS) GO TO 2
999   STOP
      END
      SUBROUTINE TRAD(S,ALAI,IDAY,TR,OP,I)
C******** TR=FRACTION OF INCOMING SOLAR RADIATION THAT IS TRANSMITTED
C********    TO THE SURFACE.
C******** OP=OPENNESS PARAMETER (1.-TR).
      DIMENSION ALAI(367,4),S(4),TR(4),OP(4)
      XN1= 0.404*ALOG(S(I))+1.49
      IF(ALAI(IDAY,I) .GT. XN1) GO TO 5
      TR(I) = EXP(-0.6*ALAI(IDAY,I))
      OP(I)=1.-TR(I)
      RETURN
5     XI1=EXP(-0.384*XN1)
      TR(I)=XI1*EXP(-0.216*ALAI(IDAY,I))
      OP(I)=1.-TR(I)
      RETURN
      END
```

```
      SUBROUTINE INTCEP(ALAI,IDAY,RAIN,TR,PI,XMR,XMI,XMS,TI,I)
C******** THIS SUBROUTINE COMPUTES THE RAINFALL INTERCEPTED BY THE PLANT
C******** CANOPY AND A SURFACE MULCH.
C******** SIP=INTERCEPTION STORAGE CAPACITY OF THE PLANT CANOPY.
C******** SIM=INTERCEPTION STORAGE CAPACITY OF THE MULCH
C******** XMS=WATER IN STORAGE IN MULCH.
      DIMENSION ALAI(367,4),XMR(366,4),RAIN(4),TR(4),PI(4),XMI(4),XMS(4)
     1,TI(4)
C******** COMPUTE PLANT INTERCEPTION
      RAINI = RAIN(I) * 25.4
      IF(ALAI(IDAY,I) .EQ. 0.) GO TO 5
      SIP=0.4*ALAI(IDAY,I)
      RAINP=RAINI*(1.-TR(I))
      PI(I)=RAINP
      IF(PI(I) .GT. SIP) PI(I)=SIP
      GO TO 10
5     PI(I)=0.
C******** COMPUTE MULCH INTERCEPTION
10    IF(XMR(IDAY,I) .EQ. 0.) GO TO 15
      SIM=0.0008*XMR(IDAY,I)
      RAINM=RAINI-PI(I)
      XMI(I)=SIM-XMS(I)
      IF(XMI(I) .GT. RAINM) XMI(I)=RAINM
      XMS(I)=XMS(I)+XMI(I)
      GO TO 20
15    XMI(I)=0.
20    TI(I)=PI(I)+XMI(I)
      RETURN
      END
      SUBROUTINE POTEVA (RAD,TMAX,TMIN,ELEV,IDAY,HO,EO,D,   DELTA,GAMMA,
     1 SALPHA,TR,NC,PANPET)
      DIMENSION TR(4),HO(4),EO(4)
      TM= ((TMIN+TMAX)/2.-32.)*(5./9.)
      XIDAY=IDAY
C     RC = 520. + 260.*SIN(.0172*(IDAY+102.))
      RC=520.+193.*SIN(0.0172*(XIDAY-80.))
      IF(RAD .GT. RC) RAD=RC
      RTM = ABS(TM - 7.75)
      RNL=(-2.61 + 0.00414*RTM**1.8) * (RAD/RC)
      P=1013.-.032*ELEV
      TC=(TMIN-32.)*(5./9.)
      GAMMA=6.6E-04*P*(1.+.00115*TC)
      BETA=0.28
      TK=TM+273.
      DELTA=(EXP(21.255-5304./TK))*(5304./(TK**2))
      COEF=(1.+BETA)*(DELTA/(DELTA+GAMMA))
      DO 5 I=1,NC
      ALBEDO=0.3067+0.3333*SALPHA-((0.23-SALPHA)/0.75)*TR(I)
      H=RAD*(1.-ALBEDO)+RNL
      HO(I)=H/58.3
      EO(I)=COEF*(HO(I))
```

Appendix C: continue....

```
      IF(EO(I) .LT. 0.) EO(I)=0.
      IF(RAD.GT.0.001)GO TO 5
      EO(I)=PANPET*25.4
      HO(I)=EO(I)/COEF
 5    CONTINUE
      RETURN
      END
      SUBROUTINE EVAP(EO,ALAI,IDAY,U,SUMES1,SUMES2,RAIN,CONA,T,ES,EP,ET,
     1 HO,D,  DELTA,GAMMA,TR,PI,XMS,XMR,EI,EM,NC)
      DIMENSION ALAI(367,4),XMR(366,4),EO(4),SUMES1(4),SUMES2(4),RAIN(4)
     1,T(4),ES(4),EP(4),ET(4),HO(4),TR(4),PI(4),XMS(4),EI(4),EM(4)
      DO 41 I=1,NC
      P=RAIN(I)
      RNS=HO(I)*TR(I)
      BETA=-.07 + 0.35*TR(I)
      EOP=(1.0+BETA)*(DELTA/(DELTA+GAMMA))*RNS
      EOS = EOP * (1.-0.105 * XMR(IDAY,I) **0.2)
      IF(SUMES1(I)-U)1,2,2
 1    IF(P-SUMES1(I))3,4,4
 3    SUMES1(I)=SUMES1(I)-P
      GO TO 5
 4    SUMES1(I)=0.
 5    SUMES1(I)=SUMES1(I)+EOS
      IF(SUMES1(I)-U)6,6,7
 6    ES(I)=EOS
      GO TO 24
 7    ES(I)=EOS-0.4*(SUMES1(I)-U)
      SUMES2(I)=0.6*(SUMES1(I)-U)
      T(I)=(SUMES2(I)/CONA)**2
      GO TO 24
 2    IF(P-SUMES2(I))9,8,8
 8    P=P-SUMES2(I)
      SUMES1(I)=U-P
      T(I)=0.
      IF(P-U)5,5,4
 9    T(I)=T(I)+1.
      ES(I)=CONA*T(I)**0.5-SUMES2(I)
      IF(P.GT.0.) GO TO 10
      IF(ES(I) .GT. EOS) ES(I)=EOS
      GO TO 11
 10   ESX=0.8*P
      IF(ESX .LE. ES(I)) ESX=ES(I)+P
      IF(ESX .GT. EOS) ESX=EOS
      ES(I)=ESX
 11   SUMES2(I)=SUMES2(I)+ES(I)-P
      T(I)=(SUMES2(I)/CONA)**2
 24   IF(ES(I) .LT. 0.) ES(I) = 0.
C******* COMPUTE MULCH EVAPORATION
      EM(I)=EOP-EOS
```

```
      IF(EM(I) .GT. XMS(I)) EM(I)=XMS(I)
      IF(EM(I) .LT. 0.)EM(I)=0.
      XMS(I)=XMS(I)-EM(I)
C******** COMPUTE PLANT EVAPORATION
      IF(ALAI(IDAY,I) .GT. 3.0) GO TO 26
      IF(ALAI(IDAY,I) .LT. 0.) ALAI(IDAY,I) = 0.
      EP(I)=(-0.21+0.70*(ALAI(IDAY,I)**0.5))*EO(I)-PI(I)
      IF(EP(I) .LT. 0.) EP(I)=0.
      GO TO 25
26    EP(I) = EO(I)-ES(I)-PI(I)-EM(I)
      IF(EP(I) .LT. 0.) EP(I)=0.
C******** COMPUTE TOTAL EVAPORATION
25    ET(I)=ES(I)+EP(I)+PI(I)+EM(I)
      EI(I)=PI(I)+EM(I)
      IF(EO(I)-ET(I))39,41,41
39    ET(I)=EO(I)
      EP(I)=ET(I)-ES(I)-PI(I)-EM(I)
      IF(EP(I) .LT. 0.) EM(I)=ET(I)-ES(I)-PI(I)
      IF(EP(I) .LT. 0.) EP(I)=0.
      EI(I)=PI(I)+EM(I)
41    CONTINUE
      RETURN
      END
      SUBROUTINE SOLWAT (ALAI,EO,EP,ES,ET,SW,RAIN,IDAY,UL,PLL,DR,PI,EM,
     1NC)
      DIMENSION ALAI(367,4),SW(4),EP(4),ET(4),ES(4),PI(4),EM(4),EO(4),
     1 RAIN(4),DR(4)
      ALLEO=PLL
      DO 82 I=1,NC
      IF(SW(I) .GT. UL) SW(I)=UL
      IF(ALAI(IDAY,I)-2.7)1,2,2
1     IF(ALAI(IDAY,I)-1.0) 21,21,22
21    ALLEO=0.8*UL-0.05*UL*ALAI(IDAY,I)
      GO TO 2
22    ALLEO=0.59*PLL*ALAI(IDAY,I)-0.44*UL*ALAI(IDAY,I)+1.19*UL-0.59*PLL
2     IF(SW(I)-ALLEO)8,9,9
8     EP(I)=EP(I)*SW(I)/ALLEO
9     CONTINUE
5     ET(I)=ES(I)+EP(I)+PI(I)+EM(I)
      IF(EO(I)-ET(I))10,11,11
10    ET(I)=EO(I)
      EP(I)=ET(I)-ES(I)-PI(I)-EM(I)
11    SW(I)=SW(I)-ET(I)+RAIN(I) + PI(I) + EM(I)
      IF(SW(I) .LE. UL) DR(I)=0.
      IF(SW(I) .LE. UL) GO TO 81
      DR(I)=SW(I)-UL
      SW(I)=UL
81    IF(SW(I) .LT. 0.) SW(I)=0.
82    CONTINUE
      RETURN
      END
```

Appendix D: Sample Input Data Files

**** INPUT DATA FILE 1 *****

```
    5    1
 04 01 82       25.4       6.0      0.10     2600.
        12.7
  WISE COUNTY, VIRGINIA   TALL FESCUE CROP
 30000000.
        1.

  2
    1 1.00
  183 1.00
  2
    1
  365
183
```

****** INPUT DATA FILE 2 *****

```
4 182     72.       29.               0.000                         0.055
4 282     73.       31.               0.000                         0.055
4 382     71.       54.               0.070                         0.055
4 482     65.       45.               0.000                         0.055
 ....     ...       ...               .....                         .....
 ....     ...       ...               .....                         .....
92786     86.       60.               0.000                         0.120
92886     84.       59.               0.000                         0.120
92986     87.       58.               0.000                         0.120
93086     87.       61.               0.000                         0.120
```

***** INPUT DATA FILE 3 *****

```
 5    1  183
6.5  2065.0  3019.0  6196.0
15  0.75  14.8  11.8  0.1
39.9  64.9  90.0
```

***** INPUT DATA FILE 4 *****

```
  12.6
  12.7
  12.7
  ....
  ....
  11.9
  11.9
  11.8
```

Appendix E: Sample Output File

```
============================================================
   YEAR       DAY      DAILY GROWTH  CUMM. GROWTH
                        KG/HA/DAY       KG/HA
============================================================
   1982         1         0.18           0.18
   1982         2         0.38           0.56
   1982         3         0.70           1.26
   1982         4         0.98           2.25
   1982         5         1.02           3.27
   1982         6         0.84           4.10
   1982         7         0.59           4.69
   1982         8         0.75           5.45
   1982         9         0.88           6.33
   1982        10         1.47           7.80
   1982        11         2.00           9.80
   1982        12         2.96          12.76
   1982        13         3.82          16.58
   1982        14         4.02          20.60
   1982        15         4.27          24.87
   1982        16         4.92          29.79
   1982        17         6.47          36.26
   1982        18         6.32          42.59
   1982        19         6.95          49.54
   1982        20         8.52          58.07
   1982        21         9.52          67.58
   1982        22         9.86          77.44
   1982        23         9.04          86.48
   1982        24        10.14          96.62
   1982        25        12.22         108.84
   1982        26        14.18         123.02
   1982        27        14.39         137.41
   1982        28        14.74         152.15
   1982        29        15.85         168.00
   1982        30        17.38         185.38
   1982        31        17.99         203.37
   1982        32        19.87         223.24
   1982        33        21.03         244.28
   1982        34        19.69         263.96
   1982        35        18.82         282.78
   1982        36        19.57         302.36
   1982        37        23.55         325.91
   1982        38        28.87         354.78
   1982        39        27.05         381.83
   1982        40        21.35         403.17
   1982        41        23.00         426.17
   1982        42        21.21         447.38
   1982        43        19.66         467.04
   1982        44        20.63         487.67
   1982        45        23.77         511.45
   1982        46        28.98         540.43
   1982        47        28.08         568.51
   1982        48        31.79         600.31
```

1982	49	33.90	634.21
1982	50	39.75	673.96
1982	51	35.67	709.63
1982	52	34.35	743.98
1982	53	38.65	782.62
1982	54	47.08	829.71
1982	55	40.97	870.67
1982	56	41.76	912.43
1982	57	40.67	953.10
1982	58	44.49	997.59
1982	59	36.73	1034.31
1982	60	29.60	1063.91
1982	61	31.48	1095.39
1982	62	44.07	1139.46
1982	63	54.60	1194.06
1982	64	51.85	1245.91
1982	65	61.35	1307.26
1982	66	64.59	1371.85
1982	67	63.17	1435.02
1982	68	53.86	1488.87
1982	69	49.06	1537.93
1982	70	40.66	1578.59
1982	71	45.32	1623.91
1982	72	62.75	1686.66
1982	73	62.47	1749.12
1982	74	64.63	1813.76
1982	75	64.75	1878.51
1982	76	61.19	1939.69
1982	77	57.24	1996.93
1982	78	66.97	2063.90
1982	79	62.67	2126.57
1982	80	64.78	2191.36
1982	81	74.81	2266.17
1982	82	69.41	2335.58
1982	83	71.01	2406.59
1982	84	70.06	2476.64
1982	85	68.67	2545.31
1982	86	57.47	2602.78
1982	87	55.34	2658.11
1982	88	58.59	2716.70
1982	89	72.59	2789.29
1982	90	67.39	2856.68
1982	91	64.09	2920.76
1982	92	73.60	2994.36
1982	93	62.96	3057.32
1982	94	58.90	3116.22
1982	95	53.67	3169.89
1982	96	42.82	3212.71
1982	97	48.12	3260.83
1982	98	46.42	3307.25
1982	99	49.80	3357.05
1982	100	63.94	3420.99
1982	101	53.81	3474.80

1982	102	56.31	3531.11
1982	103	54.31	3585.42
1982	104	52.71	3638.13
1982	105	41.69	3679.82
1982	106	46.60	3726.41
1982	107	54.68	3781.09
1982	108	38.51	3819.60
1982	109	42.44	3862.04
1982	110	50.96	3913.00
1982	111	47.48	3960.48
1982	112	38.34	3998.82
1982	113	42.63	4041.45
1982	114	57.64	4099.09
1982	115	41.47	4140.56
1982	116	36.23	4176.79
1982	117	33.76	4210.55
1982	118	30.21	4240.77
1982	119	31.09	4271.85
1982	120	41.90	4313.75
1982	121	42.81	4356.55
1982	122	43.36	4399.91
1982	123	48.98	4448.89
1982	124	50.26	4499.15
1982	125	41.87	4541.02
1982	126	29.56	4570.57
1982	127	36.22	4606.79
1982	128	37.33	4644.12
1982	129	27.63	4671.75
1982	130	32.68	4704.42
1982	131	45.37	4749.79
1982	132	38.78	4788.57
1982	133	43.35	4831.91
1982	134	51.13	4883.04
1982	135	42.25	4925.29
1982	136	40.20	4965.49
1982	137	31.24	4996.73
1982	138	37.96	5034.69
1982	139	35.87	5070.56
1982	140	33.94	5104.50
1982	141	29.99	5134.49
1982	142	33.93	5168.42
1982	143	31.81	5200.23
1982	144	34.29	5234.52
1982	145	41.35	5275.87
1982	146	37.79	5313.66
1982	147	33.57	5347.22
1982	148	32.85	5380.07
1982	149	33.80	5413.87
1982	150	33.34	5447.20
1982	151	30.75	5477.95
1982	152	31.84	5509.79
1982	153	30.71	5540.50
1982	154	33.41	5573.91

1982	155	35.45	5609.36
1982	156	27.74	5637.09
1982	157	29.42	5666.51
1982	158	27.51	5694.02
1982	159	24.64	5718.65
1982	160	24.61	5743.27
1982	161	22.59	5765.85
1982	162	23.29	5789.13
1982	163	22.57	5811.70
1982	164	19.74	5831.44
1982	165	19.33	5850.77
1982	166	20.13	5870.89
1982	167	13.40	5884.29
1982	168	13.78	5898.07
1982	169	14.55	5912.62
1982	170	16.67	5929.29
1982	171	15.85	5945.14
1982	172	16.38	5961.52
1982	173	15.91	5977.43
1982	174	16.42	5993.85
1982	175	14.60	6008.44
1982	176	13.04	6021.48
1982	177	13.16	6034.64
1982	178	11.30	6045.94
1982	179	11.34	6057.28
1982	180	11.85	6069.12
1982	181	8.60	6077.73
1982	182	8.04	6085.76
1982	183	6.02	6091.79
1983	1	0.16	0.16
1983	2	0.49	0.66
1983	3	0.63	1.29
1983	4	0.92	2.21
1983	5	1.22	3.43
1983	6	1.64	5.07
1983	7	2.22	7.29
1983	8	2.58	9.87
1983	9	3.29	13.16
1983	10	3.18	16.34
1983	11	1.41	17.75
1983	12	3.77	21.52
1983	13	4.54	26.06
1983	14	5.45	31.51
1983	15	5.89	37.40
1983	16	4.40	41.80
1983	17	4.06	45.86
1983	18	3.17	49.03
1983	19	1.12	50.15
1983	20	3.37	53.52
1983	21	6.03	59.55
1983	22	6.84	66.39
1983	23	7.75	74.15
1983	24	7.21	81.36

1983	25	10.40	91.76
1983	26	11.32	103.09
1983	27	11.34	114.43
1983	28	12.63	127.06
1983	29	14.11	141.17
1983	30	16.06	157.23
1983	31	15.23	172.46
1983	32	15.19	187.65
1983	33	19.65	207.30
1983	34	22.22	229.51
1983	35	21.53	251.04
1983	36	20.73	271.76
1983	37	20.60	292.36
1983	38	21.94	314.30
1983	39	24.96	339.26
1983	40	24.85	364.11
1983	41	24.55	388.67
1983	42	26.71	415.37
1983	43	30.88	446.25
1983	44	30.08	476.33
1983	45	33.71	510.04
1983	46	39.71	549.76
1983	47	37.63	587.38
1983	48	39.47	626.86
1983	49	44.12	670.97
1983	50	44.48	715.46
1983	51	48.75	764.21
1983	52	49.94	814.15
1983	53	47.21	861.36
1983	54	51.31	912.67
1983	55	47.10	959.77
1983	56	52.78	1012.55
1983	57	51.24	1063.79
1983	58	54.01	1117.80
1983	59	58.99	1176.80
1983	60	57.63	1234.42
1983	61	60.60	1295.02
1983	62	62.82	1357.84
1983	63	61.02	1418.87
1983	64	62.74	1481.61
1983	65	63.45	1545.06
1983	66	61.21	1606.27
1983	67	62.03	1668.30
1983	68	67.44	1735.74
1983	69	65.08	1800.83
1983	70	64.01	1864.83
1983	71	65.58	1930.41
1983	72	56.16	1986.57
1983	73	53.23	2039.80
1983	74	57.26	2097.05
1983	75	57.94	2154.99
1983	76	54.49	2209.48
1983	77	47.36	2256.84

1983	78	55.73	2312.57
1983	79	67.97	2380.54
1983	80	65.35	2445.89
1983	81	55.85	2501.74
1983	82	47.48	2549.22
1983	83	55.83	2605.04
1983	84	53.10	2658.15
1983	85	49.66	2707.81
1983	86	41.39	2749.20
1983	87	34.34	2783.53
1983	88	35.17	2818.71
1983	89	59.34	2878.04
1983	90	40.65	2918.69
1983	91	47.66	2966.35
1983	92	50.11	3016.46
1983	93	44.61	3061.07
1983	94	34.49	3095.56
1983	95	47.15	3142.71
1983	96	59.53	3202.24
1983	97	70.86	3273.10
1983	98	69.47	3342.57
1983	99	64.81	3407.38
1983	100	61.83	3469.22
1983	101	54.60	3523.81
1983	102	44.53	3568.35
1983	103	41.23	3609.58
1983	104	33.87	3643.45
1983	105	27.20	3670.64
1983	106	26.73	3697.37
1983	107	28.64	3726.01
1983	108	33.62	3759.63
1983	109	40.96	3800.59
1983	110	53.14	3853.73
1983	111	21.43	3875.17
1983	112	19.84	3895.00
1983	113	17.37	3912.37
1983	114	17.37	3929.74
1983	115	18.12	3947.86
1983	116	37.83	3985.69
1983	117	52.53	4038.22
1983	118	42.02	4080.24
1983	119	40.15	4120.39
1983	120	37.76	4158.15
1983	121	33.39	4191.54
1983	122	33.18	4224.72
1983	123	32.98	4257.69
1983	124	29.72	4287.41
1983	125	21.96	4309.36
1983	126	24.62	4333.98
1983	127	33.14	4367.12
1983	128	24.62	4391.74
1983	129	33.93	4425.67
1983	130	25.31	4450.98

1983	131	18.41	4469.38
1983	132	19.89	4489.27
1983	133	24.13	4513.40
1983	134	31.64	4545.04
1983	135	50.12	4595.15
1983	136	42.25	4637.41
1983	137	41.32	4678.72
1983	138	37.28	4716.00
1983	139	30.96	4746.96
1983	140	18.01	4764.96
1983	141	12.94	4777.90
1983	142	10.54	4788.45
1983	143	7.04	4795.49
1983	144	10.37	4805.86
1983	145	9.36	4815.21
1983	146	12.42	4827.64
1983	147	22.79	4850.42
1983	148	21.35	4871.77
1983	149	20.10	4891.87
1983	150	22.55	4914.42
1983	151	21.85	4936.27
1983	152	20.85	4957.11
1983	153	18.69	4975.80
1983	154	20.88	4996.68
1983	155	28.32	5025.00
1983	156	25.23	5050.23
1983	157	25.57	5075.80
1983	158	18.23	5094.02
1983	159	19.11	5113.12
1983	160	21.71	5134.83
1983	161	13.20	5148.03
1983	162	12.57	5160.60
1983	163	11.89	5172.48
1983	164	14.79	5187.28
1983	165	13.81	5201.09
1983	166	18.05	5219.13
1983	167	22.73	5241.86
1983	168	21.18	5263.04
1983	169	19.88	5282.92
1983	170	14.66	5297.58
1983	171	12.05	5309.62
1983	172	11.20	5320.82
1983	173	11.56	5332.37
1983	174	13.31	5345.68
1983	175	14.76	5360.45
1983	176	13.10	5373.55
1983	177	12.27	5385.82
1983	178	10.55	5396.36
1983	179	11.36	5407.72
1983	180	10.23	5417.95
1983	181	8.19	5426.13
1983	182	8.31	5434.44
1983	183	6.24	5440.68

1984	1	0.10	0.10
1984	2	0.30	0.40
1984	3	0.55	0.96
1984	4	0.97	1.92
1984	5	0.98	2.90
1984	6	1.28	4.18
1984	7	1.80	5.99
1984	8	2.08	8.06
1984	9	2.67	10.73
1984	10	3.05	13.78
1984	11	3.26	17.04
1984	12	3.89	20.93
1984	13	4.81	25.74
1984	14	5.17	30.90
1984	15	5.51	36.41
1984	16	5.71	42.12
1984	17	6.72	48.84
1984	18	5.85	54.70
1984	19	3.89	58.58
1984	20	8.40	66.99
1984	21	10.07	77.06
1984	22	10.12	87.19
1984	23	11.08	98.26
1984	24	9.54	107.81
1984	25	11.16	118.96
1984	26	9.30	128.27
1984	27	11.07	139.34
1984	28	15.82	155.16
1984	29	16.23	171.39
1984	30	17.58	188.97
1984	31	18.21	207.18
1984	32	19.55	226.73
1984	33	22.33	249.05
1984	34	24.46	273.51
1984	35	24.27	297.78
1984	36	26.45	324.23
1984	37	26.04	350.28
1984	38	27.67	377.94
1984	39	25.52	403.46
1984	40	30.16	433.62
1984	41	28.87	462.49
1984	42	31.18	493.68
1984	43	33.74	527.42
1984	44	37.46	564.88
1984	45	35.27	600.14
1984	46	36.94	637.09
1984	47	37.28	674.36
1984	48	36.73	711.09
1984	49	36.15	747.25
1984	50	38.69	785.93
1984	51	42.17	828.10
1984	52	39.23	867.33
1984	53	40.64	907.97

1984	54	47.03	955.00
1984	55	44.45	999.46
1984	56	45.87	1045.32
1984	57	39.45	1084.77
1984	58	55.70	1140.47
1984	59	60.50	1200.97
1984	60	44.40	1245.36
1984	61	57.02	1302.38
1984	62	57.17	1359.55
1984	63	52.60	1412.15
1984	64	48.87	1461.02
1984	65	41.38	1502.40
1984	66	37.92	1540.32
1984	67	35.68	1576.00
1984	68	32.49	1608.49
1984	69	39.57	1648.06
1984	70	36.39	1684.45
1984	71	39.45	1723.90
1984	72	35.38	1759.28
1984	73	29.70	1788.98
1984	74	34.63	1823.61
1984	75	36.78	1860.40
1984	76	40.74	1901.14
1984	77	40.25	1941.39
1984	78	46.96	1988.35
1984	79	40.17	2028.52
1984	80	31.54	2060.06
1984	81	35.48	2095.54
1984	82	39.68	2135.22
1984	83	58.52	2193.73
1984	84	61.98	2255.71
1984	85	50.67	2306.38
1984	86	66.76	2373.14
1984	87	67.76	2440.90
1984	88	60.01	2500.91
1984	89	48.92	2549.83
1984	90	60.35	2610.17
1984	91	70.56	2680.74
1984	92	73.44	2754.17
1984	93	68.49	2822.66
1984	94	62.53	2885.20
1984	95	62.81	2948.01
1984	96	53.47	3001.48
1984	97	70.42	3071.90
1984	98	74.07	3145.96
1984	99	77.57	3223.54
1984	100	74.34	3297.88
1984	101	61.40	3359.28
1984	102	42.25	3401.52
1984	103	32.94	3434.46
1984	104	41.43	3475.89
1984	105	40.66	3516.54
1984	106	41.21	3557.75

1984	107	41.49	3599.25
1984	108	48.01	3647.25
1984	109	59.31	3706.57
1984	110	65.57	3772.13
1984	111	65.70	3837.83
1984	112	57.30	3895.14
1984	113	53.61	3948.75
1984	114	43.16	3991.91
1984	115	46.07	4037.98
1984	116	40.94	4078.92
1984	117	31.81	4110.73
1984	118	38.54	4149.27
1984	119	53.67	4202.94
1984	120	60.97	4263.91
1984	121	64.96	4328.87
1984	122	60.06	4388.93
1984	123	55.41	4444.34
1984	124	38.51	4482.85
1984	125	34.70	4517.54
1984	126	37.37	4554.91
1984	127	38.59	4593.50
1984	128	40.26	4633.75
1984	129	33.93	4667.68
1984	130	37.30	4704.99
1984	131	27.88	4732.87
1984	132	28.93	4761.80
1984	133	32.34	4794.14
1984	134	31.15	4825.28
1984	135	33.03	4858.31
1984	136	34.65	4892.96
1984	137	28.93	4921.89
1984	138	30.38	4952.27
1984	139	32.90	4985.16
1984	140	29.04	5014.20
1984	141	28.47	5042.67
1984	142	27.89	5070.57
1984	143	31.68	5102.25
1984	144	29.44	5131.69
1984	145	29.34	5161.03
1984	146	29.85	5190.88
1984	147	36.29	5227.16
1984	148	30.77	5257.93
1984	149	29.96	5287.89
1984	150	27.61	5315.50
1984	151	24.34	5339.84
1984	152	18.91	5358.75
1984	153	17.87	5376.62
1984	154	21.63	5398.25
1984	155	18.31	5416.55
1984	156	15.24	5431.80
1984	157	32.46	5464.26
1984	158	29.72	5493.97
1984	159	25.91	5519.88

1984	160	23.67	5543.55
1984	161	20.34	5563.89
1984	162	19.99	5583.87
1984	163	16.48	5600.35
1984	164	12.12	5612.46
1984	165	9.09	5621.55
1984	166	7.98	5629.54
1984	167	6.96	5636.50
1984	168	6.55	5643.05
1984	169	11.80	5654.85
1984	170	11.31	5666.16
1984	171	10.06	5676.21
1984	172	8.33	5684.55
1984	173	5.84	5690.38
1984	174	4.68	5695.06
1984	175	1.02	5696.09
1984	176	0.88	5696.97
1984	177	1.21	5698.18
1984	178	0.85	5699.03
1984	179	3.71	5702.74
1984	180	6.42	5709.15
1984	181	5.05	5714.20
1984	182	6.66	5720.86
1984	183	4.80	5725.66
1985	1	0.10	0.10
1985	2	0.29	0.39
1985	3	0.50	0.90
1985	4	0.80	1.70
1985	5	0.78	2.48
1985	6	1.20	3.68
1985	7	1.71	5.39
1985	8	1.99	7.38
1985	9	2.57	9.94
1985	10	2.95	12.90
1985	11	3.17	16.07
1985	12	3.79	19.86
1985	13	4.70	24.56
1985	14	5.06	29.61
1985	15	5.40	35.01
1985	16	5.61	40.62
1985	17	6.61	47.24
1985	18	5.76	53.00
1985	19	3.83	56.83
1985	20	8.29	65.12
1985	21	9.95	75.07
1985	22	10.00	85.07
1985	23	10.96	96.03
1985	24	9.44	105.47
1985	25	11.05	116.51
1985	26	9.22	125.73
1985	27	10.97	136.70
1985	28	15.68	152.38
1985	29	16.10	168.48

1985	30	17.45	185.93
1985	31	18.08	204.01
1985	32	19.42	223.42
1985	33	22.18	245.61
1985	34	24.31	269.92
1985	35	24.13	294.04
1985	36	26.30	320.35
1985	37	25.91	346.25
1985	38	27.53	373.78
1985	39	25.40	399.18
1985	40	30.02	429.20
1985	41	28.74	457.95
1985	42	31.05	489.00
1985	43	33.61	522.60
1985	44	37.32	559.92
1985	45	35.14	595.06
1985	46	36.81	631.87
1985	47	37.15	669.01
1985	48	36.61	705.63
1985	49	36.04	741.67
1985	50	38.57	780.23
1985	51	42.05	822.28
1985	52	39.12	861.40
1985	53	40.53	901.93
1985	54	46.90	948.84
1985	55	44.34	993.18
1985	56	45.76	1038.93
1985	57	39.36	1078.29
1985	58	55.57	1133.86
1985	59	60.37	1194.23
1985	60	44.31	1238.53
1985	61	56.90	1295.44
1985	62	57.06	1352.50
1985	63	52.50	1405.00
1985	64	48.78	1453.78
1985	65	41.31	1495.08
1985	66	37.86	1532.94
1985	67	35.62	1568.56
1985	68	32.44	1601.00
1985	69	39.51	1640.51
1985	70	36.34	1676.84
1985	71	39.39	1716.24
1985	72	35.33	1751.56
1985	73	29.66	1781.22
1985	74	34.58	1815.80
1985	75	36.73	1852.53
1985	76	40.69	1893.22
1985	77	40.20	1933.43
1985	78	46.90	1980.32
1985	79	40.12	2020.44
1985	80	31.50	2051.94
1985	81	35.44	2087.39
1985	82	39.63	2127.02

1985	83	58.45	2185.47
1985	84	61.91	2247.38
1985	85	50.62	2298.00
1985	86	66.69	2364.69
1985	87	67.69	2432.39
1985	88	59.96	2492.34
1985	89	48.88	2541.22
1985	90	60.30	2601.52
1985	91	70.51	2672.03
1985	92	73.38	2745.41
1985	93	68.44	2813.85
1985	94	62.49	2876.35
1985	95	62.77	2939.12
1985	96	53.44	2992.56
1985	97	70.38	3062.94
1985	98	65.56	3128.50
1985	99	73.99	3202.49
1985	100	61.13	3263.61
1985	101	43.66	3307.27
1985	102	32.81	3340.08
1985	103	41.27	3381.36
1985	104	40.51	3421.87
1985	105	41.07	3462.94
1985	106	43.03	3505.97
1985	107	47.87	3553.84
1985	108	59.17	3613.01
1985	109	65.43	3678.44
1985	110	63.49	3741.92
1985	111	42.39	3784.31
1985	112	53.53	3837.84
1985	113	43.10	3880.94
1985	114	47.93	3928.87
1985	115	40.91	3969.78
1985	116	31.79	4001.58
1985	117	38.53	4040.10
1985	118	56.07	4096.17
1985	119	60.97	4157.14
1985	120	64.96	4222.10
1985	121	62.73	4284.82
1985	122	55.41	4340.23
1985	123	38.51	4378.75
1985	124	34.70	4413.44
1985	125	39.12	4452.56
1985	126	38.59	4491.15
1985	127	40.26	4531.40
1985	128	35.62	4567.02
1985	129	37.30	4604.33
1985	130	27.88	4632.21
1985	131	30.35	4662.56
1985	132	32.34	4694.90
1985	133	31.15	4726.04
1985	134	34.80	4760.84
1985	135	34.65	4795.49

1985	136	30.47	4825.96
1985	137	30.38	4856.34
1985	138	32.90	4889.24
1985	139	30.69	4919.93
1985	140	28.47	4948.40
1985	141	27.89	4976.30
1985	142	33.61	5009.90
1985	143	29.44	5039.34
1985	144	29.34	5068.68
1985	145	31.68	5100.36
1985	146	36.29	5136.65
1985	147	32.83	5169.47
1985	148	29.96	5199.43
1985	149	28.76	5228.20
1985	150	28.26	5256.45
1985	151	21.49	5277.95
1985	152	23.95	5301.89
1985	153	21.27	5323.16
1985	154	21.63	5344.79
1985	155	18.31	5363.10
1985	156	15.24	5378.34
1985	157	33.13	5411.46
1985	158	31.61	5443.08
1985	159	28.79	5471.86
1985	160	27.53	5499.39
1985	161	24.80	5524.18
1985	162	24.98	5549.16
1985	163	21.68	5570.84
1985	164	16.38	5587.22
1985	165	12.99	5600.21
1985	166	11.74	5611.94
1985	167	10.55	5622.49
1985	168	10.57	5633.05
1985	169	19.67	5652.73
1985	170	19.50	5672.23
1985	171	17.96	5690.19
1985	172	15.43	5705.62
1985	173	11.22	5716.84
1985	174	9.36	5726.20
1985	175	8.54	5734.74
1985	176	7.54	5742.27
1985	177	10.09	5752.36
1985	178	7.77	5760.13
1985	179	6.63	5766.76
1985	180	11.88	5778.64
1985	181	9.72	5788.35
1985	182	7.75	5796.09
1985	183	5.71	5801.80
1986	1	0.16	0.16
1986	2	0.32	0.48
1986	3	0.43	0.91
1986	4	0.72	1.63
1986	5	0.82	2.45

1986	6	1.00	3.45
1986	7	1.40	4.85
1986	8	1.74	6.59
1986	9	2.25	8.84
1986	10	1.73	10.56
1986	11	2.16	12.73
1986	12	2.73	15.46
1986	13	3.01	18.47
1986	14	3.15	21.62
1986	15	3.66	25.28
1986	16	3.71	29.00
1986	17	4.33	33.32
1986	18	4.81	38.14
1986	19	4.82	42.95
1986	20	5.75	48.70
1986	21	8.48	57.18
1986	22	6.76	63.95
1986	23	5.67	69.62
1986	24	9.28	78.89
1986	25	9.49	88.38
1986	26	8.47	96.85
1986	27	6.42	103.27
1986	28	8.22	111.49
1986	29	12.09	123.57
1986	30	12.87	136.45
1986	31	12.90	149.35
1986	32	16.77	166.12
1986	33	17.56	183.69
1986	34	16.15	199.83
1986	35	15.09	214.92
1986	36	13.71	228.63
1986	37	10.94	239.57
1986	38	12.27	251.83
1986	39	15.89	267.72
1986	40	15.62	283.34
1986	41	17.07	300.42
1986	42	17.52	317.94
1986	43	30.18	348.12
1986	44	27.46	375.58
1986	45	27.55	403.13
1986	46	26.98	430.12
1986	47	27.43	457.54
1986	48	28.68	486.22
1986	49	33.96	520.18
1986	50	42.06	562.24
1986	51	43.08	605.32
1986	52	44.13	649.46
1986	53	43.65	693.11
1986	54	46.60	739.71
1986	55	46.41	786.11
1986	56	49.27	835.39
1986	57	48.73	884.12
1986	58	50.07	934.19

1986	59	46.02	980.21
1986	60	42.59	1022.80
1986	61	47.37	1070.17
1986	62	39.81	1109.98
1986	63	47.41	1157.39
1986	64	51.07	1208.46
1986	65	59.15	1267.61
1986	66	44.84	1312.44
1986	67	36.76	1349.20
1986	68	33.30	1382.49
1986	69	39.66	1422.15
1986	70	34.59	1456.74
1986	71	53.39	1510.13
1986	72	33.75	1543.88
1986	73	41.77	1585.65
1986	74	35.89	1621.54
1986	75	48.98	1670.52
1986	76	39.98	1710.49
1986	77	35.21	1745.70
1986	78	36.89	1782.59
1986	79	61.68	1844.27
1986	80	51.42	1895.69
1986	81	41.64	1937.33
1986	82	35.97	1973.30
1986	83	27.65	2000.95
1986	84	24.85	2025.80
1986	85	39.64	2065.43
1986	86	49.97	2115.40
1986	87	50.28	2165.68
1986	88	32.11	2197.80
1986	89	32.29	2230.09
1986	90	25.32	2255.41
1986	91	40.88	2296.29
1986	92	27.87	2324.16
1986	93	42.69	2366.85
1986	94	39.53	2406.38
1986	95	53.76	2460.14
1986	96	43.16	2503.29
1986	97	30.37	2533.67
1986	98	24.60	2558.27
1986	99	25.18	2583.45
1986	100	43.06	2626.51
1986	101	40.09	2666.59
1986	102	42.58	2709.18
1986	103	42.55	2751.73
1986	104	42.89	2794.62
1986	105	46.73	2841.34
1986	106	24.36	2865.70
1986	107	23.14	2888.84
1986	108	21.47	2910.31
1986	109	25.57	2935.88
1986	110	22.66	2958.55
1986	111	21.58	2980.13

1986	112	24.63	3004.75
1986	113	24.38	3029.13
1986	114	26.77	3055.90
1986	115	21.59	3077.49
1986	116	24.29	3101.78
1986	117	23.35	3125.13
1986	118	17.51	3142.64
1986	119	36.60	3179.23
1986	120	23.25	3202.49
1986	121	38.08	3240.56
1986	122	47.52	3288.08
1986	123	37.79	3325.87
1986	124	38.35	3364.21
1986	125	33.54	3397.75
1986	126	32.86	3430.61
1986	127	26.33	3456.94
1986	128	20.72	3477.66
1986	129	29.98	3507.64
1986	130	28.47	3536.11
1986	131	27.62	3563.73
1986	132	27.94	3591.67
1986	133	30.25	3621.92
1986	134	27.89	3649.81
1986	135	40.55	3690.36
1986	136	25.88	3716.24
1986	137	23.84	3740.08
1986	138	26.94	3767.02
1986	139	24.39	3791.41
1986	140	30.64	3822.04
1986	141	26.97	3849.02
1986	142	24.85	3873.87
1986	143	23.86	3897.72
1986	144	22.42	3920.15
1986	145	22.37	3942.52
1986	146	28.27	3970.79
1986	147	29.36	4000.15
1986	148	24.43	4024.58
1986	149	23.21	4047.79
1986	150	29.55	4077.34
1986	151	36.14	4113.48
1986	152	35.31	4148.79
1986	153	34.58	4183.36
1986	154	38.49	4221.84
1986	155	38.70	4260.54
1986	156	26.62	4287.16
1986	157	30.40	4317.55
1986	158	25.81	4343.36
1986	159	25.02	4368.37
1986	160	24.64	4393.01
1986	161	27.53	4420.54
1986	162	24.63	4445.17
1986	163	23.29	4468.45
1986	164	19.23	4487.68

1986	165	21.25	4508.93
1986	166	21.70	4530.62
1986	167	19.28	4549.90
1986	168	20.02	4569.92
1986	169	16.66	4586.58
1986	170	18.10	4604.68
1986	171	17.66	4622.34
1986	172	18.28	4640.61
1986	173	13.42	4654.03
1986	174	11.79	4665.82
1986	175	10.08	4675.90
1986	176	8.99	4684.88
1986	177	9.48	4694.36
1986	178	6.83	4701.19
1986	179	7.43	4708.61
1986	180	7.43	4716.04
1986	181	6.80	4722.83
1986	182	5.70	4728.53
1986	183	4.20	4732.72

Appendix F: WEATHER DATA

F-1. Monthly rainfall at Pennington Gap, Virginia.

Year	Monthly rainfall, cm											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1932	16.7	14.5	13.3	14.6	8.6	17.3	3.4	9.9	4.4	14.5	5.1	15.2
1933	10.1	17.3	12.6	5.7	16.0	3.7	12.9	5.7	2.1	3.7	3.8	12.0
1934	10.2	10.0	19.2	8.7	2.2	9.7	12.8	9.7	5.7	6.8	8.0	6.8
1935	10.9	10.5	22.7	12.5	15.9	13.0	17.0	8.3	1.1	5.4	15.6	5.9
1936	19.3	11.4	16.6	14.8	2.4	6.2	14.2	17.8	8.9	11.7	4.2	18.1
1937	31.3	12.9	5.7	9.1	6.8	13.0	13.4	12.8	5.8	13.2	2.5	8.1
1938	11.8	6.4	10.8	14.8	18.8	13.5	17.5	8.9	6.3	1.1	11.0	7.0
1939	13.0	19.4	13.4	11.0	7.0	8.9	18.3	5.6	3.2	4.9	2.5	7.2
1940	4.5	10.3	14.8	15.8	5.3	12.5	12.0	13.9	2.8	3.0	8.7	6.5
1941	6.6	2.8	10.6	7.8	0.7	12.3	26.6	9.1	4.9	7.5	5.6	8.3
1942	9.2	8.0	14.6	1.7	10.7	15.7	22.1	23.0	10.4	7.2	5.8	17.9
1943	8.8	7.7	15.8	11.6	6.9	8.1	14.4	8.6	5.3	6.1	5.6	6.1
1944	4.9	27.9	20.9	9.8	7.7	6.6	3.3	7.4	16.0	4.0	8.8	10.3
1945	8.8	18.8	8.7	10.8	15.6	13.3	15.4	10.2	10.6	5.5	13.4	10.7
1946	20.8	12.9	10.5	6.5	13.3	4.1	10.4	15.6	6.6	6.6	6.3	10.8
1947	26.1	5.0	8.4	7.0	7.6	16.9	10.7	15.1	4.4	4.2	9.2	5.4
1948	11.1	16.8	16.8	9.9	5.6	6.0	15.4	8.0	6.0	3.6	22.0	13.9
1949	16.1	6.7	12.7	10.4	10.7	12.0	11.3	17.8	7.9	4.1	8.4	11.9
1950	14.6	11.8	14.0	5.4	15.0	10.1	5.8	13.9	2.0	4.1	11.1	8.4
1951	12.8	15.0	15.0	11.1	9.1	16.5	7.7	11.0	16.5	3.9	16.8	11.0
1952	18.1	7.2	16.8	6.8	10.8	8.5	9.6	11.5	5.2	3.5	9.7	9.8
1953	11.3	12.7	11.0	10.1	14.7	7.5	14.8	6.5	6.7	0.9	4.2	9.8
1954	22.1	4.3	13.0	6.5	7.9	5.4	11.3	7.5	5.3	2.6	7.4	17.9
1955	6.8	18.4	25.4	6.8	6.7	10.8	14.8	4.0	5.3	8.0	8.3	8.5
1956	7.9	29.7	18.7	15.6	9.8	11.1	23.8	10.3	7.9	1.8	7.6	13.2
1957	25.0	16.0	6.6	13.4	6.3	15.4	5.8	8.2	19.5	5.9	8.4	11.8
1958	0.2	11.2	8.8	17.1	17.3	9.3	16.5	16.2	5.5	4.0	7.2	8.5
1959	11.3	8.9	12.8	11.5	9.6	9.1	12.2	11.7	4.6	14.8	14.4	12.6
1960	8.8	9.2	15.4	3.9	4.8	10.8	16.2	11.7	6.3	7.9	7.4	8.9
1961	11.3	18.9	12.7	11.2	8.5	9.0	12.2	7.5	5.7	8.7	7.2	18.5
1962	14.1	19.1	15.4	9.3	7.5	13.8	11.6	10.0	15.3	6.5	10.4	10.2
1963	9.6	5.8	35.3	5.8	15.3	8.1	13.3	11.0	3.7	0.1	12.1	4.3
1964	14.9	12.1	15.5	11.7	5.9	10.4	12.0	13.8	14.8	12.9	10.7	13.8
1965	12.4	6.8	18.1	10.9	10.3	8.2	8.9	5.5	3.3	6.1	2.8	1.5
1966	6.9	11.6	6.6	11.3	9.6	6.4	20.2	9.8	12.7	7.6	12.9	9.4
1967	7.7	8.9	13.5	9.6	14.0	11.1	16.4	7.5	5.3	5.2	11.7	18.1
1968	8.7	2.2	9.6	13.5	12.3	4.6	18.2	4.8	9.2	5.7	7.5	6.9
1969	7.7	13.4	3.9	7.9	4.2	14.6	11.7	9.2	3.0	4.6	9.5	23.1
1970	8.3	10.9	7.0	24.3	4.4	9.4	5.7	13.6	11.9	12.4	5.4	12.5

F-1. continued...

1971	11.1	8.4	9.0	9.4	16.8	15.2	18.1	9.1	12.7	10.2	7.1	11.2
1972	27.0	15.1	13.2	15.4	11.0	13.8	14.0	2.8	11.0	13.6	10.5	22.1
1973	5.5	9.3	22.2	12.6	18.9	16.1	13.2	7.0	12.3	11.5	18.4	15.3
1974	22.2	12.5	15.7	13.0	19.2	22.5	9.4	11.0	7.8	5.9	8.8	9.7
1975	14.0	10.2	30.1	10.3	18.4	9.3	4.6	5.7	12.5	11.2	9.8	6.8
1976	10.4	11.8	16.7	0.7	11.4	8.1	9.3	5.6	12.2	14.4	3.6	4.3
1977	5.2	4.9	11.1	26.6	4.8	13.8	11.8	19.9	10.0	19.3	19.8	9.2
1978	9.7	4.1	7.6	5.4	15.5	6.9	16.0	21.4	3.1	3.7	9.4	18.5
1979	17.8	12.1	15.3	10.4	14.9	3.5	17.7	11.5	7.7	7.7	13.3	8.7
1980	13.7	6.2	13.6	11.4	11.7	4.2	9.6	9.3	7.2	4.6	6.4	4.0
1981	2.6	12.0	5.0	11.4	10.6	12.2	14.3	8.1	8.1	10.3	1.9	10.7
1982	15.1	15.1	11.5	8.3	9.1	15.2	16.4	14.3	12.9	5.4	20.4	11.3
1983	4.2	10.3	5.2	12.5	18.3	6.8	10.4	11.9	4.6	8.3	10.2	13.6
1984	5.8	14.2	12.8	10.9	18.5	14.2	10.6	3.8	3.4	14.1	14.0	8.7
1985	8.8	13.5	6.2	7.7	9.1	7.5	10.7	11.9	1.9	7.9	13.0	4.8
1986	3.0	20.4	4.9	4.3	10.6	5.0	11.9	6.7	14.0	10.0	17.4	11.8

F-2. Monthly pan evaporation at Marion, Virginia.

	Monthly pan evaporation, cm					
Year	Apr	May	Jun	Jul	Aug	Sep
1930	6.4	12.2	15.6	17.4	18.0	13.1
1931	6.4	12.2	15.7	17.4	18.0	13.2
1932	6.4	12.0	15.3	17.0	17.5	12.6
1933	6.1	11.6	14.9	16.5	17.1	12.5
1934	6.2	11.7	15.0	16.7	17.2	12.6
1935	6.3	12.1	15.5	17.2	17.8	13.0
1936	6.2	11.7	14.9	16.5	17.0	12.2
1937	6.3	12.1	15.5	17.2	17.8	13.0
1938	6.2	11.9	15.2	16.9	17.5	12.8
1939	6.1	11.6	14.9	16.5	17.1	12.5
1940	6.5	12.2	15.6	17.2	17.8	12.8
1941	6.1	11.6	14.8	16.5	17.0	12.5
1942	6.4	12.2	15.6	17.4	18.0	13.1
1943	6.1	11.5	14.8	16.4	17.0	12.5
1944	6.5	12.2	15.6	17.2	17.8	12.8
1945	6.3	12.0	15.4	17.1	17.6	12.9
1946	6.2	11.8	15.1	16.8	17.3	12.7
1947	6.2	11.7	15.1	16.7	17.3	12.7
1948	6.4	12.0	15.3	16.9	17.4	12.6
1949	5.8	11.0	14.2	15.7	16.3	11.9
1950	5.7	10.8	13.9	15.4	16.0	11.7
1951	6.1	11.7	15.0	16.7	17.2	12.6
1952	6.3	11.8	15.1	16.7	17.2	12.4
1953	5.9	11.2	14.4	16.0	16.5	12.1
1954	6.1	11.5	14.8	16.4	17.0	12.5
1955	6.2	11.7	15.1	16.7	17.3	12.7
1956	6.6	12.3	15.7	17.4	17.9	12.9
1957	6.1	11.6	14.8	16.5	17.0	12.5
1958	6.1	11.6	14.9	16.6	17.1	12.5
1959	5.9	11.2	14.4	16.0	16.5	12.1
1960	6.2	11.7	14.8	16.4	16.9	12.2
1961	6.2	11.8	15.1	16.8	17.3	12.7
1962	6.1	11.5	14.8	16.4	17.0	12.5
1963	5.9	11.2	14.4	16.0	16.6	12.1
1964	6.2	11.7	14.8	16.4	16.9	12.2
1965	5.7	10.9	14.0	15.5	16.1	11.8
1966	5.9	11.2	14.3	15.9	16.4	12.0
1967	5.9	11.2	14.3	15.9	16.5	12.1
1968	6.1	11.4	14.6	16.1	16.6	12.0

F-2. Continued ...

1969	5.9	11.2	14.4	16.0	16.5	12.1
1970	5.9	11.3	14.5	16.1	16.6	12.2
1971	5.9	11.2	14.4	16.0	16.6	12.1
1972	6.4	11.9	15.2	16.8	17.3	12.5
1973	5.9	11.2	14.4	16.0	16.5	12.1
1974	6.0	11.5	14.7	16.3	16.9	12.4
1975	6.1	11.5	14.8	16.4	17.0	12.4
1976	5.9	11.0	14.0	15.5	15.9	11.5
1977	6.0	11.3	14.6	16.2	16.7	12.2
1978	5.8	11.0	14.2	15.7	16.3	11.9
1979	5.4	10.2	13.1	14.6	15.1	11.1

F-3. Number of monthly rainy days at Pennington Gap, Virginia.

Year	Number of rainy days per month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1932	15	10	11	11	11	14	7	9	8	10	5	15
1933	12	16	11	9	12	5	13	12	5	4	7	10
1934	8	4	18	13	6	11	15	11	6	8	7	12
1935	11	10	18	13	13	10	15	8	5	7	10	14
1936	19	11	11	13	6	4	14	11	9	10	6	11
1937	19	11	8	11	12	15	10	12	8	11	13	15
1938	11	12	16	13	15	13	15	9	7	3	11	6
1939	13	13	11	14	12	12	11	10	4	6	6	8
1940	10	15	14	10	12	12	12	8	3	6	14	11
1941	11	9	11	9	6	14	16	8	7	10	7	9
1942	10	16	10	2	10	17	17	14	10	9	11	17
1943	7	8	15	13	9	13	13	7	4	8	5	11
1944	8	19	16	11	13	11	7	9	12	6	8	15
1945	11	13	13	11	14	12	10	8	10	5	14	15
1946	16	11	18	11	17	10	10	11	6	4	7	11
1947	18	12	13	11	12	13	9	13	5	7	14	6
1948	15	14	12	8	9	9	16	8	8	5	16	15
1949	17	8	16	10	13	13	10	19	8	5	8	13
1950	13	10	12	8	16	11	11	15	8	5	12	7
1951	12	11	17	14	13	16	11	11	10	5	10	11
1952	11	11	8	13	14	9	9	15	7	5	9	13
1953	13	6	6	13	14	9	11	7	6	2	5	13
1954	10	6	11	13	11	8	7	11	3	9	11	14
1955	11	9	18	12	8	11	15	6	4	8	13	9
1956	11	23	12	12	11	11	18	9	7	6	8	16
1957	14	17	12	13	10	13	6	6	16	7	9	11
1958	2	12	11	15	15	6	13	13	5	6	8	6
1959	7	7	8	9	6	8	10	11	5	12	6	11
1960	10	9	11	5	7	9	10	13	7	8	8	9
1961	9	11	15	12	8	13	16	6	5	7	10	13
1962	11	9	13	12	8	10	12	9	7	6	10	11
1963	8	7	12	5	12	10	13	11	3	1	13	8
1964	9	9	11	12	6	7	11	12	6	9	9	14
1965	12	6	10	9	7	8	12	12	3	4	5	4
1966	10	9	4	10	10	4	11	11	8	7	11	5
1967	6	8	7	5	15	6	12	10	5	5	9	10
1968	9	2	6	10	15	5	13	7	10	7	15	7
1969	8	10	9	10	7	11	9	8	6	5	6	13
1970	12	9	10	8	6	11	3	9	10	4	7	7

F-3. continued...

1971	10	7	10	6	8	10	14	8	10	8	6	8
1972	15	12	14	11	10	10	14	5	7	10	9	14
1973	8	9	15	8	15	11	13	7	9	8	8	8
1974	16	12	9	6	12	10	11	13	11	3	8	9
1975	13	10	16	9	15	9	7	8	8	11	6	8
1976	12	9	12	2	8	7	7	6	8	9	3	7
1977	10	7	10	7	7	14	7	11	11	7	12	6
1978	12	8	6	7	12	6	9	12	3	6	7	11
1979	14	12	10	11	11	5	14	6	7	6	5	6
1980	11	9	8	12	8	5	7	7	10	6	6	3
1981	5	10	8	10	10	7	14	6	5	7	4	10
1982	7	13	15	10	11	12	13	8	8	8	14	8
1983	7	7	9	13	14	7	7	9	4	8	12	7
1984	8	11	12	15	12	9	11	8	4	9	11	12
1985	11	7	9	7	9	8	15	10	3	10	14	8
1986	4	11	6	5	15	5	5	6	14	9	13	10

F-4. Monthly maximum and minimum temperatures at Pennington Gap, Virginia.

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1932	Max	55.7	58.3	54.0	67.8	75.8	84.0	88.1	87.1	82.8	69.9	58.0	49.4
	Min	36.4	35.8	29.0	42.6	50.8	59.8	62.9	62.2	54.3	42.2	30.9	28.7
1933	Max	50.9	46.9	56.1	67.0	78.5	85.2	86.6	83.7	85.8	72.7	47.1	47.8
	Min	30.0	24.9	33.4	40.3	55.7	58.1	61.2	60.7	57.7	40.3	31.3	33.6
1934	Max	47.4	47.9	46.0	65.1	79.1	86.1	87.9	82.9	81.6	72.2	59.4	42.9
	Min	41.1	30.8	31.4	42.9	49.8	59.7	65.4	64.0	55.5	41.4	32.9	26.7
1935	Max	42.6	43.0	57.1	57.2	72.5	74.6	82.8	85.5	81.3	75.2	60.0	38.8
	Min	27.4	26.4	37.5	43.5	49.9	55.8	62.6	61.3	51.9	38.0	35.9	20.3
1936	Max	40.6	43.7	59.3	64.0	84.1	88.6	86.6	87.8	84.4	71.2	55.3	52.5
	Min	18.9	19.7	33.4	37.6	53.5	55.5	63.0	62.6	55.6	45.0	27.7	29.0
1937	Max	54.5	45.3	51.7	65.0	74.6	82.9	84.1	85.8	76.5	66.2	53.8	45.8
	Min	38.1	27.4	30.1	40.8	48.1	59.2	59.4	63.1	52.1	38.8	27.8	25.0
1938	Max	46.2	55.7	62.7	68.3	74.7	79.8	85.4	87.1	80.4	75.7	62.5	48.5
	Min	23.7	33.2	35.6	41.3	49.5	54.9	63.3	63.3	55.7	39.3	31.0	24.2
1939	Max	49.2	53.1	59.9	64.7	77.0	84.9	84.8	85.8	84.2	74.5	54.8	48.3
	Min	26.1	28.8	34.7	39.8	51.5	63.3	61.9	61.2	54.0	42.9	29.8	26.4
1940	Max	32.3	45.1	52.3	64.5	73.2	82.1	83.0	84.3	80.0	73.0	56.5	54.6
	Min	14.9	25.4	30.7	40.1	46.0	58.9	62.2	62.3	49.3	40.4	32.6	30.0
1941	Max	46.4	40.9	49.3	71.0	79.6	82.2	84.9	87.4	86.4	76.9	58.8	52.4
	Min	25.8	19.4	26.8	43.2	48.0	58.6	64.9	62.0	54.4	46.9	30.6	30.3
1942	Max	44.7	40.6	57.4	70.6	76.8	82.7	85.9	83.4	78.1	71.0	60.0	44.0
	Min	20.6	22.7	34.2	40.2	49.5	60.8	63.3	60.5	54.3	43.1	34.8	26.1
1943	Max	46.6	49.5	54.1	62.6	77.6	89.0	84.8	87.3	80.0	68.7	53.2	45.3
	Min	26.8	30.1	28.1	38.4	52.1	63.5	63.5	59.1	48.6	37.4	27.8	24.6
1944	Max	47.8	52.1	55.5	64.1	80.5	87.7	88.1	86.3	79.3	69.7	55.1	40.8
	Min	24.1	29.2	33.1	39.8	53.3	60.2	58.6	59.6	55.4	40.2	32.1	21.8
1945	Max	42.5	48.9	66.0	70.4	70.3	80.4	85.5	85.3	80.6	71.5	48.7	39.8
	Min	23.2	27.1	40.5	42.6	44.7	56.1	59.7	73.0	72.8	41.6	32.1	23.0
1946	Max	45.5	51.5	65.0	70.0	73.5	82.3	86.7	80.6	80.0	71.8	64.6	52.6
	Min	27.0	26.7	39.2	44.0	50.1	56.6	62.4	55.9	53.3	41.7	35.7	27.2
1947	Max	50.6	37.6	45.4	69.1	74.1	81.8	80.2	87.0	83.0	75.8	54.3	49.8
	Min	30.9	17.4	25.1	43.2	46.9	57.3	56.7	64.9	54.9	47.2	36.0	24.4
1948	Max	38.9	50.1	59.4	72.4	75.2	84.6	85.5	85.1	81.2	68.0	62.3	49.3
	Min	19.3	30.2	37.8	45.5	48.7	56.9	62.6	58.6	52.6	37.4	36.8	28.9
1949	Max	53.4	55.7	54.4	64.2	75.3	84.0	86.1	83.5	80.5	70.8	54.4	51.3
	Min	35.1	33.4	33.5	40.0	49.4	59.4	60.4	62.1	53.1	39.7	29.9	28.5
1950	Max	47.9	48.9	53.3	62.2	77.3	84.3	86.0	81.3	78.0	70.6	52.9	41.4
	Min	28.6	27.7	30.9	36.0	53.7	58.3	60.0	57.3	53.0	39.2	27.8	19.8
1951	Max	47.4	50.1	56.5	63.7	76.4	82.2	86.2	84.0	80.3	69.3	50.7	47.3
	Min	26.7	26.9	33.2	39.3	47.5	57.1	59.8	59.8	51.8	37.2	27.7	25.8
1952	Max	49.2	51.3	55.8	67.6	77.4	89.1	92.0	86.3	81.5	67.8	55.9	47.4
	Min	31.0	30.6	31.2	41.8	49.7	60.6	60.4	61.1	48.4	32.7	29.4	26.3
1953	Max	49.2	47.9	48.9	63.2	79.0	86.7	87.1	88.8	84.4	75.4	60.5	46.3
	Min	30.0	28.1	33.5	38.1	53.1	58.2	60.6	58.2	48.8	39.7	27.8	23.8

F-4. continued...

1954	Max	47.3	53.1	53.4	72.0	69.1	84.2	88.4	85.4	84.8	70.9	53.2	43.0
	Min	25.2	28.0	28.5	44.1	44.6	55.5	60.6	60.3	51.8	41.1	29.7	24.2
1955	Max	42.4	47.8	57.5	70.1	77.5	76.4	85.4	87.2	84.9	68.5	53.5	44.3
	Min	22.0	24.8	34.9	42.3	50.8	51.5	62.9	61.1	52.1	38.9	26.9	21.5
1956	Max	40.0	51.1	55.7	61.5	76.2	80.5	82.7	82.9	75.4	73.6	56.3	54.4
	Min	20.4	31.8	29.6	36.8	49.1	54.6	59.8	57.9	49.7	43.8	28.7	35.0
1957	Max	44.2	54.4	56.0	70.3	78.8	82.2	85.5	83.0	78.9	70.2	55.2	46.8
	Min	24.5	32.1	32.1	42.5	48.8	58.1	58.0	55.2	56.7	40.7	28.9	25.0
1958	Max	36.8	37.4	49.9	65.6	75.6	82.2	84.5	82.3	77.5	68.0	61.8	43.9
	Min	26.3	16.0	33.0	41.9	50.3	55.4	64.4	60.7	51.8	39.2	31.7	18.3
1959	Max	42.1	51.1	55.1	66.3	79.0	80.7	84.0	85.7	79.7	67.9	54.2	48.3
	Min	19.4	24.9	27.4	40.0	53.5	56.4	62.0	62.7	53.2	45.1	27.7	25.8
1960	Max	44.5	44.8	42.0	70.7	71.8	81.4	83.0	83.2	79.5	69.4	57.9	41.1
	Min	27.1	21.8	17.7	38.6	44.5	56.2	60.6	62.3	54.9	43.8	27.0	16.3
1961	Max	41.9	52.0	59.1	59.9	72.2	79.0	80.7	81.9	80.3	68.3	58.5	46.3
	Min	15.6	28.0	34.7	36.0	43.1	52.9	59.2	58.7	53.8	36.9	34.9	26.0
1962	Max	42.7	52.8	51.8	62.8	82.5	80.1	82.1	82.4	75.1	69.1	54.9	44.3
	Min	21.1	27.1	29.7	36.8	54.2	57.2	61.1	58.6	53.0	43.4	31.6	20.9
1963	Max	39.9	39.8	59.2	69.1	74.9	81.7	82.0	82.0	77.9	75.8	58.3	37.6
	Min	15.9	16.9	33.4	40.3	48.4	56.6	58.3	58.7	50.4	39.5	32.8	15.8
1964	Max	43.9	42.6	56.1	67.9	79.8	82.0	82.1	80.2	78.5	66.0	62.8	48.5
	Min	17.2	20.8	30.1	44.2	49.2	57.6	60.7	58.7	52.3	36.3	33.3	26.6
1965	Max	46.7	46.2	52.5	71.9	80.6	79.5	83.3	83.1	80.0	66.4	59.1	49.3
	Min	24.4	21.5	32.8	46.0	52.9	57.6	61.6	60.1	55.7	38.5	33.2	24.8
1966	Max	36.7	45.8	59.4	63.8	75.4	84.1	87.0	83.0	76.6	69.2	58.6	44.9
	Min	15.0	26.0	30.2	39.8	47.7	53.7	61.1	60.0	52.6	38.4	35.7	26.6
1967	Max	49.7	45.6	65.6	74.8	73.2	82.0	81.3	80.4	78.2	73.0	55.0	55.5
	Min	26.3	23.5	36.7	41.6	48.0	57.2	59.8	59.9	47.2	39.2	29.0	30.5
1968	Max	47.1	42.1	64.7	70.5	74.8	84.0	85.2	86.8	79.8	70.0	56.3	44.7
	Min	23.7	16.7	32.9	42.3	49.8	57.0	61.2	61.8	51.4	42.1	32.7	22.7
1969	Max	44.3	46.7	52.7	73.7	79.5	84.5	87.8	84.8	80.8	71.8	54.9	42.8
	Min	22.7	27.7	26.5	42.1	48.0	57.5	64.3	59.8	51.3	41.2	27.4	25.6
1970	Max	39.2	47.7	58.2	72.1	80.2	82.1	88.3	85.4	83.0	72.1	55.8	51.8
	Min	17.0	24.7	33.5	42.9	49.4	56.3	61.0	61.8	59.6	45.9	39.6	29.3
1971	Max	42.4	50.8	54.2	72.2	74.0	84.6	83.2	84.4	81.2	74.0	56.8	56.4
	Min	24.8	23.8	30.1	35.0	45.4	59.8	60.4	59.4	59.6	51.2	32.6	34.9
1972	Max	49.4	46.6	59.0	69.7	75.8	79.9	84.6	85.5	82.6	67.8	56.1	53.4
	Min	27.9	24.4	32.4	40.8	48.6	53.5	60.9	61.7	56.7	42.9	35.0	34.3
1973	Max	47.5	49.5	67.1	71.0	73.0	84.1	85.2	85.0	82.7	73.8	61.7	50.0
	Min	23.8	24.7	40.1	39.6	45.6	59.8	63.7	61.7	58.6	45.7	34.8	27.1
1974	Max	56.0	52.3	64.2	71.2	77.4	79.9	86.4	83.5	76.0	71.0	58.8	48.8
	Min	37.5	27.6	39.3	40.2	51.3	54.3	61.1	60.6	54.4	35.5	33.0	27.8
1975	Max	51.8	54.6	57.0	69.8	80.9	83.8	87.9	89.5	80.7	73.6	63.1	51.6
	Min	28.1	30.6	32.7	39.2	53.3	56.7	59.8	62.4	53.3	44.8	35.1	26.8
1976	Max	45.0	60.6	65.7	74.3	75.9	84.5	86.9	85.9	80.1	65.3	53.4	48.5
	Min	21.0	31.1	35.8	35.5	46.3	55.3	57.4	55.3	50.3	38.6	26.0	20.9
1977	Max	33.9	51.4	65.8	75.1	81.6	83.1	89.4	86.8	81.8	67.4	61.1	48.4
	Min	12.7	20.1	35.2	53.6	50.9	56.2	62.3	60.2	56.3	39.9	37.8	24.5
1978	Max	38.5	42.3	59.9	72.5	75.6	84.9	87.0	86.4	85.2	72.1	65.5	51.6
	Min	18.0	18.9	33.1	41.5	49.4	57.0	61.3	60.6	55.3	34.0	33.1	26.3

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1979	Max	40.1	42.9	60.8	68.7	75.1	80.6	81.3	83.3	78.7	68.5	61.5	52.2
	Min	20.4	23.1	35.8	41.6	49.7	58.0	62.6	61.0	57.1	41.7	36.1	24.7
1980	Max	48.0	45.5	57.5	70.3	78.1	83.9	91.3	90.5	84.9	70.7	58.9	50.8
	Min	29.6	19.8	32.3	40.6	49.1	56.9	62.0	62.1	56.9	35.3	28.6	22.0
1981	Max	41.0	64.0	57.0	78.0	76.0	88.0	87.0	84.0	83.0	71.0	64.0	44.0
	Min	40.0	29.0	27.0	46.0	50.0	69.0	65.0	60.0	56.0	39.0	33.0	25.0
1982	Max	43.6	53.8	63.5	67.3	82.3	81.8	86.8	84.5	78.2	72.4	61.6	56.1
	Min	20.6	29.1	35.4	37.9	50.9	55.0	59.9	56.2	49.1	40.8	36.5	34.0
1983	Max	47.9	52.5	61.5	63.9	75.0	83.5	88.7	89.8	81.5	72.4	60.0	46.6
	Min	25.7	27.5	34.2	38.4	46.1	54.7	60.3	62.5	51.5	41.9	34.4	25.3
1984	Max	44.7	56.2	58.4	66.9	74.5	86.1	84.2	86.4	80.9	76.5	58.1	57.9
	Min	21.4	27.9	32.1	41.2	46.3	60.1	60.2	61.5	48.7	49.4	28.4	31.8
1985	Max	37.6	48.4	63.0	72.7	76.1	81.2	82.7	82.3	82.2	76.2	65.9	44.5
	Min	16.1	22.0	32.2	39.5	47.7	54.9	59.9	58.3	49.3	47.8	43.4	22.2
1986	Max	46.3	51.8	62.1	74.4	78.0	86.9	90.0	85.5	81.4	72.5	61.0	50.6
	Min	18.7	30.6	32.7	43.1	50.2	61.8	64.8	57.9	56.4	45.0	40.5	26.7