INTERFACE OF FOREST AND AGRICULTURE IN NONPOINT POLLUTION CONTROL

by

John M. Fowler
Earl O. Heady
Douglas A. Christensen

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Iowa State University
578 Heady Hall
Ames, Iowa

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CHAPTER I. INTRODUCTION

Management practices of agriculture, including conservation and tillage options, recently have received a great deal of attention with respect to their impact upon the environment. Research efforts have focused both on the direct impacts of reduced on-site productivity resulting from the erosion of topsoil and on determining the indirect impacts of suspended sediment in the nation's waterways [102]. On-site damages include the loss of topsoil, lower site productivity, scarred topography, and degradation of aesthetics. Indirect downstream damages include impairment of aquatic life, increased costs of downstream water treatments, increased downstream flooding, diminished aesthetic qualities, and reduced channel, reservoir, and lake capacities [90].

Silviculture: An Additional Source

Other nonpoint sources such as the forest sector also have come to the attention of the public. The Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500) requires the administrator of the Environmental Protection Agency to develop "guidelines for identifying and evaluating the nature and extent of nonpoint sources of pollutants and processes, procedures, and methods to control pollution resulting from agriculture and silvicultural activities, including runoff from fields and crops and forest lands." [24]

Public Law 92-500 has set interim goals for control of water pollution: best practical technology was to have been achieved by 1977, and best available technology by 1983. It was emphasized that water degradation caused by non-point pollution may well emerge as the major barrier to achievement of P.L. 92-500's goal. Control of point sources of pollution is being attained but nonpoint sources are more intangible, difficult to monitor, and hard to enforce [98]. Section 208 of the 1972 federal Water Pollution Control Act Amendment cited forest land as a potential sediment source contributing to environmental deterioration [24]. Intensive silvicultural activity and road construction for site access on forest land have been designated as major contributors to excessive sediment rates [97, 1]. The forest environment was selected as an area requiring detailed research particularly for the harvest activities. Research of this nature will enable the forest industry to meet national demands for forest products and simultaneously stay within acceptable environmental standards.

The approach undertaken by managing and regulating agencies was to develop management activities that would allow the operator to extract the forest product and yet stay within acceptable environmental standards. Best Management Practices (BMPs) were conceptualized to fill this need. Conferences and seminars were conducted to determine the state of the art in forest management and to develop concrete definitions of what were the hypothetical BMPs for different spatial locations [71].

It became apparent that there was not a universal BMP or even a set of BMPs that filled the void and, furthermore, the standard or guidelines for acceptable environmental impacts were not known [71]. The general concensus was that the residuals produced must be within nature's assimulative capacity. But how quickly this goal must be attained and exactly what were the numerical magnitudes to use as standards for abatement were not as yet supported by empirical research.

Study Objectives

Water quality was recognized as a key criterion for environmental management and functions as a common element for point and nonpoint sources alike. Urban construction, crop and forage production, and wood fiber production behave as competitive uses for the existing land area and also as alternative sources of residuals production. However, the focus of this study is first on the nation's forest sector as a separate entity and second on the interface between the forest and agriculture sectors. Policy options may then be analyzed that encompass both the agriculture and forest sectors.

Construction of an interactive model requires both a macro spatial orientation and a detailed forest site information base. The forest sector must be constructed with sufficient depth to interact with complex agriculture models already constructed [38, 54, 56]. The specific objectives of this study are:

(a) To develop functional relationships between the dominant site characteristics of forested areas and the rate of suspended sediment generated; and to estimate the functional relationship between suspended sediment levels and related physical phenomena of mass erosion and fire.

(b) To integrate the results obtained from the site-specific local research on the forest sector into a comprehensive national model encompassing the equation results, forest resource base, demand levels, activity costs, and the transportation mechanism of residuals.

(c) To analyze selected environmental and resource policies that are consistent with national, river basin, or producing area objectives.

The model and analysis conducted in this effort include normative and positive orientations for the forest sector as a separate entity. The model for the forest sector is then applied in a forest-agriculture interface. The normative programming orientation is, in essence, an initial unconstrained solution of the model. This model is not restrained by historic patterns of spatial harvest location or restraints on the technology used for the harvest process. This normative approach deletes any institutional restrictions from the optimization process of economic and physical phenomena. Follow-up model solutions include current harvest techniques and spatial restrictions. Relevant policy variations are analyzed as to the sensitivity of response between the forest and agricultural sectors for both the restricted and unrestricted solutions.

CHAPTER II. THE ROLE OF THE FOREST ENVIRONMENT AS A CONTRIBUTOR TO SUSPENDED SEDIMENT

Sediment that enters the public's waterways is the end result of soil erosion [85]. Sediment from forest lands may originate from any of the following sources: surface erosion, also known as sheet and rill, mass erosion, and channel erosion [87, 96]. Surface erosion typically refers to movement of soil particulates from the overall ground surface whereas mass erosion may be in the form of mud slides or avalanches where the lower soil horizons are also displaced. Channel erosion is derived from the banks slumping into the waterway or from degradation of the channel itself. In most U.S. streams, the largest component of the total sediment load is suspended sediment [40]. Suspended sediment is material held in suspension by the water that will precipitate out when the kinetic energy of the flowing water is reduced, this differs from the dissolved solids that remain in solution or the bedload material moving along the chanel bottom. Suspended sediment accounts for greater than 80 percent of the total sediment transported [85]. Differences in sediment discharge rates from watersheds can be attributed to both differences in erosion from the actual watershed and to differences in the transport of eroded materials through the watershed drainage system. The rate of suspended sediment generated from an area represents a weighted average of the sediment discharge from all parts of the watershed including the channel itself [81].

The forest environment typically is regarded as stable with respect to soil movement. Streamflow from undisturbed forests represents a high standard of water quality [68]. Concurrent with the desire to protect the forest environment, the pressure for alternative goods from forest and multiple usage gives rise to conflicts of interest. At some level, increased goods and services from the forests must be at the expense of water quality.

Forest use is often a residual use since forests are located in adverse sites such as areas of poor drainage, shallow soils, and steep mountain terrain. These fragile environments may be drastically affected by careless management activities. Activity occurring in a small portion of a watershed may visually damage the water quality of the entire watershed [66]. Forest litter removed in the overland flow may be an additional organic pollutant. Litter and sediment are rated as the most significant pollutants from silvicultural activity [96].

Forest conditions act as a buffer zone and reduce erosion and sediment production to a minimum rate [35]. Overland flow may be considered nonexistent or negligible in forest stands that are presumed to have ideal infiltration characteristics. This is particularly true when high infiltration rates are found in conjunction with high water storage capacity in the soil and rock mass. Infiltrated water does not contribute to floods, floods are typically caused by overland flow [67].

In the South, pine stands planted on abandoned agricultural land are one of the surest ways to reduce or permanently eliminate sediment production from bare sites. But pines may require up to 10 years after planting to fully protect the site by intercepting rainfall and accumulating litter on the soil surface [25]. The soil surface is the key to minimizing erosion and suspended sediment contribution on nonchannel portions of forest watersheds [91].

Suspended sediment is the quality index most closely associated with environmental deterioration [88]. Management activities such as forest harvesting result in varying degrees of disturbance that result in alternative accelerated suspended sediment rates. Sediment may then be considered a joint product realized in the harvest process that contributes negatively to the overall well-being of society. Therefore, sediment potential should influence silvicultural decisions [78]. The selection of the optimal harvest method with which to harvest the forest product should be undertaken with sediment production as an additional argument in the decision process.

Theoretically, the harvesting operation should be forced to internalize the abatement costs of the joint suspended sediment into its production function and operating costs. This requires that the rate of suspended sediment produced from the particular undisturbed forest stand be known. This base level is needed to isolate the accelerated portion of the suspended sediment occurring after the initiation of the activity. Because sediment concentrations vary widely under undisturbed conditions, a universal undisturbed suspended sediment rate is not realistic. Isolated samples do not adequately represent watershed conditions [48]. Long-run relationships between suspended sediment and significant site characteristics must be developed before sediment concentrations can be used to evaluate the acceleration contributions resulting from alternative treatments or harvest operations for the forest sector of the United States.

CHAPTER III. LONG-RUN RELATIONSHIPS BETWEEN SITE CHARACTERISTICS AND THE UNDISTURBED RATE OF SUSPENDED SEDIMENT

Development of the relationship between specific site characteristics and the rate of suspended sediment is not a new concept. The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith [103] related gross erosion to site characteristics on agricultural land areas. Anderson has done a great deal of work in the Southwest in relating erosion to forest site conditions [6, 7, 8]. This study incorporates concepts from both of these analyses: an equation of national scope as developed by Wischmeier is used in conjunction with Anderson's work relating erosion and sediment to site specific forest conditions. The study applies the developed methodology to the estimation of instream suspended sediment loads at a national level.

Variable Selection

Detailed site specific data such as that utilized by Anderson [5, 9, 101) are not available for large areas or major river basins. To obtain the macro aspects desired by this study, independent variables that are homogenous across large areas are required. An extensive survey of the available literature revealed several site characteristics that were deemed significant by various professionals; referenced in Table 1.

The dominant site characteristics that were uniformly measured are: the size of the drainage area in acres, the erosive nature of the

Table 1. Site characteristics of natural forests by regions

Author	Date of publication	Location (county/ state)	Suspended sediment (TAY)	Drainage area (acres)	Parent material (type)	Rainfall (inches)	Snow (1,0)	Runoff (inches)	Elevation (feet)	Slope (percent)
Northeast region										
Lull + Reinhart [50]	1972	Grafton-N.H.	.050	39	Sedimentary	37	1	23	2,000	25
Lull + Sopper [51]	1967	Grafton-N.H.	.010	105	Sedimentary	37	1	23	2,000	25
USGS [18]	1971	Oxford-ME.	.090	44,480	Sedimentary	44	1	34	2,750	65
USGS [18]	1971	Burlington-N.J.	.040	1,478	Basic Igneous	44	1	13	162	10
USGS [18]	1971	Ulster-N.Y.	.030	38,080	Sedimentary	42	1	25	2,388	35
USGS [18]	1971	Franklin-Penn.	.080	29,568	Sedimentary	38	1	17	1,470	35
Central East region										
Auberton + Patric [12]	1974	Tucker-W.V.	.180	94	Sedimentary	58	0	30	2,500	30
Copley [19]	1944	Tredell-N.C.	.237	6	Acid Igneous	29	0	6	870	19
Ellertsen [30]	1968	Union-Tenn.	.030	1,715	Acid Igneous	47	0	18	782	6
Miss. Water Conf. [82]	1972	Henderson-Tenn.	.030	88	Acid Igneous	60	0	10	782	6
O'Bryan + McAvoy [57]	1966	Baltimore-MD.	.080	224,000	Acid Igneous	46	1	18	1,010	8
Patric + Reinhart [61]	1971	Tucker-W.V.	.017	96	Sedimentary	57	0	30	2,610	20
Smith + Stamey [70]	1965	Tredell-N.C.	.002	0[a]	Acid Igneous	47	0	0	870	10
USFS [84]	1957	Macon-N.C.	.070	6,100	Basic Igneous	80	0	39	2,760	50
USGS [18]	1971	Perry-Tenn.	.440	286,080	Sedimentary	52	0	22	757	35
USGS [18]	1971	Haywood-N.C.	.540	31,488	Sedimentary	49	0	30	4,290	65
Wolman + Schick [104]	1967	Allegany-MD.	.320	72	Acid Igneous	42	1	17	1,200	8
Southeast Region										
Dissmeyer [24]	1973	Berkeley-S.C.	.001	999,999	Sedimentary	45	0	8	320	8
Ursic [100]	1969	Lafayette-Miss.	.112	7	Basic Igneous	53	0	6	46	25
Ursic [100]	1969	Lafayette-Miss.	.001	3	Sedimentary	56	0	0	68	25
Ursic [100]	1969	Lafayette-Miss.	.006	4	Sedimentary	56	0	1	64	25
Ursic [100]	1969	Lafayette-Miss.	.015	3	Sedimentary	56	0	4	40	25
Ursic [100]	1969	Yalobusha-Miss.	.033	7	Sedimentary	49	0	8	43	25
Ursic [100]	1969	Yalobusha-Miss.	.049	5	Sedimentary	49	0	8	59	25
Ursic [100]	1969	Yalobusha-Miss.	.051	6	Sedimentary	49	0	7	63	25
Ursic [100]	1969	Yalobusha-Miss.	.068	4	Sedimentary	49	0	4	58	25
Ursic [100]	1969	Yalobusha-Miss.	.020	4	Sedimentary	49	0	3	62	25
USGS [18]	1971	Aiken-S.C.	.020	55,680	Sedimentary	44	0	14	365	10
USGS [18]	1971	Perry-Miss.	.090	33,408	Sedimentary	60	0	20	220	10
USGS [18]	1971	Wakulla-Fla.	.200	62,656	Sedimentary	56	0	25	80	10
USGS [18]	1971	Rabun-GA.	.006	36,160	Sedimentary	68	0	40	3,690	65
USGS [18]	1971	Winston-Ala.	3.300	58,240	Sedimentary	52	0	26	800	10

Table 1. (continued)

Author	Date of publication	Location (county/ state)	Suspended sediment (TAY)	Drainage area (acres)	Parent material (type)	Rainfall (inches)	Snow (1.0)	Runoff (inches)	Elevation (feet)	Slope (percent)
North Central region										
Smith & Stamey	1965	Muskingum-Ohio	.001	2	Acid Igneous	37	1	1	1,100	14
USGS [18]	1971	Florence-Wisc.	.010	83,840	Sedimentary	29	1	12	1,500	35
USGS [18]	1971	Pennington-S.D.	.013	53,120	Sedimentary	20	1	2	6,515	35
USGS [18]	1971	Scioto-Ohio	.470	8,192	Sedimentary	43	1	15	905	35
USGS [18]	1971	Keweenaw-Mich.	.050	8,704	Sedimentary	28	1	13	997	10
USGS [18]	1971	St. Louis-Minn.	.016	161,920	Basic Igneous	28	1	10	1,780	10
USGS [18]	1971	Winona-Minn.	.060	64,640	Sedimentary	30	1	4	1,015	10
USGS [18]	1971	Dearborn-Ind.	.450	24,448	Sedimentary	40	1	12	787	10
USGS [18]	1971	Decatur-Ia.	.600	33,600	Sedimentary	32	1	6	275	35
Verry [101]	1973	Itasca-Minn.	.010	24	Sedimentary	31	1	4	1,400	0
South Central region										
Daniel [21]	1943	Logan-Okla.	.010	6	Sedimentary	29	0	0	1,200	5
Rogerson [65]	1971	Saline-Ark.	.010	4	Sedimentary	53	0	6	1,350	15
Smith + Stamey [70]	1965	Smith-Tex.	.050	0[a]	Sedimentary	41	0	0	1,780	13
Smith + Stamey [70]	1965	Logan-Okla.	.010	0[a]	Sedimentary	31	0	0	1,200	8
USGS [18]	1971	Burnet-Tex.	.008	21,888	Sedimentary	30	0	3	1,053	10
USGS [18]	1971	Comanche-Okla.	.020	15,744	Basic Igneous	29	0	4	1,805	35
USGS [18]	1971	Leflore-Okla.	.020	25,664	Sedimentary	56	0	23	1,775	35
USGS [18]	1971	Grant-La.	.010	32,640	Basic Igneous	56	0	16	184	10
Northwest region										
ASCE [4]	1975	Boise-Id.	.001	1	Basic Igneous	32	1	5	5,005	62
Brown [15]	1972	Lincoln-Ore.	.010	750	Sedimentary	100	1	12	850	35
Brown + Krygier [16]	1971	Lincoln-Ore.	.200	500	Sedimentary	100	1	13	740	35
DeByle + Packer [22]	1973	Flathead-Mont.	.001	2,000	Basic Igneous	25	1	10	4,600	24
DeByle + Packer [22]	1973	Mineral-Mont.	.001	1,800	Acid Igneous	40	1	10	4,800	55
Fredricksen [33]	1970	Lane-Ore.	.034	237	Basic Igneous	90	1	13	2,612	63
Helvey [39]	1977	Chelan-Wash.	.030	1,171	Basic Igneous	22	1	7	4,900	50
Helvey [39]	1977	Chelan-Wash.	.005	1,395	Basic Igneous	22	1	6	4,600	50
Helvey [39]	1977	Chelan-Wash.	.004	1,267	Basic Igneous	22	1	4	4,420	50
Kidd + Megahan [42]	1972	Valley-Id.	.001	10	Basic Igneous	28	1	5	5,000	67
Megahan + Kidd [53]	1972	Valley-Id.	.040	10	Basic Igneous	28	1	5	5,000	70

Table 1. (continued)

Author	Date of publication	Location (county/ state)	Suspended sediment (TAY)	Drainage area (acres)	Parent material (type)	Rainfall (inches)	Snow (1,0)	Runoff (inches)	Elevation (feet)	Slope (percent)
USFS [84]	1973	Lane-Ore.	.021	75	Basic Igneous	90	1	13	2,612	63
USGS [18]	1971	Carbon-Wy.	.080	46,528	Basic Igneous	30	1	17	9,800	35
USGS [18]	1971	Teton-Wy.	.230	6,400	Sedimentary	30	1	19	8,552	65
USGS [18]	1971	Grays Harbor-Wash.	.090	47,424	Sedimentary	200	1	145	3,433	65
USGS [18]	1971	Wallowa-Ore.c.	.002	153,000	Acid Igneous	40	1	25	5,720	35
USGS [18]	1971	Glacier-Mont.D.	.002	20,096	Acid Igneous	80	1	64	7,500	65
USGS [18]	1971	Kootenai-Id.	.020	14,080	Basic Igneous	40	1	20	3,900	65
Southwest region										
Bailey + Copeland [13]	1960	Davis-Utah	.001	1,378	Sedimentary	47	1	12	7,500	45
Brown [17]	1974	Coconino-Ariz.	.020	275,000	Acid Igneous	25	0	5	7,400	3
Dunford [26]	1954	El Paso-Co.	.001	0	Acid Igneous	17	1	2	7,600	18
Krammes + Burns [48]	1973	Mendocino-CA.	.180	1,255	Sedimentary	48	0	12	3,400	10
Leaf [49]	1966	Jefferson-CO.	.016	667	Sedimentary	27	1	5	8,500	39
Leaf [49]	1966	Jefferson-CO.	.011	306	Sedimentary	30	1	5	8,500	36
Meeuwig [52]	1970	Davis-Utah	.010	137	Sedimentary	47	1	9	7,890	24
Meeuwig [52]l	1970	Davis-Utah.	.010	217	Sedimentary	47	1	18	7,973	20
Rich [63]	1972	Apache-Ariz.	.020	1,163	Acid Igneous	25	0	3	8,210	14
Rich [63]	1972	Apache-Ariz.	.001	900	Acid Igneous	25	0	2	8,210	13
Rich + Gottfried [64]	1976	Gila-Ariz.	.001	521	Acid Igneous	33	0	3	7,157	2
Rich + Gottfried [64]	1976	Gila-Ariz.	.020	248	Acid Igneous	33	0	3	7,157	7
Rich + Gottfried [64]	1976	Gila-Ariz.	.004	318	Acid Igneous	33	0	3	7,157	3
USGS [18]	1971	Salt Lake-Utah	.070	4,640	Sedimentary	25	1	10	6,820	65
USGS [18]	1971	Grant-N.M.	.020	44,160	Basic Igneous	13	0	4	8,144	65
USGS [18]	1971	San Miguel-N.M.	.011	34,048	Sedimentary	24	0	7	10,472	65
USGS [18]	1971	Nye-Nev.	.220	12,800	Sedimentary	20	0	3	9,094	65
USGS [18]	1971	White Pine-Nev.	.090	7,104	Sedimentary	30	0	5	9,100	55
USGS [18]	1971	Pima-Ariz.	.002	23,296	Basic Igneous	25	0	2	4,825	65
USGS [18]	1971	Mendocino-Cal.	4.600	4,160	Sedimentary	80	0	50	2,825	65
USGS [18]	1971	Mariposa-Cal.	.310	115,840	Basic Igneous	55	0	25	8,950	65
USGS [18]	1971	Lake-CO.	.020	14,720	Sedimentary	30	1	18	12,085	65
USGS [18]	1971	La Plata-Co.	.080	46,144	Sedimentary	40	1	20	10,992	65

[a] Refers to a small experimental plot usually .01 of an acre. In all cases the plot was less than .50 of an acre.

site parent material, the area rainfall measured in inches per year, the area runoff also measured in inches per year, the presence of snow events in the area, the average site elevation in feet above sea level, and the average drainage area slope in percent. Table 1 summarizes suspended sediment in tons per acre per year (TAY) for the specified sites and drainage areas. The table also lists the author or agency that contributed the information. These data are used to develop the equations for estimating the suspended sediment generated from undisturbed forest lands. Figure 1 displays the regional breakdown utilized to reduce problems of heterogeneity across forest ecotypes.

Data Measurement and Units Conversion

Examination of the relevant literature revealed that there are two basic approaches used to estimate annual suspended sediment from a drainage area. The first, primarily for a larger drainage area, is the use of instream samplers to obtain measurements of the suspended sediment concentration in parts per million (PPM). A technique to normalize the effect of abnormal years by reducing the variation in sediment yield as associated with discharge is also done by assuming the flow each year was equal to the long-term mean in volume and distribution, and utilizing a relationship between sediment concentration and daily discharge. The sediment yields that were obtained provide an indication of the average expectancy of a change associated with treatments [16, 83].

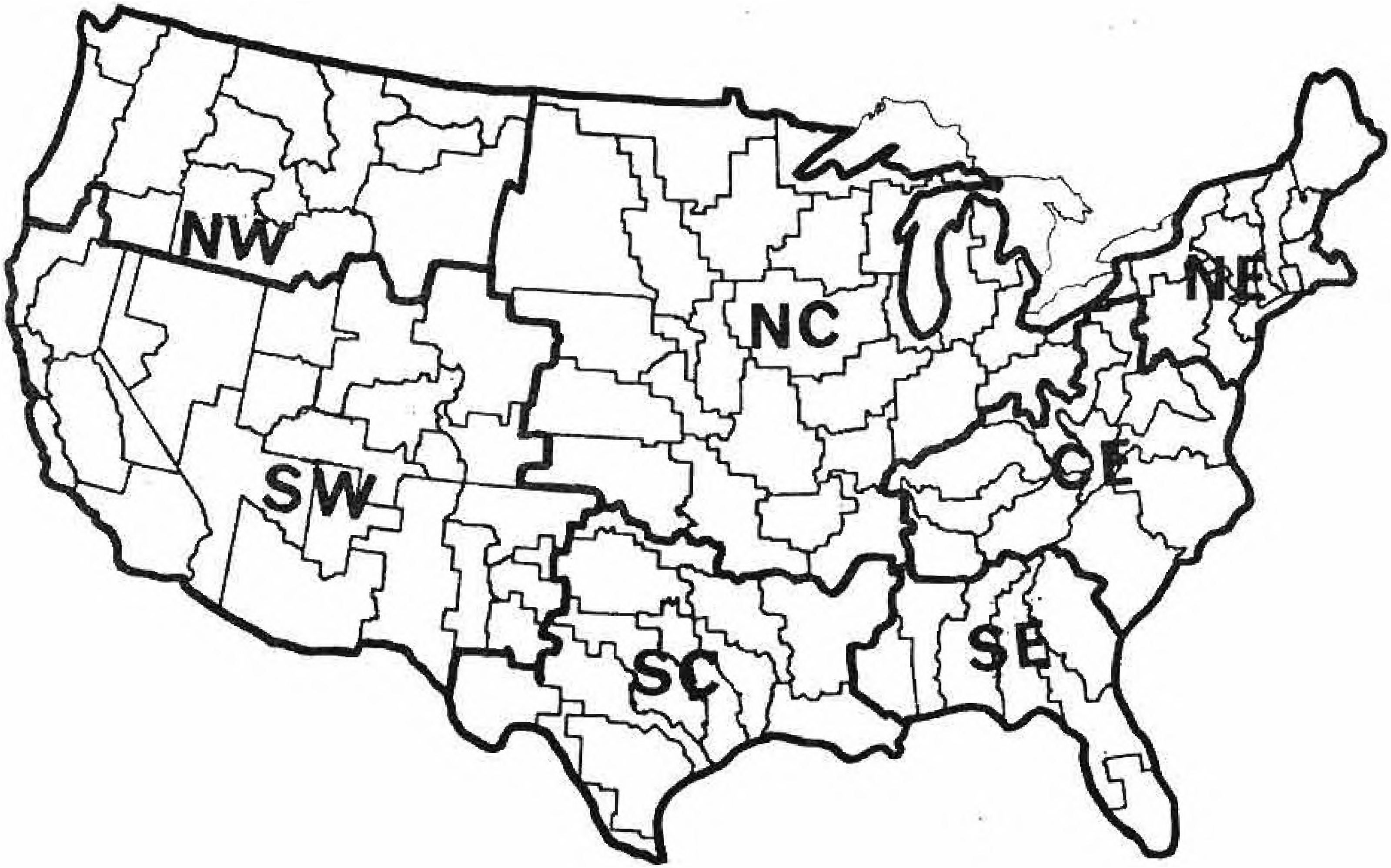

Figure 1. General regions for equation determination

The calibration process must be continued long enough to accurately reflect streamflow patterns. If climatic events are not adequately sampled, conclusions about treatment effects are likely to be erroneous. A volume measurement is typically provided in tons per unit per year. If not, the following conversion equation is used. The annual suspended sediments (SS) in tons per square miles per year equals a weighted average of the suspended sediment concentration in parts per million (PPM) times the mean annual streamflow in cubic feet per second (CFS) times a conversion factor:

$$(1) \qquad SS = PPM * cfs * .0984^{(1)}$$

The second major approach to measurement of annual sediment, used primarily to measure small drainage areas, is to capture the runoff behind weirs, sediment basins, or ponds allowing the suspended materials to settle out and then measure the volume of collected materials. This approach uses conversion standards of 65 to 90 pounds per cubic foot of collected material depending upon the composition of the sediment collected [36, 72]. The greater the organic matter content the less the weight per unit volume; corresponding to a range of 1,420 to 1,960 tons per acre foot of sediment [68]. Other conversion units used are 150 tons per acre inch for gross erosion [72] and 1.35 tons per cubic yard of material deposited [36]. Research reported in Jackson turbidity

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(1) Determined from personal correspondence with H. W. Anderson.

units were not included because there is no generally accepted method of converting turbidity data to particle matter loss [60].

The small watershed approach of measuring the accumulated particles has the drawback of including both the suspended sediment and bedload components, particulates moving on the channel bottom, of the total sediment contribution. However, in small forested watersheds the bedload component of total sediment is quite small except in special areas such as the Wisconsin driftless area [18] and the Idaho Batholith [42, 53]. The bedload component is normally derived from the channel. The assumption then is that the channel contribution in small watersheds is negligible.

Regional Delineation and Equation Development

The initial objective of this study was to develop a "universal" equation for explaining the rate of sediment production for undisturbed forest land areas. Repeated attempts resulted in the conclusion that a universal equation for the forest sector is not possible with the available set of independent variables currently measured in the field. The forest environment is too heterogenous when viewed across the United States to enable a single equation to be developed.

Regional delineations were established with various geographic breakdowns of a more homogeneous nature. Equations with suspended sediment per acre per year regressed on the various site characteristics monitored is used as the estimation procedure. The dependent variable is the suspended sediment rate (SS) in tons per acre per year (TAY) or its natural log (ln SS). The independent variables are the forest site characteristics presented in Table 1. The independent variables are estimated using classical multiple regression.[1]

The general proposition for selecting the operation equation for each region is: the simpler the equation, the greater the probability of on-the-ground usage. The general proposition was reinforced by the criteria of a high coefficient of determination, significant t-tests for included independent variables, a significant F-test indicating goodness of fit for the overall equation, and finally, the variables ease of use in field measurement.

Equation Interpretation and Application

The estimated equations and individual statistics for the regions are displayed in Table 2. The site characteristics that are significant in at least one geographic region are drainage area (DA) in acres, annual runoff (RO) in inches, mean elevation (EL) in feet, mean slope (SL) in percent, annual rainfall (RF) in inches, and the three dummy variables (X_1, X_2, X_3). The dummy variables are for the parent material on the site as categorized by the Environmental Protection Agency (EPA) into low hazard (X_1), moderate hazard (X_2), and high hazard (X_3) [96, 97].

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[1] The specification of the parameters in the regression models was conducted using the assumptions of the "classical normal linear regression model" in the framework of multiple regression as outlined by Kmenta [46]. Multicollinearity was not apparent among variables in this analysis.

Table 2. Selected suspended sediment rate equations and statistics for forestland by region

North East

$$SS = 5.759\times10^{-2} - 3.69\times10^{-3}RO - 2\times10^{-5}EL + 3.4\times10^{-3}SL \qquad R^2 = .99$$

t-values (49.2) (-32.3) (-30.09) (106.94)

Central East

$$SS = 5.796\times10^{-1} - 1.13\times10^{-2}RF + 7.9\times10^{-3}SL \qquad R^2 = .762$$

t-values (3.56) (-3.46) (4.48)

South East

$$LSS = -5.0367 - 5\times10^{-6}DA + 2.719\times10^{-1}RO - 2.87\times10^{-3}EL \qquad R^2 = .82$$

t-values (-9.52) (-4.30) (4.98) (4.38)

North Central

$$SS = -5.01389\times10^{-1} + 1.245\times10^{-2}RF + 1.099\times10^{-2}RO + 6.811\times10^{-3}SL \qquad R^2 = .92$$

t-values (-4.02) (3.00) (2.07) (3.18)

South Central

$$SS = -1.0759\times10^{-1} + 2\times10^{-6}DA + 1.25\times10^{-3}RF + 9\times10^{-5}EL - 4.74\times10^{-3}SL \qquad R^2 = .94$$

t-values (-3.02) (2.95) (2.14) (3.87) (-3.34)

North West $R^2 = .708$

$$SS = 3.247\times10^{-2} - 6.159\times10^{-2}X_1 + 9.732\times10^{-2}X_2 - 9\times10^{-4}RO + 2\times10^{-5EL} + 5.1\times10^{-4}RF$$

t-values (-.535) (-3.03) (4.49) (-1.13) (2.11) (.725)

South West

$$SS = 1.4588 - 2.137\times10^{-2}RF + 9.243\times10^{-2}RO - 1.7\times10^{-4}EL \qquad R^2 = .84$$

t-values (2.23) (-1.53) (5.42) (-3.36)

Analysis of the signs across the regions becomes difficult when it is observed that the sign of rainfall is positive as is expected and then suddenly switches to have a negative effect in another region. A possible explanation for this change is that there are ranges in the variables themselves. It has been observed that erosion reaches a maximum when the annual rainfall is between 10 and 15 inches. Below 10 inches there is not enough rainfall to move large amounts of sediment. Above 15 inches the additional vegetation at the soil surface acts as a buffering agent and reduces erosion and resultant suspended sediment. [68]

The equations developed estimate instream suspended sediment contribution, which is an important water quality index. The undisturbed rate of suspended sediment then serves as the benchmark of the particular forest watershed from which deviations resulting from an activity or treatment can be compared.

Dominant Sediment Rates

The data presented in Table 1 along with additional general sources such as river basin reports [35, 58, 80], general references [50, 68], and Environmental Protection Agency publications [96, 97] are used to develop a representative suspended sediment rate for undisturbed forest lands. The primary data reported in Table 1 are used as representative of the area and are averaged into the dominant rate of the area. In those producing areas (PAs) which do not have primary data reported but do have forest land, general estimates for the undisturbed forest areas are consolidated to function as the dominant rate of the area. This spatial orientation allows the on-the-ground manager to compare his site-specific benchmark rates developed from the regression equations to the dominant rate for his general area.

The estimated dominant suspended sediment rate per acre, the total number of forested acres, and the estimated total contribution of each producing area to the national suspended sediment loads are presented in Table 3. Figures 2 and 3 spatially display the total forested land and the estimated dominant undisturbed suspended sediment rate, respectively, for the 105 producing areas. The total suspended sediment component in public waterways is determined for each of the 18 major river basins shown in Figure 4. This is accomplished by a simple summation of the sediment loads generated in each producing area that lies within the boundary of the river basin as shown in Figure 5. This basin accounting mechanism is used for policy alternatives with upper limits to the total suspended sediment loads applied to whole river basins.

Figure 2 spatially locates the current areas of forests in the United States. It shows concentration of forest land in the general regions of the Southeast, Central East, Northwest, and Great Lakes regions. When the forest land area is simultaneously viewed with its natural suspended sediment rates for the same area, it is apparent that the Northwest and Southeast are regions which contribute heavily to the suspended sediment loads. The erosion and resultant suspended sediment

Table 3. Estimated suspended sediment rates generated annually from forest lands

Producing area	Suspended sediment (TAY)	Total forest land	Total suspended sediment	Producing area	Suspended sediment	Total forest land	Total suspended sediment
		(000 acres)	(000 tons)			(000 acres)	(000 tons)
1	.090	16,811	1,513	27	.003	1,120	3
2	.135	3,149	425	28	.013	1,904	25
3	.105	2,066	217	29	.223	5,446	1,214
4	.183	1,932	354	30	.090	6,670	600
5	.010	6,252	63	31	.122	10,102	1,232
6	.195	3,248	633	32	.240	2,961	711
7	.030	6,250	188	33	.190	6,112	1,161
8	.244	709	173	34	.054	8,024	433
9	.040	4,527	181	35	.050	3,322	166
10	.080	10,428	834	36	.083	5,971	496
11	.080	9,211	737	37	.210	10,370	2,178
12	.320	5,304	1,697	38	.030	5,632	169
13	.118	14,713	1,736	39	.010	7,637	76
14	.070	16,488	1,154	40	.220	7,913	1,741
15	.015	15,905	239	41	.025	2,117	53
16	.061	9,796	598	42	.014	1,741	24
17	.060	2,981	179	43	.057	3,789	216
18	.200	12,061	2,412	44	.052	4,525	235
19	.242	14,132	3,420	45	.030	17,470	524
20	3.300[1]	10,254	33,838	46	.025	6,348	159
21	.090	8,815	793	47	.001	6,292	6
22	.030	14,291	429	48	.017	230	4
23	.010	5,947	59	49	.002	2,081	4
24	.006	339	2	50	.024	741	18
25	.002	6,508	13	51	.046	4,576	210
26	.050	4,111	206	52	.013	2,525	33

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[1] Based on publication by U.S. Geological Survey for Winston, Alabama [18].

Table 3. (continued)

Producing area	Suspended sediment (TAY)	Total forest land	Total suspended sediment	Producing area	Suspended sediment	Total forest land	Total suspended sediment
		(000 acres)	(000 tons)			(000 acres)	(000 tons)
53	.010	205	2	81	.025	239	6
54	.030	4,587	138	82	.020	7,981	160
55	.030	838	25	83	.001	9,114	9
56	.030	77	2	84	.080	6,932	555
57	.017	524	9	85	.010	6,040	60
58	.026	156	4	86	.020	6,415	128
59	.062	387	24	87	.010	11,412	114
60	.070	5,193	364	88	.020	3,467	71
61	.087	7,763	675	89	.014	3,702	52
62	.010	3,117	31	90	.150	6,291	944
63	.010	481	5	91	.010	1,050	10
64	.015	8,302	125	92	.010	16,267	163
65	.018	2,682	48	93	.010	15,636	156
66	.018	2,728	31	94	.060	9,107	546
67	.018	0	0	95	.002	11,712	23
68	.021	1,282	27	96	.070	20,367	1,426
69	.033	9,146	302	97	.040	7,628	305
70	.050	6,686	334	98	.070	2,328	163
71	.023	5,188	119	99	2.300[2]	12,490	28,727
72	.018	109	2	100	.530	12,261	6,498
73	.019	3,060	58	101	.015	8,177	123
74	.043	0	0	102	.770	1,773	1,365
75	.020	3,550	71	103	.015	3,528	53
76	.030	2,545	76	104	.017	4,880	83
77	.051	1,958	100	105	.015	1,762	26
78	.145	10,212	1,480	U.S. Total	---	614,216	109,650
79	.063	514	32				
80	.011	1,420	16	Average	.17 tons per acre per year		

[2] Based on publication of U.S. Geological Survey for Mendocino, California [18].

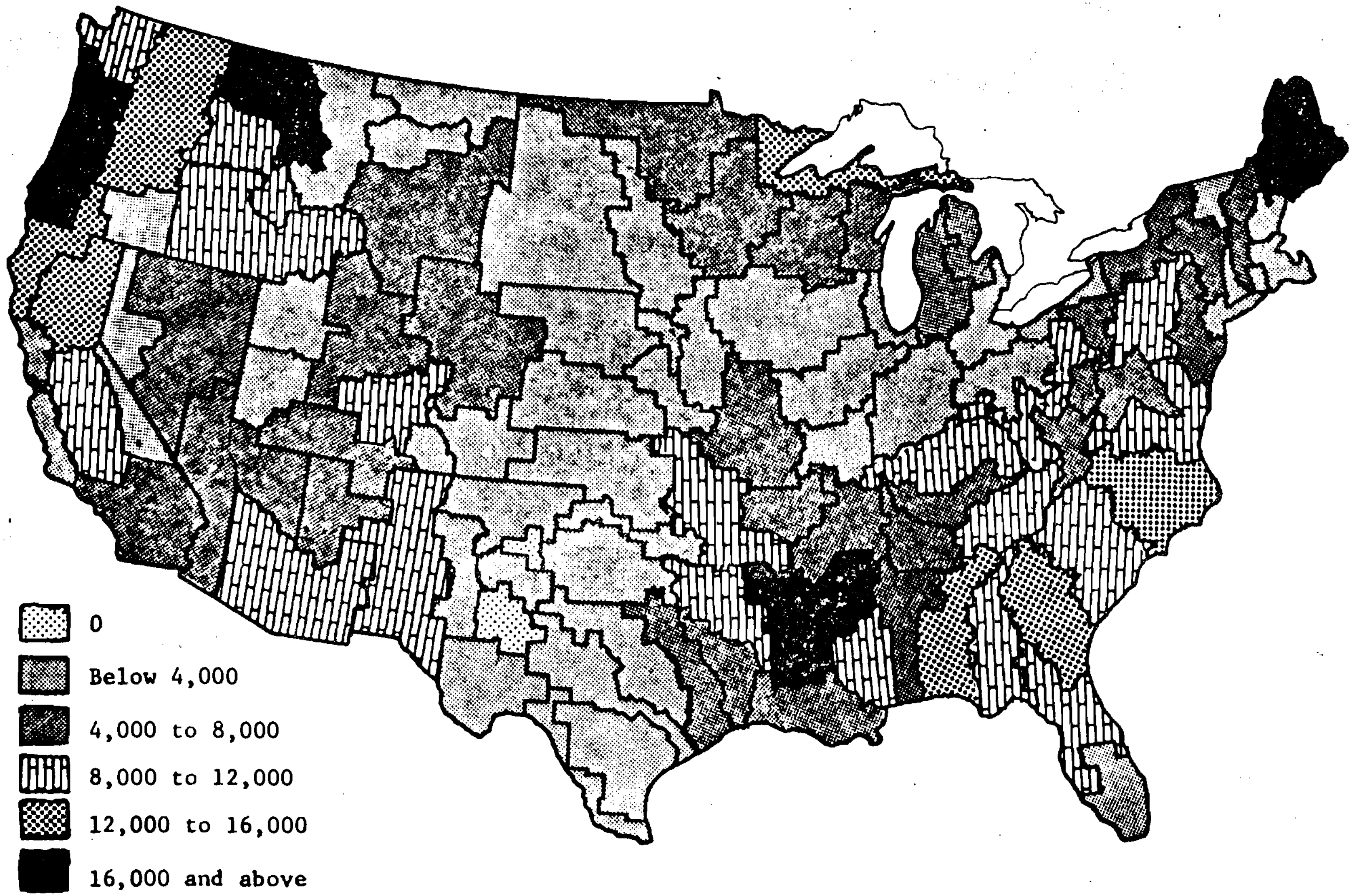


Figure 2. Total forest land acreages by producing area (in thousand acres)

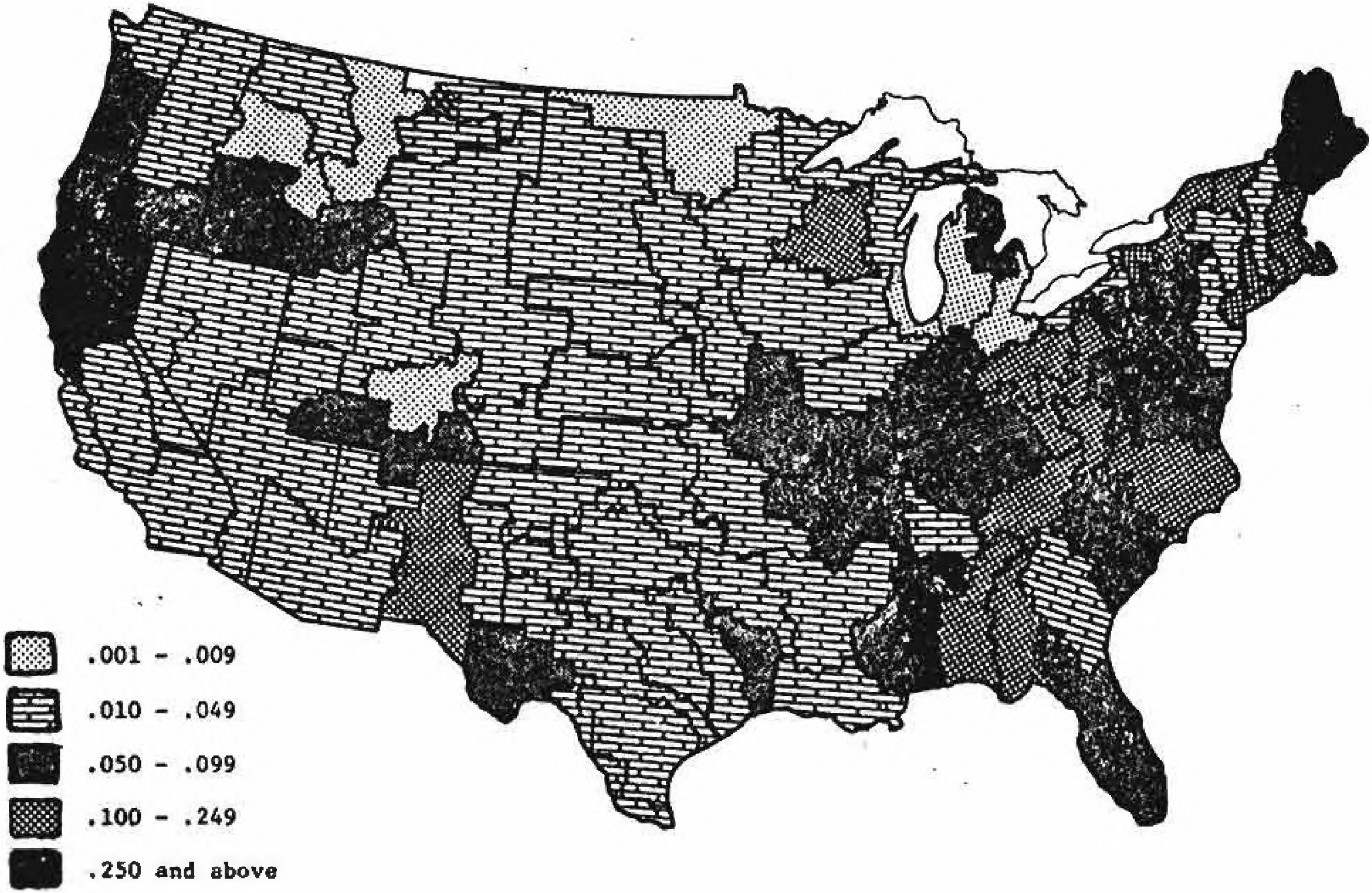
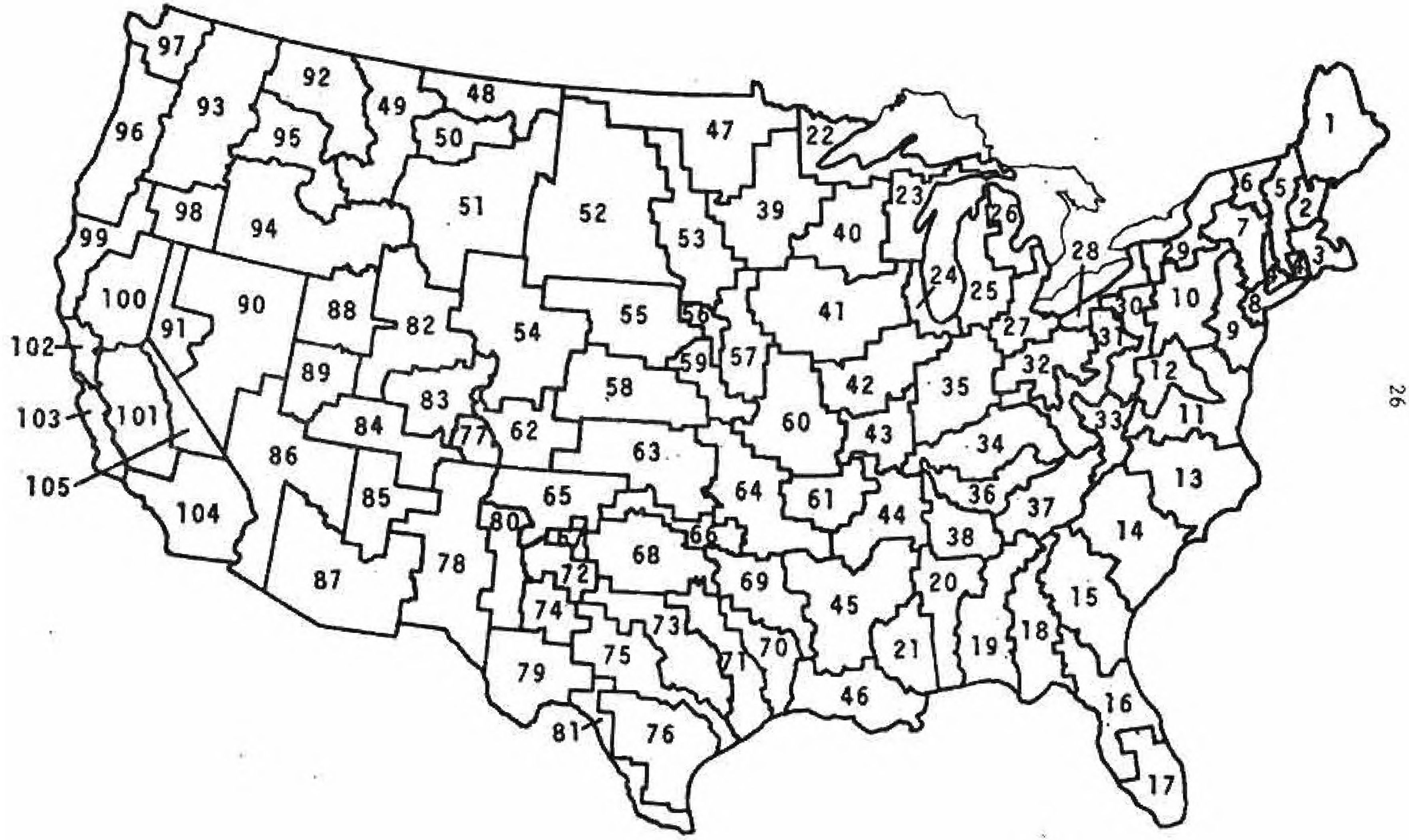


Figure 3. Dominant undisturbed forest sediment rate generated annually for each producing area (in TAY).

Figure 4. River basins with county boundaries



·Figure 5. River basins with enclosed producing areas does not include the mass erosion component that occurs naturally and is documented as a major source of sediment in the Pacific Northwest [33, 76].

Research is needed on the impacts of harvest practices, particularly in inherently unstable areas, to understand the much higher suspended sediment production rates that occur as a result of site disturbance from management activities. Locating the Pacific Northwest and Southeast (Table 3) as particular problem areas even in an undisturbed condition accentuates the need for quick development of relevant Best Management Practices (BMP's) for the area, rapid implementation of the practices, and strict enforcement. These three steps are all needed if the suspended sediment production is to be reduced toward the undisturbed rates.

CHAPTER IV. FIRE AND ITS INFLUENCE ON SUSPENDED SEDIMENT

The purpose of this chapter is to estimate the component of suspended sediment that originates from burned forest land to determine the magnitude of fire's impact upon the physical environment. The U.S. Forest Service fire statistics [93] are used as the basic source of data for the spatial location of burned acreages and also for the distinction between man-caused fires and those occurring naturally (Table 4). The results are for 1976 as well as the acres burned during the year of the states' forest and range resource survey. This corresponds to the year of the land base inventory.

The literature indicates that only severe fires cause drastically accelerated sediment production [44, 99]. Prescribed burns are conducted under carefully controlled moisture and fuel conditions to minimize the danger of out-of-control fires. Wildfire, on the other hand, usually occurs when the forests are dry during the summer and fall seasons, conditions which are optimal for fires severe enough to destroy the stabilizing influence of forest covers.

Burning can drastically decrease the proportion of ground surface protected by plants, litter, and logging residues. The protective influence can be reduced to less than 50 percent of prefire conditions [59]. The loss of vegetation increases the detachment of soil particulates by raindrop splash [95]. On the other hand, heat from a ground fire can kill the lower foliage of the forest canopy, which upon falling, can provide a protective litter reducing the impact of rainfall.

Table 4. Forest and range area and acreage burned for conterminous United States[1]

	(1976)						
States	Forest and range area	Forest and range area burned naturally	Forest and range area burned man-caused	Year of inventory	Forest area (year of inventory)	Forest area burned naturally	Forest area burned man-caused
	(000 acres)	(acres)	(acres)		(000 acres)	(acres)	(acres)
Alabama	25,723	692	151,950	1972	21,355	652	69,081
Arizona	64,651	20,444	15,636	1971	18,584	24,318	10,309
Arkansas	23,375	648	87,751	1969	18,283	810	105,691
California	72,893	7,003	211,116	1970	41,913	6,727	296,748
Colorado	33,551	7,126	2,746	1970	22,522	266	6,181
Connecticut	2,390	0	3,031	1972	1,859	0	1,231
Delaware	557	0	325	1972	392	0	55
Florida	28,316	10,849	143,914	1970	17,938	48,275	500,739
Georgia	28,589	939	59,777	1972	25,261	1,389	27,373
Idaho	45,829	15,601	167,361	1970	21,608	11,360	14,255
Illinois	8,709	0	6,651	1962	3,874	0	5,345
Indiana	7,517	0	7,112	1967	3,966	0	10,575
Iowa	7,616	0	32,770	1974	1,569	0	195
Kansas	19,952	29,766	192,260	1965	1,344	34	36,883
Kentucky	17,603	81	124,650	1963	11,865	0	31,186
Louisiana	21,790	128	87,616	1974	14,569	579	36,086
Maine	17,863	115	6,265	1971	17,749	91	692
Maryland	3,719	0	3,599	1964	2,965	16	1,048
Massachusetts	3,638	1	9,714	1972	2,953	7	2,684
Michigan	23,042	74,285	8,400	1966	19,384	42	2,791
Minnesota	26,937	4,251	152,700	1962	19,048	185	60,338
Mississippi	21,287	155	113,796	1967	16,915	4	68,607
Missouri	25,339	266	99,574	1972	12,926	581	55,770
Montana	85,741	5,356	6,051	1970	15,132	7,374	4,479

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[1] U.S. Department of Agriculture, Wildfire Statistics [89].

Table 4. (Continued)

	(1976)						
States	Forest and range area	Forest and range area burned naturally	Forest and range area burned man-caused	Year of inventory	Forest area (year of inventory)	Forest area burned naturally	Forest area burned man-caused
	(000 acres)	(acres)	(acres)		(000 acres)	(acres)	(acres)
Nebraska	27,914	5,251	19,146	1970	1,326	604	5,705
Nevada	67,544	7,632	4,568	1970	7,941	188	1,003
New Hampshire	5,315	5	325	1973	4,985	0	405
New Jersey	2,780	251	13,869	1972	1,930	0	1,426
New Mexico	69,987	5,268	29,849	1970	18,462	1,447	6,137
New York	20,767	7	21,339	1968	17,172	42	15,509
North Carolina	22,876	6,895	83,120	1974	20,029	198	31,219
North Dakota	4,461	351	8,229	1970	780	23	741
Ohio	10,609	0	2,287	1968	6,401	11	7,325
Oklahoma	28,416	916	292,020	1966	9,135	53	294,119
Oregon	55,791	828	8,981	1973	29,980	73,766	10,796
Pennsylvania	20,085	22	14,918	1965	17,075	338	4,952
Rhode Island	512	0	1,405	1972	405	0	566
South Carolina	14,062	94	84,004	1968	12,498	430	111,536
South Dakota	40,024	2,484	17,495	1974	1,699	1,396	2,677
Tennessee	13,534	160	64,191	1971	13,142	1,583	38,764
Texas	26,620	36,837	2,202,200	1965	23,669	406	97,490
Utah	48,718	18,094	51,392	1970	15,288	212	2,380
Vermont	4,900	0	1,134	1968	4,323	1	713
Virginia	20,517	549	14,867	1966	16,303	94	141,314
Washington	26,768	133	37,855	1973	22,892	301	13,317
West Virginia	13,794	2,043	86,324	1961	11,472	176	41,081
Wisconsin	20,800	96	30,015	1968	14,951	42	16,699
Wyoming	59,839	10,279	11,535	1970	8,374	1,006	3,310

Another aspect of vegetation removal is that the evapotranspiration rate from the site is reduced [45]. This increases the water supply available for runoff and the probability of a mass erosion event. One of fire's most evident impacts is on the organic matter of the soil mantle. Removal of the organic matter may adversely affect the structural stability of the burned areas [2, 4, 59].

Regression equations were used to estimate accelerated rates of sediment production resulting from a fire event. The first year suspended sediment contribution after fire, measured in tons per acre, is regressed as a linear function of the natural rate for the forest site. The data used for the regression are presented in Table 5. Analysis of the results indicate that a universal equation regressing the first year suspended sediment contribution on the natural rate for the area is the most plausible method. The natural rate of suspended sediment has the area's site characteristics embodied in it. The fire equation developed in this study and the relevant statistics are as follows:

$$FST = .64 + 3.53NR \qquad F\text{-ratio} = 107$$

$$(2) \quad \alpha_1 = (.002) \quad \alpha_1 = (.0001) \qquad R^2 = .79$$

where FST is the first year suspended sediment levels after fire measured in tons per acre per year (TAY), NR is the undisturbed suspended sediment rate before the fire measured in tons per acre per year, and α_1, α_2 = alpha levels of significance for each variable's t-test. The

Table 5. The impact of fire on suspended sediment rates

Author	Region	Natural rate TAY	Rate first year after fire TAY
Copley [19]	C.E.	.002	3.08
McGinnis [90]	S.E.	.025	.33
Ursic [99]	S.E.	.150	.59
Daniel [21]	S.C.	.010	.11
Ferguson [90]	S.C.	.100	.21
Pope [90]	S.C.	.050	.36
Barnard [90]	S.W.	.080	95.66
Rice [62]	S.W.	2.300	60.32
Striffler [73]	S.W.	.030	37.50
Rich [63]	S.W.	.010	29.08
Henrick & Johnston [1]	S.W.	.080	98.50
Rowe [28]	S.W.	.000	4.00
USDA [89]	S.W.	.026	19.64
Brown & Krygier [16]	S.W.	.178	.89
Krammes [47]	S.W.	.056	.73
Corbett & Rice [20]	S.W.	.056	.28
Rich & Gottfried [64]	S.W.	.005	.61
Willis & Anderson [3]	S.W.	1.480	7.40
USDA [81]	S.W.	2.550	8.43
		2.550	26.78
Krammes [47]	S.W.	.260	4.31
		.340	3.12
Anderson [8]	N.W.	.233	1.32
Mersereau [55]	N.W.	.070	3.04
Packer & William [59]	N.W.	.001	.10
Frederiksen [33]	N.W.	.013	.87
DeByle [22]	N.W.	.002	.03
ASCE [3]	N.W.	.280	1.39
ASCE [3]	N.W.	.360	2.55
Helvey & Klock [37]	N.W.	.030	.81
		.005	.12
		.004	.05
Mersereau & Dryness [55]	N.W.	.070	1.47
Brown & Krygier [16]	N.W.	.232	1.93
		.258	1.62
Frederiksen [33]	N.W.	.019	.27
Frederiksen [33]	N.W.	.023	.13
		.023	1.18
Frederiksen & Rothacker [23]	N.W.	.020	1.06

regression coefficient indicates that the first year impact of fire is positively related to the natural rate for the area.

Table 6 indicates the producing areas where the fire events are located, based upon U.S. Forest Service statistics [93]. An estimated five million tons of suspended sediment are generated from this influence alone. This quantity is probably underestimated because it does not account for the additional, although much smaller, marginal contributions that continue beyond the first year's accelerated rate.

Table 6. Exogenous accelerated suspended sediment generated from a fire event for the average acre burned in each PA each year measured in tons per year (TAY)

Producing area	Fire rate (TAY)	Average acres burned per year	Accelerated suspended sediment (TAY)	Producing area	Fire rate (TAY)	Average acres burned per year	Accelerated suspended sediment (TAY)
1	.95770	6,042	5,786	27	.65059	3,114	2,026
2	1.11655	484	540	28	.68589	1,807	1,239
3	1.01065	6,869	6,942	29	1.42719	6,769	9,661
4	1.28599	2,897	5,012	30	.95770	18,768	17,974
5	.67530	4,161	2,810	31	1.07066	51,009	54,613
6	1.32835	2,375	3,115	32	1.48720	1,219	1,813
7	.74590	7,407	5,525	33	1.31070	36,978	48,467
8	1.50132	3,359	5,043	34	.83062	73,740	61,250
9	.78120	14,181	11,078	35	.81650	5,907	4,823
10	.92240	9,782	9,023	36	.93299	44,777	41,776
11	.92240	9,082	8,377	37	1.38130	42,316	58,451
12	1.86969	15,811	27,979	38	.74590	33,506	24,992
13	1.05654	52,953	55,947	39	.67530	57,084	38,549
14	.88710	98,200	87,113	40	1.41660	19,473	27,585
15	.69295	48,980	34,634	41	.72825	28,554	20,794
16	.85533	72,685	62,170	42	.68942	6,332	4,365
17	.85180	25,719	21,907	43	.84121	21,865	18,393
18	1.34600	58,538	78,792	44	.82356	26,561	21,875
19	1.49426	95,117	142,130	45	.74590	101,726	75,877
20	12.28900	72,559	891,678	46	.72825	38,460	28,008
21	.95770	59,170	56,667	47	.64353	53,313	34,309
22	.74590	79,582	59,360	48	.70001	173	121
23	.67530	17,219	11,628	49	.64706	1,569	1,015
24	.66118	634	419	50	.72472	559	405
25	.64706	27,415	17,740	51	.80238	9,231	7,407
26	.81650	17,536	14,318	52	.68589	22,810	15,645

Table 6. (continued)

Producing area	Fire rate (TAY)	Average acres burned per year	Accelerated suspended sediment (TAY)	Producing area	Fire rate (TAY)	Average acres burned per year	Accelerated suspended sediment (TAY)
53	.67530	2,820	1,904	81	.72825	22,613	16,468
54	.74590	6,052	4,514	82	.71060	19,000	13,501
55	.74590	15,418	11,500	83	.64353	5,890	3,790
56	.74590	1,417	1,057	84	.92240	21,081	19,445
57	.70001	20,874	14,612	85	.67530	11,696	7,898
58	.73178	16,191	11,848	86	.71060	14,214	10,100
59	.85886	46,195	39,674	87	.67530	22,032	14,878
60	.88710	79,893	70,873	88	.71060	17,287	12,284
61	.94711	47,614	45,096	89	.68942	16,826	11,600
62	.67530	1,366	922	90	.16950	9,665	1,638
63	.67530	25,748	17,388	91	.67530	1,613	1,089
64	.69295	165,552	114,719	92	.67530	47,522	32,092
65	.70354	5,787	4,071	93	.67530	16,888	11,404
66	.70354	40,280	28,339	94	.85180	63,471	54,065
67	.70354	30	0	95	.64706	83,932	54,309
68	.71413	51,132	36,515	96	.88710	13,353	11,845
69	.75649	307,144	232,351	97	.78120	12,658	9,888
70	.81650	556,931	454,734	98	.88710	762	676
71	.72119	490,857	354,001	99	8.75900	50,573	442,969
72	.70354	7,902	5,559	100	2.51090	63,807	160,213
73	.70707	289,518	204,709	101	.69295	42,554	29,488
74	.79179	0	0	102	.35810	9,227	3,304
75	.71060	335,879	238,676	103	.69295	18,360	12,723
76	.74590	240,792	179,607	104	.70001	25,396	17,777
77	.82003	858	704	105	.69295	9,170	6,354
78	1.15185	19,424	22,374				
79	.86239	48,632	41,940	Total			5,346,528
80	.67883	2,701	1,834				

CHAPTER V. MASS EROSION AND ITS CONTRIBUTION TO SUSPENDED SEDIMENT

Mass erosion, in general, involves a simultaneous movement of large quantities of soil and water often initiated by a rain event which acts as a lubricant for the gravitational forces. There are several alternative forms of mass erosion such as dry ravel [4], soil creep [4, 75] and soil slip [20], landslide [5], debris flow [77], and debris movement [32, 77]. Information obtained about these alternative forms is aggregated into a single category referred to as mass erosion events.

Regression analyses were conducted to estimate the cause of variation for the volume of suspended sediment resulting from a mass erosion event. Aggregation is necessary because of the deficiency of recorded information about specific mass events and the difficulty of accurately monitoring the erosion and resulting suspended sediment. The random spatial and temporal unpredictability of a mass event requires that the site be previously monitored before quantitative measurements of actual occurrence and magnitudes become available. Another manner by which the magnitude of impact can be estimated is expost, here a volume estimate of material displaced is determined. This, of course, is a gross on-site erosion estimate and does not reflect the magnitude entering the stream.

Table 7 displays the number of events, the rate of disturbance per unit area, and the annual gross volume of earth moved for a typical location in the Northwest. It also differentiates among the alternative land uses ranging from low intensity natural forest up to severe intensity road construction.

Table 7. Frequency and extent of occurrence of mass erosion events[a]

Land use	Number of events	Number/square mile	Total tons	Tons/Event
Natural forest	32	3.0	40,972	1,280
Harvest areas	36	12.0	37,004	1,028
Road sites	71	122.0	75,079	1,057

[a] SOURCE: Swanson and Dyrness [74].

Development of Sediment Contribution

Building a separate sediment sector requires information on the spatial location of an activity and also the magnitude of the impact. The forest sector was previously incorporated by Wade and Heady [102] in an exogenous manner in an agricultural model. The number of forest acres times the contribution per acres was used as the forest contribution.

The forest model developed in this study also incorporates the naturally occurring mass erosion component in an exogenous manner. The location of mass erosion events is bounded into the final solution for the producing areas of known occurrence. The producing area's proportion in these landslide areas is the basis for the weighting scheme. The average number of events that occur naturally on a forest site are summarized in Table 8 for susceptible PA's.

Table 8. Mass erosion events occurring naturally and after harvest

Producing area	Author	Natural rate of occurrence	After harvest rate of occurrence
		(number of events per acre)	
92	USDA-ARS [83]	.4	220
93	Swanson & Dyrness [74]	3.9	134
95	USDA-ARS [83]	.4	220
96	Amer. Forest Institute [1]	.6	203
97	Swanston & Swanson [79]	5.4	68

A major assumption is needed to bridge the gap between the number of events per acre and the possible number of acres susceptible to mass erosion. The number of events for each producing area is not the necessary unit for linking with the contribution per acre of a mass erosion site. In effect, it is assumed that on the average, across all possible forms of mass erosion, the area of disturbance is one acre. This assumption, in conjunction with susceptible land area and events per acre, permitted the derivation of a single figure for the acres of mass erosion occurring annually. The acres of occurrence for the relevant PAs are presented in Table 9.

Mass Erosion Equation

Once the spatial location is established, the primary estimation problem is the magnitude of contribution per acre. When equations are

Table 9. Average acres of exogenous mass erosion activity occurring annually in each PA

Producing area	Acres/year	Producing area	Acres/year
10	6,518	78	2,127
12	1,658	99	7,806
30	4,169	102	1,108
31	6,314	103	2,205
61	4,852	104	1,107
77	1,224		

estimated with suspended sediment from mass erosion events regressed upon the natural rates, the results are quite poor.

A reevaluation of the available data sources provides another possible approach to equation estimation. It is observed that several activities or occurrences are present during the mass erosion measurement. These occurrences are classified into six additional binary variables: undisturbed forest conditions, rain after a snow event during measurement period, roads constructed in the area, recent burning of the site, and harvesting activity on the site. These variables are included as binary variables in that if they did occur a one was placed in the matrix and, if not, a zero. This implies that the effect is upon the intercept, i.e., shifting up and down, and proves to be an effective means for accounting for a larger component of variability.

Table 10 depicts the binary variable arrangement in addition to the natural rates for each published result. The estimated equation that performed best under the criteria of R^2, t-test, and the overall F-test was as follows:

$$\begin{array}{lllllll} \text{Ln ASSR} = & 2.148 & - .81NF & + 2.29RS & + .58RD & - 1.45HVST & + .82NR \\ (3) & (.0001) & (.2589) & (.0002) & (.2680) & (.0146) & (.0001) \end{array}$$

$$R^2 = .63$$

$$\text{F-Ratio} = 10.89$$

where ln ASSR is the natural logarithm of the accelerated suspended sediment rate after a mass erosion event, NF is the undisturbed natural forest conditions present, RS is a rain after snow event, RD is road construction in the mass event area, HVST is harvest activity at the mass erosion site, and NR is the natural undisturbed rate of suspended sediment for the area.

The most significant binary variable is the rain after snow event. The implication is that the initiation of silvicultural activity should not be undertaken when the probability of a rain after snow event is high. This is consistent with a sound land management viewpoint of prohibiting access of the forest during the spring runoff season. The negative sign of the harvest variable is consistent with experimental results that indicate that it is not the actual felling of trees that causes the accelerated sediment rates, but rather the disturbance associated with site access.

Table 10. Binary variable approach to regression equation estimation for mass erosion events

Source	Region	Accelerated rate	Natural forest	Rain on snow	Roads	Burns	Harvest	Natural rate
		TAY						TAY
Anderson [7]	NW	12.50	1	1	1	1	1	.115
Anderson & Company [10]	SW	3.50	1	0	0	0	0	2.510
Anderson & Company [10]	SW	.72	1	0	0	0	0	.200
ASCE [4]	SW	15.08	0	0	0	1	0	1.160
Brown [14]	NW	56.25	0	1	1	1	1	.115
Fredriksen [33]	NW	3.24	0	0	1	1	1	.325
Fredriksen [33]	NW	.73	0	0	1	0	1	.360
Kidd & Megahan [42]	NW	6.74	0	1	1	0	0	.016
Kidd & Megahan [42]	NW	29.08	0	1	1	0	0	.040
Kidd & Megahan [42]	NW	.15	0	0	0	1	0	.030
Kidd & Megahan [42]	NW	.42	0	1	1	1	1	.005
Krammes [47]	SW	10.20	0	0	0	1	0	2.700
Krammes [47]	SW	28.95	0	0	0	1	0	1.650
Krammes [47]	SW	24.19	0	0	0	1	0	2.880
Krammes [47]	SW	24.67	0	0	0	1	0	2.690
Krammes [47]	SW	4.84	0	0	0	1	0	.260
Krammes [47]	SW	3.78	0	0	0	1	0	.260
Krammes [47]	SW	2.17	0	0	0	1	0	.550
Krammes [47]	SW	4.08	0	0	0	1	0	.260
Krammes & Burns [48]	SW	1.11	0	0	1	0	0	.414
Megahan & Kidd [55]	NW	22.00	0	1	1	0	0	.040
Swanson & Dyrness [74]	NW	.31	1	1	0	0	0	.115
Swanson & Dyrness [74]	NW	.87	0	1	0	0	1	.115
Swanson & Dyrness [74]	NW	9.30	0	1	1	0	0	.115
Swanson & Dyrness [74]	NW	.87	0	0	0	0	1	.310
Swanson & Dyrness [74]	NW	9.30	0	0	1	0	0	.310
Swanson & Dyrness [74]	NW	2.51	0	0	1	0	0	.100
Swanson & James [75]	NW	.27	0	1	1	0	0	.016
Swanson & James [75]	NW	.85	0	1	0	0	1	.016

Table 10. (Continued)

Source	Region	Accelerated rate	Natural forest	Rain on snow	Roads	Burns	Harvest	Natural rate
		TAY						TAY
Swanston & Swanson [79]	NW	11.34	1	0	1	0	0	.068
Swanston & Swanson [79]	NW	.11	0	0	0	0	1	.043
Swanston & Swanson [79]	NW	14.92	0	0	1	0	0	.043
Swanston & Swanson [79]	NW	.07	0	0	0	0	1	.005
USDA [81]	NW	23.00	0	1	1	0	0	.115
USDA [89]	NW	6.36	0	1	1	0	0	.012
USDA [86]	SW	12.90	0	1	0	0	1	.026
USDA [86]	SW	29.08	0	1	0	1	0	.026

Modeling Orientation

The approach taken in handling mass erosion is that the portion of total mass erosion events that occur naturally in each producing area is incorporated into the model solution exogenously. The area of occurrence and the contribution per acre generated from the estimated equation is produced regardless of man's management options. This orientation was accomplished by a lower bound of acres (Table 9) for each producing area where mass erosion is known to be active.

The accelerated mass erosion component is developed based upon the method of harvesting, the amount of roads required for each harvest method, the surface disturbance of the roads, and the sediment resulting primarily from the roads of each harvest method. By relating the harvest method to the amount of required roads and, therefore, to the resulting sedimentation, the mass erosion component enters endogenously via harvest method selection. Table 7 displays the number of mass erosion events that occur per square mile in natural forest conditions as well as events after logging for those PAs that are modeled endogenously. The events per square mile column does not adequately reflect the disturbance characteristics of the individual harvest method. Tractor harvesting uses more road access and, therefore, constitutes greater surface disturbance resulting in a higher propensity for mass erosion events than does any of the other harvest methods.

A breakdown in the aggregate category of the logging mass erosion is included in Table 11 for those producing areas where mass erosion is a major contributor to overall suspended sediment. The portion of the area, in conjunction with the contribution per acre for the mass erosion event, is then an endogenously controllable component of the interactive model.

When a harvest method is entered into the solution, it contributes not only to suspended sediment from the surface source but also contributes suspended sediment from a mass erosion source. This relationship allows the model to select the appropriate harvest method.

Table 11. Proportion of the harvested area that also experiences a mass erosion activity by producing area (events per acre)

PA	Natural rate	Harvest rate				
		Tractor	High lead	Skyline	Balloon	Helicopter
92	6.25×10^{-4}	1.15×10^{-1}	9.60×10^{-2}	5.66×10^{-2}	5.20×10^{-2}	2.40×10^{-2}
93	6.09×10^{-3}	7.01×10^{-2}	5.95×10^{-2}	3.45×10^{-2}	3.17×10^{-2}	1.46×10^{-2}
95	6.25×10^{-4}	1.15×10^{-1}	9.60×10^{-2}	5.66×10^{-2}	5.20×10^{-2}	2.40×10^{-2}
96	9.38×10^{-4}	1.06×10^{-1}	8.86×10^{-2}	5.22×10^{-2}	4.80×10^{-2}	2.22×10^{-2}
97	8.44×10^{-3}	3.56×10^{-2}	2.97×10^{-2}	1.75×10^{-2}	1.61×10^{-2}	7.42×10^{-3}

CHAPTER VI. THE TIMBER HARVEST SECTOR AND ENVIRONMENTAL IMPACTS

Technological developments such as skyline, helicopter, and balloon logging create less site disturbance than the more conventional methods of harvest such as tractor and high lead logging. Logging operations cause surface disturbance ranging from removal of the protective organic litter to complete removal of topsoil. Amounts of erosion and stream sedimentation following logging may vary directly with the degree of disturbance caused by timber removal [29]. When timber is removed from marginally stable slopes, a temporary acceleration of erosion activity is likely to result.

Oregon studies have shown that a logged watershed yields an 80 percent greater sediment discharge than an uncut watershed [83]. In Colorado, sediment yields from logged watersheds were relatively high during years immediately following harvest treatment [49]. However, under some conditions logging may have no measurable effect on erosion rates. Clear-cutting an oak-hickory forest in the Rose Lake watershed in northern Michigan resulted in no reduction in infiltration rates. Consequently, surface runoff and erosion did not increase [86]. In Colorado sediment production remained less than .1 ton per acre per year following careful harvesting. However, in most cases, logging does have a significant accelerating effect on the undisturbed suspended sediment at least for a few years after harvest.

Descriptions of Alternative Harvest Methods Analyzed

Tractor

Tractor skidding is done with either four-wheeled or crawler tractors. A winch is used to snake logs to the tractor before skidding them to the yarding area. Two improvements are often used to minimize scarification of the site: skid pan and a high-wheeled arch yarder. Tractor skidding is the most common method used in the Northeast and South, and on lands with less than 30 percent slope in the Intermountain, Northwestern, and California regions. Even on level to rolling land, however, tractors can expose more bare soil than other methods of log transport [96].

Skyline

This method employs a cable to carry the full weight of the logs as they are transported. Aerial cables are attached to the towers which are constructed at opposite ends of the logging sites, and logs are mechanically lifted off the ground and moved along the cable to the yarding area. Since a large volume of timber is required to justify this type of setup, the method is used principally on clear-cut logging operations.

Balloon

This method employs a large balloon usually filled with helium and capable of static lifts of 5-10 tons. A cable system similar to high lead is used to control the horizontal movement of the balloon over the logging site. Balloon logging, adapted to steep slopes, causes soil disturbance and erosion only at the yarding areas where the logs are loaded onto trucks [96].

Helicopter

Logs are lifted from the ground at the point of felling and transported to the yarding area [96]. Logging by helicopter requires fewer access roads and, therefore, probably results in minimized sediment pollution of streams. Helicopter logging is the most versatile and expensive system of moving logs from where they are cut to a yarding area for truck loading and hauling [97].

Equation Development for Harvest Options

For purposes of the analysis, equations to explain the relationship between the alternative harvest methods and the accelerated suspended sediment rates were needed. The equations were developed from published literature summarized elsewhere [30]. As in the relationship with fire and its impact on the rate of suspended sediment, harvest operations impacts were the most important in the first year after implementation.

To attain the initial objective of developing the relationship between harvest methods and their impacts upon suspended sediment production, primary data reported on harvest operation in all parts of the country were assembled [31]. Regression analysis was used to determine the relationship of the accelerated suspended sediment rates (ASR) to the known natural rate of suspended sediment of the specific harvested area and to the percentage of soil disturbance. Only one dependent variable was used. The first year accelerated suspended sediment rate was regressed upon the natural rate of the area, which, of course, has all of the relevent physical site characteristics incorporated into it. The dependent variables were the accelerated sediment rate (ASR) measured in tons per acre per year or its natural logarithm (LnASR) and the independent variable was the natural sediment rate (NSR) or its natural logarithm (LnNSR).

The estimated equations and relevant statistics for the skyline, high lead, and tractor methods are in Table 12. The simple equations all have positive signs on the independent variable and the coefficients are greater than one as expected. It is apparent from the equations that the high lead method has a greater positive coefficient, implying a more severe impact than skyline logging. This corresponds to the degree of disturbance associated with each method. The tractor logging method's total impact could be larger or smaller than either the high lead or the skyline because the total impact is composed of two parts: the effect of the intercept and the coefficient and independent variable interaction. The tractor equation has the only positive intercept of the equations presented; the magnitude of its total impact is dependent on the size of the NSR for the site. If the NSR is relatively large for the site, then both skyline and high lead logging have the potential for producing greater accelerated sediment rates than the tractor logging method. The order of magnitude for the natural sediment is typically quite low for the forested environment.

Table 12. Selected accelerated sediment rate equations and statistics by harvest method

Skyline

$$\mathrm{ASR} = -3.364 \times 10^{-2} + 1.200 \times 10^{1}\ \mathrm{NSR} \qquad R^2 = .856$$

t-values (-.78) (4.23)

High lead

$$\mathrm{ASR} = -4.390 \times 10^{-2} + 4.431 \times 10^{1}\ \mathrm{NSR} \qquad R^2 = .880$$

t-values (-1.18) (8.99)

Tractor

$$\mathrm{ASR} = 3.592 \times 10^{-2} + 1.531 \times 10^{1}\ \mathrm{NSR} \qquad R^2 = .917$$

t-values (.54) (12.46)

Balloon[2]

$$\mathrm{ASR} = 2.128 \times 10^{-1} \times \text{Tractor ASR}$$

Helicopter[a]

$$\mathrm{ASR} = 2.482 \times 10^{-2} \times \text{Tractor ASR}$$

[a] The equations presented for balloon and helicopter logging are representations of simple ratios and are not the result of regression analysis.

Therefore, the equations yield the expected ordinal ranking of tractor, high lead, and skyline in decreasing magnitude of impact.

Quantitative data measurements do not exist for either the balloon or helicopter methods of logging. The equations presented in Table 12 represent simple ratios of the accelerated sediment rate from tractor logging to that of balloon and helicopter logging. The ratio is based upon the literature relating the amount of surface disturbance of balloon and helicopter to that of tractor logging. The equations are gross simplifications of the complex interaction occurring during a forest harvest operation. The equations presented represent the first attempt at approximating such a relationship for the continental United States.

CHAPTER VII. THE BASIC MODEL FRAMEWORK

Simultaneous achievement of production and environmental goals for the agriculture sector of the continental United States was the intent of the work completed by Wade and Heady [102]. It became apparent that although agriculture is the largest per acre nonpoint source of residuals, the sector constitutes less than 15 percent of the total land area. Therefore, in many river basins, there is not enough adjustment capacity in agriculture to significantly influence the environmental variables under consideration. The forest environment also is known as a nonpoint source of residuals and occupies more than 600 million acres of land in the continental United States.

The approach taken in this study is basically twofold: first, to develop a forest subsystem capable of existing independently from agriculture; and second, to orient the forest sector in a manner to allow interaction with the agricultural sector in the model. This structure allows the trade-offs between agriculture and forestry in sedimentation to be analyzed.

Description of Model Core

The core elements of the linear programming model used are briefly described in this section. Emphasis is on the separate forest sector, although the major areas are briefly described as they pertain to the interaction. The forest sector is defined to fit into the general model framework outlined by the following simplified matrix equations:

$$(4)\ \text{Minimize } Z = \sum_{i=1}^{105} \sum_{j=1}^{m} \sum_{k=1}^{n} C_{ijk} X_{ijk} + \sum_{i=1}^{105} \sum_{j=1}^{m} t_{ij} T_i$$

$$+ \sum_{i=1}^{105} C_{il} X_{il}$$

i = 1 to 105 producing areas,
j = 1 to m land quality classes,
k = 1 to n acres of production activity,
l = acres of forest harvest activity.

Subject to: $Ax \leq b$, $Bx \geq d$, $Sx - Tx_T \leq 0$, $x \geq 0$, and $r_T \geq X_T \geq 0$,

where Z is the total production and transport cost of agricultural and production costs of forest products; x is the commodity and sediment production vector; C is the production cost vector; A is the resource requirements matrix; b is the resource availability vector; B is the commodity output matrix; S is the suspended sediment matrix; X_T is the sediment transport vector; T_i is the transport ratio matrix; t_{ij} is the transport cost matrix; and R_T is the restraint vector on transported sediment.

Spatial Orientation and Regions

The development of an interregional competitive model requires logical regional delineation with hydrologic consistency. The regions selected should aggregate to provide an approximation of the basins boundaries of the major rivers of the United States. The lowest level of data credibility is the county—the 3,069 counties in the continental United States are aggregated to 105 producing areas (PAs), and they aggregate to the 18 major river basins as spatially displayed in Figure 4.

The producing areas comprising each river basin are shown by the heavy lines which are county boundary approximations for the major river basins drainage areas (Figure 5). Both crop production activities and forest activities are determined at the PA level along with their corresponding input requirements, product generation, and residuals production. The analysis of the interregional competition between PAs for meeting national demands, and more specifically the suspended sediment movements among PAs, is the main purpose of this study; especially the shifts between the agriculture and forest sectors as the source of the sediment. The arrows in Figure 6 show the hydrologically consistent river flows within the basins.

Sector Explanation

Wade and Heady [102] provide specification of the crop production activities, land requirements, yields, production costs, livestock production possibilities, exogenous crop production, commodity transportation, and water usage that are integral components of the national model. This study uses the same specifications and only aggregated trends and changes are noted in reporting results. Therefore, detailed description, development, and specification of the former aspects of the model of the agriculture sector are not undertaken here. However, the erosion component of the agriculture sector is pertinent and merits further explanation.

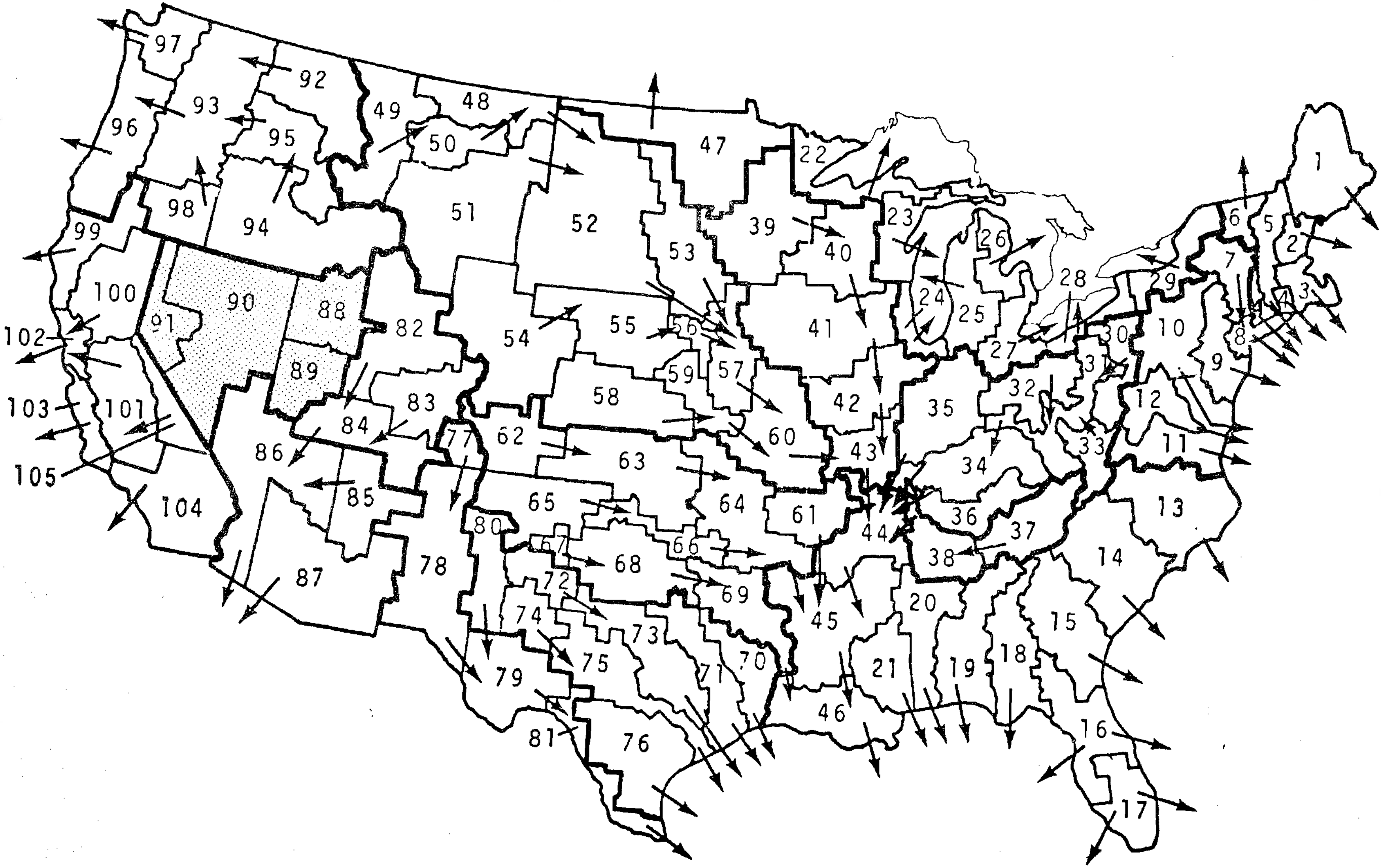

Figure 6. Water flows within river basins

Erosion Sector

Erosion from cropland is of major importance in the agriculture model. The universal soil loss equation (USLE) developed by Wischmeier and Smith [103] is used to compute the sheet and rill erosion contributions in the eastern United States. The support data are provided by the Soil Conservation Service (SCS) [54]. Western cropland erosion rates are not suitable for estimation by the USLE which is designed under the assumption of slopes of less than 30 percent. The erosion rates for the western agricultural lands are taken directly from the Soil Conservation Service questionnaire for the five land classes used in the agriculture model and documented by Meister and Nicol [54].

An interesting variation of the model structure is the usage of suspended sediment in the forest model rather than on-site erosion. Methods are established by this research effort to estimate the instream suspended sediment contribution. As specified in previous chapters, suspended sediment is the portion of the erosion materials that enters the public waterways.

Transportation Sector

Wade and Heady [102] approximate the complex hydrologic movement and flow of water through the stream network with a sediment transport system. The transportation system is not structured on stream-specific hydrology, but rather on a mechanism to provide for interaction among water quality objectives at the national level. The river system is assumed to flow uniformly into downstream PAs or oceans (Figure 6).

Main stream channels unencumbered by water entrapments such as locks, dams, or other flow-interrupting structures, transport the suspended portion of their sediment loads completely through without significant reduction. A stream of this nature has a transport ratio of 1; all suspended sediment that enters the PA leaves the PA. A more realistic stream representation, especially for the main rivers, is that only a portion of the sediment that enters the upper boundary of the respective PAs is actually transported into the next downstream PA. The remainder is entrapped by the impoundment system designed primarily for flood control, hydrologic power, recreation, and irrigation. The transport ratios for those PAs that flow into another PA are presented in Table 13. A blank indicates that there are no upstream PAs flowing into or through the particular PA.

The production of sediment in both cropland and forest land is integrated into a single accounting mechanism. The common unit is the instream suspended sediment which is the estimated variable for the forest sector and the transformed measurement from the agriculture sector represented as delivery ratios. Equation (5) represents the calculations necessary to determine the delivered sediment (X_i^D) that is available for movement by the transport mechanism through the river basins.

Table 13. Delivery rates and transport ratios of hydrologic movementthrough river basins by PAs.

PA	Delivery ratio[1]	Transport ratio[2]	PA	Delivery ratio[1]	Transport ratio[2]	PA	Delivery ratio[1]	Transport ratio[2]	PA	Delivery ratio[1]	Transport ratio[2]
1	.016		27	.030		53	.007		79	.059	.190
2	.016		28	.030		54	.032		80	.022	
3	.041		29	.030		55	.032	1.000	81	.001	.330
4	.041		30	.030		56	.032	1.000	82	.064	
5	.041		31	.064	.513	57	.112	1.000	83	.058	
6	.040		32	.030		58	.037		84	.213	.040
7	.025		33	.030		59	.037	1.000	85	.077	
8	.025	1.000	34	.185	.735	60	.111	1.000	86	.023	
9	.012		35	.030		61	.074		87	.001	
10	.016		36	.010		62	.030		88	.010	
11	.010		37	.010		63	.024	.270	89	.010	
12	.008		38	.134	.010	64	.032	.230	90	.010	
13	.006		39	.001		65	.004		91	.010	
14	.005		40	.028	.700	66	.022	.111	92	.010	
15	.004		41	.049	.400	67	.010		93	.043	1.000
16	.003		42	.050	.540	68	.019	.070	94	.010	
17	.003		43	.050	.950	69	.053	1.000	95	.057	.256
18	.002		44	.043	1.000	70	.006		96	.068	1.000
19	.016		45	.035	1.000	71	.112		97	.010	
20	.019		46	.258	1.000	72	.007		98	.010	
21	.012		47	.014		73	.018	.030	99	.378	
22	.030		48	.079	1.000	74	.001		100	.021	
23	.030		49	.074		75	.018	.010	101	.003	
24	.030		50	.161	.030	76	.008		102	.018	1.000
25	.030		51	.322		77	.010		103	.107	
26	.030		52	.003	.01	78	.001	.110	104	.005	
									105	.010	

[1] Delivery ratio reflects the portion of gross on-site erosion that actually enters the PA system.

[2] Transport ratio reflects the instream impoundment system of sediment that is transported in the waterflow from upstream PAs.

$$(5)\qquad D_i * \sum_{j=1}^{5} \sum_{k=1}^{n} S_{ijk} * X_{ijk} + \sum_{f=1}^{10} TFSS_{if} = X_i^D$$

f = 1 to 10 for the forestry activities,
j = a number of land classes for agriculture,
k = 1 to n for the agricultural activities, and
i = 1 to 105 for the producing areas,

where D_i is the delivery ratio that represents the portion of eroded soil from cropland that reaches the stream system in each PA, S_{ijk} is the tons per acre of eroded soil from activity k on land class j in PA_i for cropland, $TFSS_{if}$ is the total instream suspended sediment generated from forest land; and X_i^D is the tons of suspended sediment delivered from PA_i.

Sediment transport

The sediment transported through a producing area is determined by the physical nature of the river network. The transportation is expressed by the following relationship,

$$(6)\qquad T_i * \sum_{m=1}^{n} X_m^D + \sum_{p=1}^{o} X_P^T = X_i^T$$

m = 1 to n for the adjacent PAs sediment loads, and
p = 1 to 0 for those PA sediment loads reduced by upstream transport ratios,

where X_m^D is the suspended sediment delivered directly from the adjacent upstream PA and not reduced by another transport ratio, X_p^T is the suspended sediment transported through an adjacent upstream PA but originating from a PA farther up the Basin, T_i is the portion of suspended sediment moved from upstream boundary down through PA_i and entering the next lower PA, and X_i^T is the amount of suspended sediment transported through PA_i.

River basin accounting

The sediment entering the river system at any point thus has two possible means of entry; it can be produced directly in the PA or it may be transported into the PA from all upstream PAs. The point of concern will be centered on the point of outflow from the relevant PA. The final PA is the collector of the total suspended sediment for the whole basin. The relationship is characterized by the following equation:

$$(7) \qquad X_i = X_i^T + X_i^D$$

The total suspended sediment, S_i, that flows out of the ith PA consists of the amount delivered in the ith PA (X_i^D) and that which is transported through the ith PA (X_i^T) from all contributing upstream PAs.

The Forest Sector as a Separate Model

As stated in the objectives section, a major thrust is to develop a forest model which may interact with the present agriculture model and still have the capacity to function as a separate entity. The general structure of the forest model is presented in Figure 7. The 614 million forest acres produce approximately 110 million tons of sus-

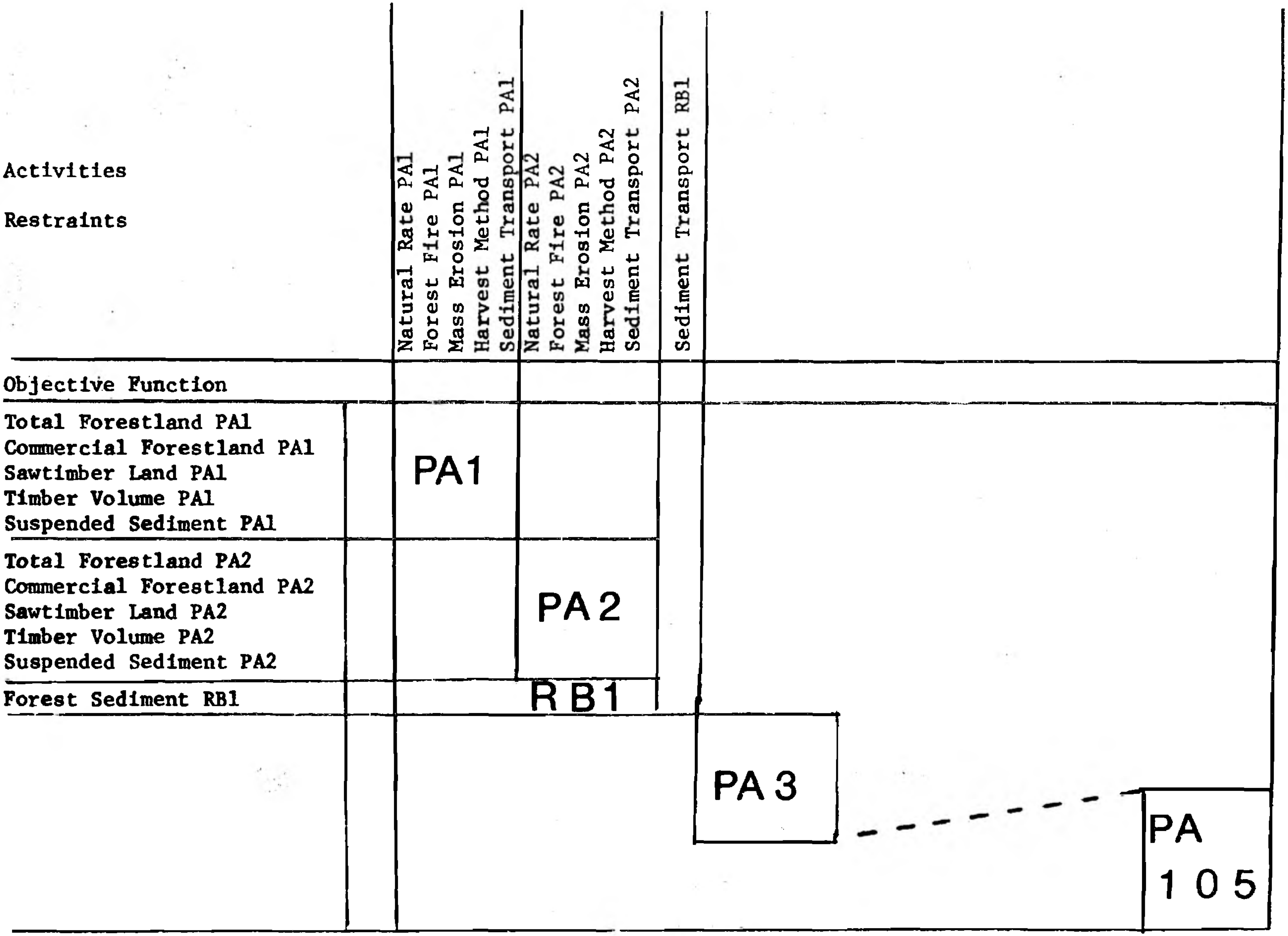

Figure 7. Interactions of the general forest model

pended sediment due solely to the geologic natural rate of production (Table 3). Any acceleration of this rate because of fire, mass erosion, and silvicultural activity has the potential of being altered by management practices and policy.

The land base

The United States Forest Service (USFS) is responsible for surveying the land areas, recording volumes, species, etc., and has assembled much relevant data by counties. These USFS resource bulletins provide the background data for the forest resource base used in the forest model.

The developed land base categories are selected for the following reasons. The forested areas that receive no harvesting management activity are the productive reserved lands and the noncommercial areas. Productive reserved areas are institutionally constrained from harvest activity and noncommercial areas produce less than 20 cubic feet per acre per year. The productive reserved and noncommercial lands, therefore, are assumed to produce suspended sediment at the undisturbed natural rate.

The commercial forest land provides the bulk of the managed or harvested land areas. Attention is concentrated on these forest lands. The ownership breakdown is designed to allow for alternative objective functions based on different planning horizons. Details of these data are presented in the appendix of Fowler [31].

Forest Model Structure

The breakdown of forest land into noncommercial and commercial acreages for each PA in the contiguous United States is presented in Table 14. The noncommercial acreages, as well as the commercial forest land that is not subject to management, fire, or mass erosion events, have the undisturbed rate of forest sediment production in the model. The spatial distribution of commercial and noncommercial forest land areas are displayed in Figure 8 for the contiguous United States. The Southwest has the highest concentration of noncommercial forest land (Figure 8), thus implying a small degree of responsiveness of suspended sediment from forest lands. Only the commercial areas are subject to management decisions. The Northwest and Southeast portions of the United States have the largest erosion impact potential as indicated by the concentration of commercial acreage in these regions.

Forest activities and relevant assumptions

Identifying, locating, and assembling the forest resource base is the first major step in model formation. The preceding pages presented information on the major types of forest activity that influence the suspended sediment production rates of undisturbed forest land.

The impacts of fire also are simplified by assumptions made as to intensity, origin, and site influence. The acres of fire are determined exogenously according to the acreage present in the fire statistics [89]. Exogenous determination of mass erosion and fire is necessary because these activities do not produce a demanded product.

Table 14. Forest land acreage by producing area in thousand acres

Producing area	Noncommercial forest land	Commercial forest land	Total forest land	Producing area	Noncommercial forest land	Commercial forest land	Total forest land
1	847	15,964	16,811	27	28	1,092	1,120
2	84	3,064	3,149	28	85	1,819	1,904
3	89	1,977	2,066	29	541	4,905	5,446
4	66	1,866	1,932	30	61	6,609	6,670
5	288	5,964	6,252	31	80	10,022	10,102
6	529	2,719	3,248	32	39	2,922	2,961
7	1,628	4,622	6,250	33	134	5,978	6,112
8	77	632	709	34	120	7,904	8,024
9	188	4,339	4,527	35	60	3,262	3,322
10	236	10,192	10,428	36	53	5,918	5,971
11	256	8,955	9,211	37	702	9,668	10,370
12	223	5,081	5,304	38	17	5,615	5,632
13	74	14,639	14,713	39	479	7,158	7,637
14	104	16,384	16,488	40	262	7,651	7,913
15	372	15,533	15,905	41	96	2,021	2,117
16	163	9,633	9,796	42	28	1,713	1,741
17	1,539	1,442	2,981	43	90	3,699	3,789
18	30	12,031	12,061	44	60	4,465	4,525
19	29	14,103	14,132	45	27	17,443	17,470
20	5	10,249	10,254	46	35	6,313	6,348
21	4	8,811	8,815	47	1,033	5,259	6,292
22	1,012	13,279	14,291	48	96	134	230
23	156	5,791	5,947	49	758	1,323	2,081
24	36	303	339	50	248	493	741
25	68	6,440	6,508	51	2,741	1,835	4,576
26	39	4,072	4,111	52	441	2,084	2,525

Table 14. (Continued)

Producing area	Noncommercial forest land	Commercial forest land	Total forest land	Producing area	Noncommercial forest land	Commercial forest land	Total forest land
53	47	158	205	81	239	0	239
54	1,566	3,021	4,587	82	5,799	2,812	7,981
55	304	534	838	83	5,736	3,378	9,114
56	3	74	77	84	5,350	1,582	6,932
57	24	500	524	85	4,774	1,266	6,040
58	7	149	156	86	5,356	1,059	6,415
59	14	373	387	87	8,830	2,528	11,412
60	275	4,918	5,193	88	2,208	1,359	3,567
61	205	7,558	7,763	89	3,002	700	3,702
62	1,961	1,156	3,117	90	6,187	104	6,291
63	318	163	481	91	1,029	21	1,050
64	1,191	7,111	8,302	92	794	15,573	16,267
65	1,891	791	2,682	93	3,827	11,809	15,636
66	1,275	453	1,728	94	4,390	4,717	9,107
67	0	0	0	95	4,213	7,499	11,712
68	1,096	186	1,282	96	1,490	18,877	20,367
69	341	8,805	9,146	97	2,456	5,171	7,628
70	45	6,641	6,685	98	705	1,623	2,328
71	865	4,323	5,188	99	3,299	9,191	12,490
72	109	0	109	100	5,463	6,798	12,261
73	2,717	343	3,060	101	6,107	2,070	8,177
74	0	0	0	102	1,356	417	1,773
75	3,440	110	3,550	103	3,376	152	3,528
76	2,460	85	2,545	104	4,642	238	4,880
77	814	1,144	1,958	105	1,424	338	1,762
78	6,932	3,280	10,212				
79	464	50	541	Total	137,959	476,257	614,216
80	1,086	334	1,420				

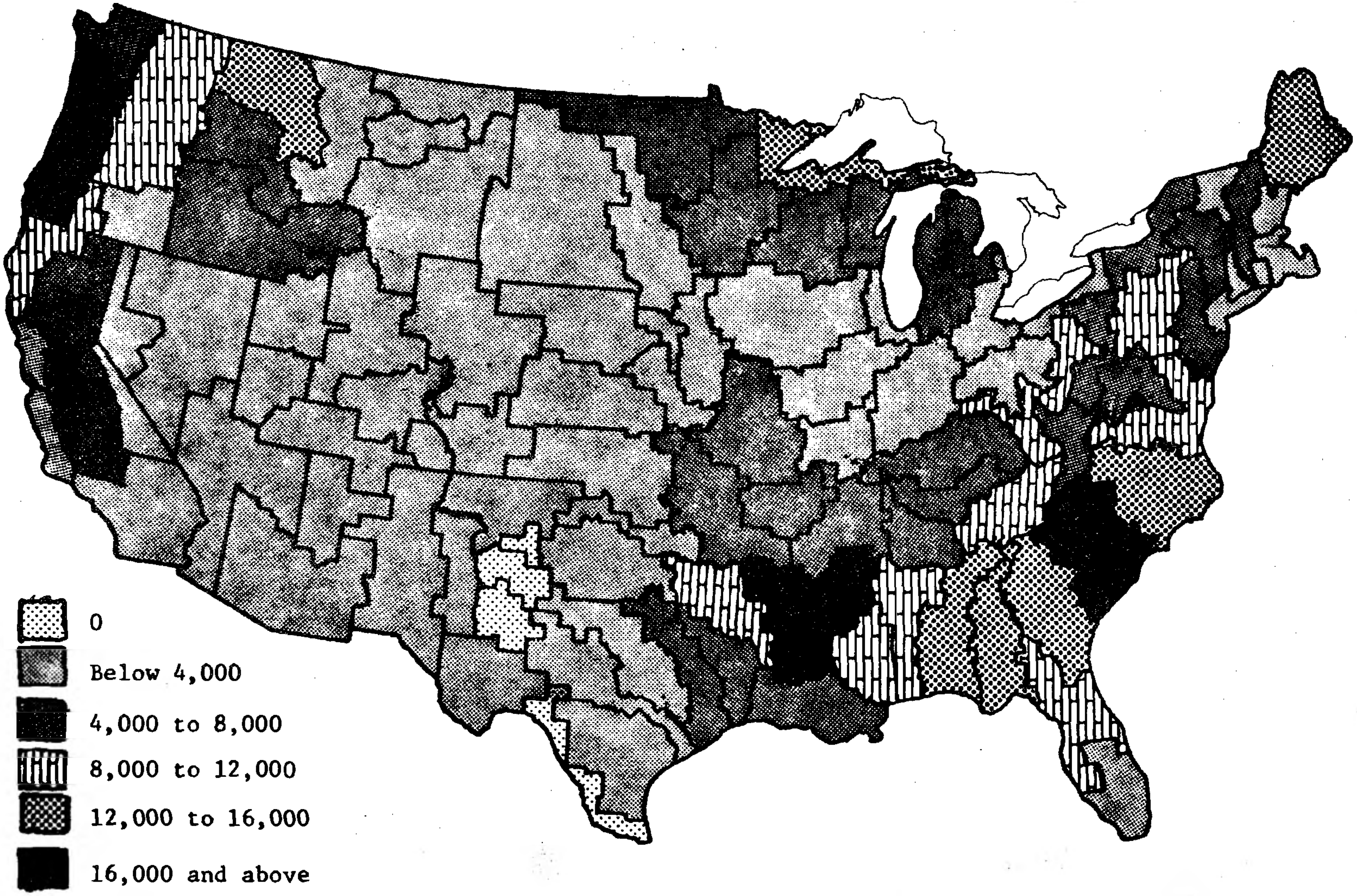

Figure 8. Commercial forest land acreages by producing area in thousand acres

Rather, their product is like that of a negative externality and, therefore, escapes the market mechanism. If not exogenously determined, these activities would enter an optimal solution at the zero level.

Stock-flow problem

Cropland is usually harvested annually and, therefore, contributes sediment annually, whereas forests are commercially harvested only once in a rotation length.[1] Assuming that only commercial land areas are harvested to meet national demand, what then is the optimal harvest pattern to minimize production costs and maintain environmental consistency? Without reductions in the stock according to rotation lengths, all of the forest products would be harvested in one PA if its stock was large enough to meet the national demand. Such an arrangement is both institutionally unacceptable and physically impossible. The concept of reducing the available commercial acres for harvest in any one year according to the rotation length is comparable to the rotation structure of cropland.

Table 15 indicates the selected PA rotation lengths recommended by the U.S. Forest Service.

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[1] Forest stands are also partially harvested in a commercial or precommercial thinning operation as well as timber stand improvement work but these are assumed to have minor impacts on sediment production when compared to site impacts of the final forest end product harvest.

Table 15. Suggested rotation lengths by producing areas

PA	Forest service rotation[1] length (years)	All-ownership rotation length(years)	PA	Forest service rotation[1] length (years)	All-ownership rotation length (years)	PA	Forest service rotation length (years)	All-ownership rotation length (years)
1	120	80	36	100	67	71	80	53
2	120	80	37	100	67	72	100	67
3	120	80	38	100	67	73	80	53
4	120	80	39	120	80	74	100	67
5	120	80	40	120	80	75	100	67
6	120	80	41	120	80	76	80	53
7	120	80	42	120	80	77	120	80
8	120	80	43	120	80	78	120	80
9	120	80	44	80	53	79	120	80
10	120	80	45	60	43	80	120	80
11	100	67	46	60	40	81	80	53
12	120	80	47	120	80	82	140	93
13	60	40	48	120	80	83	140	93
14	60	40	49	120	80	84	120	80
15	60	40	50	120	80	85	120	80
16	60	40	51	120	80	86	120	80
17	60	40	52	120	80	87	120	80
18	80	53	53	120	80	88	140	93
19	80	53	54	120	80	89	140	93
20	80	53	55	120	80	90	140	93
21	80	53	56	120	80	91	140	93
22	120	80	57	120	80	92	120	80
23	120	80	58	120	80	93	120	80
24	120	80	59	120	80	94	140	93
25	120	80	60	120	80	95	120	80
26	120	80	61	100	67	96	85	57
27	120	80	62	120	80	97	85	57
28	120	80	63	130	80	98	129	79
29	120	80	64	100	67	99	140	93

---

[1] Based on the maximum mean annual increment for the timber.

Table 15. (Continued)

PA	Forest service rotation[1] length (years)	All-ownership rotation length(years)	PA	Forest service rotation[1] length (years)	All-ownership rotation length (years)	PA	Forest service rotation length (years)	All-ownership rotation length (years)
30	120	80	65	120	80	100	140	93
31	120	80	66	100	67	101	140	93
32	120	80	67	100	67	102	140	93
33	100	67	68	100	67	103	140	93
34	120	80	69	80	53	104	140	93
35	120	80	70	80	53	105	140	93

[1] Based on the maximum mean annual increment for the timber.

The range is from 60 in the Southeast, increasing to 140 years in the West. The rotation lengths are based upon the maximum mean annual increment of growth attained by merchantable trees. This rotation length is mandated by law for the public forest areas for sustained yield. The rotation length can be much shorter for pulpwood products than for sawtimber. As reflected in the rotation lengths used for the various PAs.

The cost structure of forest harvest

A vital segment of the forest model is the cost structure of the alternative harvest activities. Inclusion of road construction costs as a component of the harvest cost does not alter the relative ranking of the harvest alternatives although it does change the absolute costs. With or without road costs included, costs progress upward from high lead, tractor, skyline, balloon, and helicopter. Harvest costs excluding road construction, at 1975 price levels, are presented in Table 16. Road costs are included in Table 17. Significant increases occur in the real cost of the more traditional methods such as tractor and high lead in favor of the more environmentally oriented methods such as skyline, balloon, and helicopter.

Logging costs are defined to include road construction, as well as the typical components of felling, yarding, loading, hauling, and administration. Road costs are based on Satterlund [68] and Klock [43] for each harvest method and are presented in Table 16. Road costs plus harvest cost represent the total harvest cost in dollars per thousand

Table 16. Logging costs by harvest means (excluding road costs)

Author	Date of publication	Cost ($/MBF)
	Tractor	
Kemper & Davis [41]	1976	30.00
		43.00
		45.00
Klock [43]	1976	34.85
		34.85
		38.50
	High Lead	
Atkinson, et al [11]	1974	35.25
Dykstra & Froehlich [27]	1976	21.90
		29.93
		23.77
		26.88
		24.95
		23.97
		20.83
		23.86
		28.69
Klock [43]	1976	35.00
Sauder & Nagy [69]	1977	40.76
	Balloon	
Gardner, et al [34]	1973	50.00
Sauder & Nagy [69]	1977	50.35
	Helicopter	
Klock [43]	1976	74.98

Table 17. Average total logging costs by harvest means

Harvest means	Harvest costs	Road costs	Total costs ($/MBF)
- - - - - - - - - - - - - - - - dollars per MBF - - - - - - - - - - - - - - - -			
Tractor	39.21	10.78	49.99
High Lead	33.95	8.99	42.94
Skyline	45.39	5.30	50.69
Balloon	50.17	4.87	55.04
Helicopter	74.98	2.25	77.23

board foot (MBF) and are reported at 1975 prices in Table 17. This cost in dollars per MBF, when used in conjunction with the reported volume in MBF of the forest site, yields the cost of the harvest operation. With the inclusion of road construction costs, skyline, balloon, and helicopter logging become competitive with the traditional methods of tractor and high lead.

Demand Estimation for Timber Products

The demand for forest products is the driving mechanism in the forest model presented in this chapter. The forest model demands are fixed and represent the mechanism which brings harvest activities into solution.

Few timber products are consumed directly in the form in which they are harvested. Instead, raw products move to major markets where they are milled, planed, and manufactured to become a component or total product that is ultimately used by the individual consumer. The consumer's demand for final products also affects the final product price which, in turn, affects the demand for the raw timber product. Therefore, demand for most timber products is a derived demand.

House construction is a major component of the economic activity that determines timber demand. Use of timber products in nonresidential construction has been strongly influenced by interest rates, building code restrictions, and growing urbanization. Shifts toward materials made of metals and chemical synthetics as substitutes for wood in the construction industry have a depressing influence on the demand for timber products [99].

Other developments have tended to increase forest products usage [88]. The demand for certain paper and board products is rather insensitive to price changes because of the lack of acceptable low cost substitutes for paper and board in most end-uses. Also, for many items such as books, tissue papers, and various kinds of containers, the cost of paper or board to the final consumer is small in relation to the total of the product consumed or to consumer income. Even fairly large percentage changes in paper and board prices appear unlikely to have much impact on consumption. An additional positive influence on demand may be the eventual realization of the high energy requirements of metal alloys and steel products as opposed to the low rates for comparable wood products [96].

The present study focuses on the determination of the demand parameters for timber products at a national level, in units of million board feet for raw forest products demanded. Several possible independent variables are tested in trying to estimate the statistical best fit demand equation. The data used are national aggregates across all products running for 22 years from 1951 to 1972. The time-series is likely to yield results influenced by autocorrelation. Therefore, restrictive interpretations of demand over time are suggested. The general linear form of the demand function is as follows:

$$(8) \qquad C^d = \alpha + \beta_1 N_t + \beta_3 M_t + \beta_3 W_t P + \beta_4 LP_t + \beta_6 T_t + U_t$$

where:

C^d = the apparent consumption of timber products in billion board feet;

N = U.S. population in million;

M = the index of the manufacturing products (1967 = 100);

WP = the wholesale price index (1967 - 100);

LP = all lumber and wood products price index (1967 - 100);

I = the disposable personal income (in dollars);

T = time (in years);

U = residual error; and

α = constant.

Ordinary least squares (OLS) regression analyses were used. As expected, the results were found to be autocorrelated, the Durban-Watson statistic exceeded the upper deviation. The first-order autoregression technique was then used to correct the autocorrelated errors.

The estimated national demand equation and its relevant statistics are as follows:

$$(9) \qquad C^{d} = -126.3 + .84N - .10M - .13WP + .09LP - 2.93T$$

$$\text{t-values} \qquad (-4.07)\ (4.46)\ (-3.73)\ (5.41)\ (5.25)\ (-4.73)$$

$$MSE = .057 \qquad\qquad R^{2} = .94$$

The coefficient of manufacturing product-index is negative. It indicates that if there is an increase in use of the substitute products of timber (e.g., metals or plastics) the demand for direct use of timber products falls.

The coefficient of average wholesale price index is negative while the coefficient of lumber and wood price index is positive. A plausible explanation could be that the increase in consumer price index decreases the use of some timber products in construction activities and furniture manufacturing which have close substitutes; while lumber and certain wood products prices such as paper, boards, and other household products (e.g., tissue papers) made of wood, increase as income increases. Furthermore, the price of timber products relative to the average wholesale price of all commodities has not changed very much during the past two decades [88]. This indicates that although the lumber and wood price index has increased during the period under study, it did not increase as fast as the wholesale price index. In other words, lumber and wood prices were relatively low when compared to prices of other substitutes and competing products.

The coefficient of time is negative. A plausible explanation is that the rapid change in technological and institutional structures in the U.S. economy have induced improved and comparatively cheap substitute products for timber. With the passage of time, demand for timber products may continue to decline as close substitutes are extensively used in residential and other new construction purposes [105].

The results of this demand estimation are inconclusive. Forest products demand can substantially increase or decrease with swings in the economy over time. Fast increases in timber's own price as in 1968-69 and again in 1971-72 appears to have had very limited initial impacts on consumption of timber products indicating rather inelastic demand curves. However, high interest rates in the 1980's checked demand greatly. The Forest Service projections given in Timber Outlook [92] also indicate a relatively constant forest products demand. Following our analysis here, we decided to use a demand of 61.7 billion board feet of timber products.

The national demand for saw timber products is disaggregated into seven regional delineations presented in Figure 1. The disaggregation is based upon a consumption data breakdown of the Timber Outlook [92].

CHAPTER VIII. ANALYSIS OF ALTERNATIVE MODEL SOLUTIONS

The preceding discussion provides the groundwork for an in-depth examination of the interactions between the forestry and agriculture subsectors. The focus is initially directed toward the forest sector and then to trade-offs between forestry and agriculture in producing sedimentation. The trade-off centers around meeting demands for commodities on one hand, and maintaining a quality environment on the other. The level of comparison is national in scope. However, the model structure developed allows disaggregation to the smaller producing areas.

The Forest Model Solutions

Four alternatives for the forest model were analyzed: (1) The Minimum Cost (Mincost) alternative, (2) the Minimum Sediment (Minsed) alternative, (3) the Sediment/Cost (Sedcost) alternative, and (4) the Cost/Sediment (Costsed) alternative. The Mincost solution incorporated the demand levels for forest products and established the minimum cost production pattern for meeting the demand levels. The Minsed alternative also used the 1985 demand levels for forest products, but its objective was to meet these demands with the minimum amount of sediment being generated in the harvest process. The Sedcost alternative maintained the minimum cost level but minimized sediment subject to their minimum cost. The Costsed alternative maintains the minimum sediment pattern but minimizes costs subject to their minimum sediment.

Given the restraints and objective functions, a goal of each solution was to determine the optimal production pattern of silviculture; namely, the optimal spatial location where forests should be harvested and the method by which they should be harvested. In each solution the generation of suspended sediment and its movement was traced through the nation's waterways.

The Minsed and Mincost alternatives did not simulate the historic patterns of forest harvest practices. The intent of the Minsed solution was sediment minimization in each PA. The objective was to minimize the sediment contribution at the PA level rather than minimizing the sediment transported or the amount deposited into the surrounding oceans. This focused attention on the potential direct on-site losses in site productivity and the amount of suspended sediment that enters the river system rather than the indirect water and sediment transport problems.

Full comparative advantage, subject to the stated restraints, was allowed in all alternatives. Timber production was allocated and resources used among areas and regions so that an efficient national production pattern was attained, given the restraints of the model.

The Sedcost and Costsed alternatives determine if a trough or plateau exists on the production surfaces of cost or sediment minimization. In the Sedcost alternative, the minimum level of sedimentation in the Minsed solution was maintained, alternative combinations of activities were examined to determine a pattern which would lower costs even further. In the Costsed alternative, the minimum cost of the Mincost solution was maintained while examination was made for alternatives which would lower sedimentation even further. If the trough exists, i.e. a flat segment on the production surface indicating the existence of multiple optimal solutions, alternative harvest patterns would enter the solution that still meets the minimum cost objective (minimum sediment objectives) but with reduced sediment (cost) production.

Minimum cost (Mincost)

The Mincost alternative served as the base with which other alternatives were compared. The demand level used to drive the model is 61.7 billion board feet of forest products in 1985. The commercial land area available for forest harvest was reduced by the rotation lengths of Table 15 and presented by river basin in Table 18. The first five columns of Table 18 represent the Mincost solution in terms of answering the questions of how much to harvest, where, and by what method. The harvest method selected was the method expected *a priori*. When road construction costs were included, the high lead method resulted in the lowest cost per unit volume of timber harvested.

The forest model solutions for sediment are presented in Table 19 and show the sediment transported by PA as well as the destination. The latter represents the departure areas for the continental United States. Once the sediment reaches either the oceans or the bordering countries it is beyond the influence of U.S. policy. The oceans act as

Table 18. River basin results obtained from Mincost and Minsed solutions for the forest model

	River basin	Maximum commercial areas	Volume harvested	Mincost		Minsed	
				Method of harvest	Commercial acres harvested	Method of harvest	Commercial acres harvested
			Million BF				
1.	New England	392,387	1,807	High lead	312,715	Helicopter	312,715
2.	Middle Atlantic	445,151	1,915	High lead	373,739	Helicopter	373,739
3.	S. Atlantic Gulf	2,137,631	14,477	High lead	2,113,750	Helicopter	2,134,914
4.	Great Lakes	471,262	2,493	High lead	359,050	Helicopter	367,592
5.	Ohio	563,292	1,072	High lead	205,110	Helicopter	187,565
6.	Tennessee	229,234	706	High lead	84,221	Helicopter	84,221
7.	Upper Mississippi	278,023	845	High lead	336,149	Helicopter	336,149
8.	Lower Mississippi	634,773	5,272	High lead	634,776	Helicopter	634,776
9.	Souris-Red-Rainy	65,737	417	High lead	65,737	Helicopter	65,739
10.	Missouri	194,948	1,149	High lead & Skyline	125,361	Helicopter	126,949
11.	Ark.-White-Red	421,076	1,891	High lead	296,092	Helicopter	296,092
12.	Texas-Gulf	244,619	928	High lead	136,150	Helicopter	136,764
13.	Rio Grande	60,100	173	High lead	19,100	Helicopter	59,475
14.	Upper Colorado	79,347	568	High lead	59,572	Helicopter	79,347
15.	Lower Colorado	61,337	486	High lead	61,337	Helicopter	61,337
16.	Great Basin	23,400	210	High lead	23,400	Helicopter	23,400
17.	Columbia-N. Pac.	931,217	22,438	High lead	884,515	Helicopter	908,243
18.	Cal. S. Pacific	228,699	4,824	High lead	192,573	Helicopter	176,062

Table 19. Sediment transport patterns for four alternative forest model solutions by PA

From PA	To PA or Ocean[a]	Mincost Sediment (000 tons)	Minsed Sediment (000 tons)	Costsed Sediment (000 tons)	Sedcost Sediment (000 tons)
1	200	2,279	1,518	2,279	1,560
2	200	518	426	518	438
3	200	334	223	334	229
4	200	358	358	358	358
5	200	94	65	94	71
6	200	636	636	636	636
7	8	265	193	265	197
8	200	443	370	443	374
9	200	283	192	283	197
10	200	1,291	855	1,291	872
11	200	1,204	745	1,204	770
12	200	1,730	1,730	1,730	1,730
13	200	3,969	1,786	2,969	1,850
14	200	2,283	1,235	2,283	1,293
15	200	474	272	474	316
16	900	1,281	655	1,281	690
17	900	291	199	291	204
18	300	4,377	2,480	4,553	2,590
19	300	6,483	3,540	5,802	3,661
20	300	34,490	34,490	34,490	34,490
21	300	1,524	845	1,524	882
22	400	694	486	694	498
23	400	99	71	99	76
24	400	3	2	3	3
25	400	34	31	34	34
26	400	219	219	327	225
27	400	7	5	7	7
28	400	38	26	38	28
29	400	1,223	1,223	1,223	1,223
30	31	625	625	625	625

Table 19. (Continued)

From PA	To PA or Ocean[a]	Mincost Sediment (000 tons)	Minsed Sediment (000 tons)	Costsed Sediment (000 tons)	Sedcost Sediment (000 tons)
31	34	2,601	2,601	2,601	2,601
32	31	712	712	712	712
33	31	1,203	1,203	1,203	1,203
34	44	2,629	2,402	2,629	2,415
35	44	208	171	171	171
36	44	849	534	849	551
37	38	2,227	2,227	5,514	2,227
38	44	321	215	321	222
39	40	149	114	149	121
40	41	1,869	1,844	1,869	1,849
41	42	847	811	847	814
42	43	498	466	498	469
43	44	1,503	1,402	1,509	1,410
44	45	5,930	4,980	5,797	5,028
45	46	8,083	6,562	7,950	6,645
46	300	9,247	7,334	9,118	7,440
47	500	41	41	41	41
48	52	30	22	30	24
49	50	6	5	6	6
50	48	24	18	24	20
51	52	262	217	217	217
52	57	65	51	64	52
53	57	5	4	5	4
54	55	189	142	189	145
55	56	234	178	234	181
56	56	238	181	238	185
57	60	331	259	335	264
58	59	15	15	17	16
59	60	79	76	81	76
60	43	839	764	845	769

Table 19. (Continued)

From PA	To PA or Ocean[a]	Mincost Sediment (000 tons)	Minsed Sediment (000 tons)	Costsed Sediment (000 tons)	Sedcost Sediment (000 tons)
61	45	726	726	726	726
62	63	38	32	38	33
63	64	32	31	33	31
64	45	324	259	325	263
65	66	60	52	60	53
66	64	65	64	70	65
67	68	0	0	0	0
68	69	62	62	65	62
69	46	815	586	818	600
70	300	833	761	826	765
71	300	550	462	550	468
72	73	7	7	7	7
73	300	263	258	263	258
74	75	0	0	0	0
75	300	304	303	304	303
76	300	251	249	251	249
77	78	133	102	133	104
78	79	1,522	1,518	1,777	1,532
79	81	366	363	413	366
80	79	19	17	19	18
81	300	143	142	158	142
82	84	192	173	192	174
83	84	13	13	13	13
84	86	581	580	648	584
85	86	74	68	74	69
86	600	162	151	163	152
87	600	141	129	141	131
88	700	953	83	95	84
89	700	67	63	67	64
90	700	961	954	961	954

Table 19. (Continued)

From PA	To PA or Ocean[a]	Mincost Sediment (000 tons)	Minsed Sediment (000 tons)	Costsed Sediment (000 tons)	Sedcost Sediment (000 tons)
91	700	12	12	12	12
92	93	277	196	277	277
93	96	236	174	236	235
94	95	606	597	646	599
95	93	238	231	248	236
96	800	2,761	1,663	2,761	1,796
97	800	547	391	547	432
98	93	224	164	224	167
99	800	27,773	29,281	29,638	29,281
100	102	8,257	6,588	8,257	6,676
101	102	200	184	200	200
102	800	10,022	8,189	9,911	8,293
103	800	67	66	67	67
104	800	103	101	103	103
105	101	35	33	35	35

[a] 200 = Atlantic Ocean
300 = Gulf of Mexico
400 = Great Lakes
500 = Canada
600 = Mexico
700 = Closed Basins
800 = Pacific Ocean
900 = Atlantic Ocean and/or Gulf of Mexico

accountants for the transported sediment loads and are numbered from 200 to 900 to distinguish them from the PAs which are numbered consecutively from 1 to 105. The sediment (in thousand tons) consists of the contributions from the undisturbed forest lands, burned forest acreages, acres of mass erosion, and harvested acreages. The summation of sediment across the 105 PAs for the Mincost alternative exceeds that of the total sediment produced in the nation. For example, Table 19 shows that 443,000 tons of sediment are transported for PA 8, including the suspended sediment from PA 7 transported through PA 8 into the ocean. Therefore, a simple summation results in a double counting of the sediment transported from an inland PA.

Table 20, on the other hand, provides a summation of sediment produced across the PAs for the 18 major river basins. Sediment transported through the basins is not included. The Mincost alternative produces nearly 140 million tons of suspended sediment in the continental United States. This is a substantial contribution to the nation's sediment problem. But even this quantity does not necessarily represent a maximum from the forest sector. Increased harvest to fulfill higher demands would increase the sedimentation still further. Even with demand constant, the sediment levels would be higher if tractor logging was the lowest cost harvesting method.

Minimum sediment (Minsed)

The Minimum Sediment solution reflects the lowest level of sediment that can be produced with the available technology and still meet

Table 20. Sediment production patterns for alternative forest model solutions aggregated to river basin levels

River basin	Mincost Sediment Produced (000 tons)	Minsed Sediment Produced (000 tons)	Costsed Sediment Produced (000 tons)	Sedcost Sediment Produced (000 tons)
1. New England	4,220	3,226	4,220	3,292
2. Middle Atlantic	4,951	3,891	4,951	3,943
3. South Atlantic Gulf	54,174	45,502	53,668	45,977
4. Great Lakes	2,317	2,063	2,425	2,094
5. Ohio	5,612	5,033	5,575	5,063
6. Tennessee	2,526	2,420	2,526	2,427
7. Upper Mississippi	2,286	2,213	2,286	2,223
8. Lower Mississippi	1,872	1,039	1,770	1,083
9. Souris-Red-Rainy	41	41	41	41
10. Missouri	1,134	1,007	1,095	1,014
11. Arkansas-White-Red	2,021	1,715	2,029	1,735
12. Texas-Gulf	2,208	2,040	2,201	2,050
13. Rio Grande	1,754	1,720	2,008	1,736
14. Upper Colorado	777	758	845	763
15. Lower Colorado	365	335	365	339
16. Great Basin	1,135	1,112	1,135	1,114
17. Columbia-North Pacific	4,490	3,082	4,530	3,347
18. California-South Pacific	47,965	37,638	39,720	37,744
TOTAL SEDIMENT Produced in U.S.	139,847	114,834	131,390	115,985
TOTAL COST of harvesting in U.S.	2.65 Billion	4.75 Billion	2.67 Billion	3.27 Billion

the national demands for timber products. The Minsed solution advocates exclusive usage of helicopter logging, an advanced method presently being used in less than one percent of the nation's timber harvest operations. Implementation of helicopter logging for the whole nation is a normative viewpoint of what should be; if the objective is solely to minimize sediment then helicopter logging would be the optimal method to achieve this goal.

The cost data for the alternative harvest methods and the sediment production equations shed new light on the production-residuals tradeoff. The cost increase from the least to the most expensive harvesting method is approximately double, whereas the sediment reduction potential is much greater depending upon the particular PA under consideration. Contingent upon society's value for sediment reduction, the marginal benefits from adoption of the helicopter logging could greatly outweigh the marginal costs of implementing helicopter logging.

The sediment transport patterns displayed in Table 19 reveal the expected result; namely, that the volume of sediment moved is reduced across the United States under the Minsed alternative. The sediment reductions by river basins are displayed in Table 20. The largest reductions occur along the East Coast, the lower Mississippi and the West Coast. These areas currently have the greatest amount of timber harvested. Therefore, the greatest sediment reduction could be expected when the harvest method is changed from high lead to helicopter. The change in harvest methods occur in the Lower Mississippi river basin and result in the greatest percent change in sediment levels. The other means of reducing the suspended sediment loss, in addition to changing the method, is in shifts among PAs in amount harvested. The California South Pacific river basin has a marked decrease in acres harvested under the Minsed solution (Table 18).

Costsed and Sedcost Solutions

A priori the deviations between the Costsed and Sedcost solution runs are not expected to be great. But as previously mentioned, the reduction in sediment or cost will be at no added sacrifice as compared to the Mincost or Minsed solutions, respectively. If troughs do exist for either the sediment production or cost relationships then the Costsed and Sedcost alternatives are designed to select the lowest sediment production level from the alternative minimum cost activities.

Costsed

The Costsed solution, when compared to the Mincost solution, yields significant differences among river basins. Information presented in Table 21 indicates that the South Atlantic Gulf, Ohio, Upper Mississippi, Missouri, and California South Pacific river basins have reduced acreages harvested under the Costsed alternative. The Great Lakes, Arkansas-White-Red, Upper Colorado, and the Columbia North Pacific river basins have increased acreages harvested when compared to the Mincost alternative displayed in Table 18.

Table 21. Method of harvest and commercial acres harvested in the Costsed and Sedcost solutions for the forest model by river basins

River basin	Costsed: Method of harvest	Costsed: Commercial acres harvested	Sedcost: Method of harvest	Sedcost: Commercial acres harvested
New England	High lead	312,715	Balloon and Skyline	335,074
Middle Atlantic	High lead	373,739	Balloon	335,938
South Atlantic Gulf	High lead	1,812,171	Balloon, Skyline, and Helicopter	1,875,089
Great Lakes	High lead	409,950	High lead, Balloon, Skyline, and Helicopter	409,950
Ohio	High lead	187,565	Balloon	187,565
Tennessee	High lead	84,221	Balloon	84,221
Upper Mississippi	High lead	136,149	Skyline and Balloon	136,149
Lower Mississippi	High lead	588,699	Balloon	588,699
Souris-Red-Rainy	High lead	65,737	High lead	65,737
Missouri	High lead	110,536	High lead, Skyline, and Balloon	105,874
Arkansas-White-Red	High lead	307,748	Skyline and Balloon	304,959
Texas Gulf	High lead	132,769	Balloon	133,932
Rio Grande	High lead	59,475	Skyline and Balloon	59,475
Upper Colorado	High lead	79,347	High lead and Balloon	79,347
Lower Colorado	High lead	61,327	Skyline and Balloon	61,327
Great Basin	High lead	23,400	Skyline and Balloon	23,400
Columbia North Pacific	High lead	900,120	High lead, Skyline, and Balloon	900,120
California South Pacific	High lead, Skyline, and Balloon	176,062	High lead, Balloon, and Helicopter	176,062

The increases occur in those river basins where sediment rates on both undisturbed and harvested land areas are relatively small. The Great Lakes river basin had the largest increase in acreage. The result reflects the gently topography and high infiltration rates of the area. The Arkansas-White-Red river basin has increased harvested acreages probably because of a favorable mixture of topographic characteristics and ample rainfall for vegetation growth. The area experiencing the largest loss under the Costsed alternative was the South Atlantic Gulf. The erosive soil of the area and high intensity rainfall are expected to have a large effect on this acreage shift.

The sediment production patterns at a river basin level (Table 20) suggests that there are minor shifts and changes among PAs but the net effect is minimal for the basin except in the California South Pacific river basin. The sediment for this river basin is 17 percent less under the Costsed alternative than under the Mincost solution. This reduction is not caused entirely by acreage shifts. A shift in harvest methods occurs in the California South Pacific (Table 21) when balloon and skyline logging enter the solution. Both methods create less site disturbance than the high lead method and result in reduced sediment contributions.

Sedcost

For purposes of comparison, the Sediment/Cost model is compared to the Minsed model, (Column 8, Table 22). There are several shifts among PAs in terms of the acreage of commercial timber harvested. The

Table 22. Sediment leaving the continental United States annually by zones of departure in million tons for the alternative model solutions

Departure zones[a]	Mincost (mm tons)[b]	Minsed (mm tons)[b]	Percent change[c]	Costsed (mm tons)[b]	Percent change[d]	Sedcost (mm tons)[b]	Percent change[e]
200	14.90	10.41	-30%	14.89	0%	10.69	+2%
300	58.47	50.86	-13%	57.84	-1%	51.25	+1%
400	2.32	2.06	-11%	2.42	+4%	2.09	0%
500	.04	.04	0%	.04	0%	.04	0%
600	.30	.28	-1%	.30	0%	.28	0%
700	1.14	1.11	0%	1.13	0%	1.11	0%
800	51.27	39.69	-23%	43.03	-16%	39.97	1%
900	1.57	.85	-45%	1.57	0%	.89	4%
Total	130.01	105.30		121.22		106.32	

[a] 200 = Atlantic Ocean
300 = Gulf of Mexico
400 = Great Lakes
500 = Canada
600 = Mexico
700 = Closed Basins
800 = Pacific Ocean
900 = Atlantic Ocean and/or Gulf of Mexico

[b] mm = Million tons

[c] Percent change from Mincost to Minsed solutions

[d] Percent change from Mincost to Costsed solutions

[e] Percent change from Minsed to Sedcost solutions

largest harvest area reduction occurs in PA 44 of the Lower Mississippi river basin. The largest area of increased harvest occurs in PA 26 of the Great Lakes basin.

The harvested acreage shifts are minimal between the Minsed alternative and the Sedcost solutions. The primary changes occur in the method of harvest. The Minsed alternative supports the most environmentally sensitive harvesting method and results in helicopter logging being implemented across the nation. The Sedcost solution, however, allows a much higher degree of flexibility in terms of the optimal harvest method selected.

The only method noticeably absent in the solutions is conventional tractor logging. The absence of tractor logging from the solutions emphasizing cost minimization is caused by the inclusion of road construction costs. The presence of roads in tractor logging also prohibits the method from being selected in the minimum sediment options. The roads also create extensive site disturbance and resultant sediment production.

An interesting result is apparent in the totals presented in Table 20 for the nation. The sediment difference between the Minsed and Sedcost alternatives is 1.15 million tons of suspended sediment. The extra 1.15 million tons of suspended sediment is associated with a 1.48 billion dollars reduction in the total cost of harvest operations. The implications of this trade-off are staggering; each additional ton of sediment saved in the Minsed solution has a cost of more than a thousand dollars per ton. Hence, extreme environmental policies would come at very high costs. There are more efficient means of abating suspended sediment other than that helicopter logging be used, as is indicated in the Minsed solution.

Forest and Agriculture Model Linkage

A general model framework and development of a "stand alone" forest model have been presented. This model was used to examine spatial patterns of forest harvesting, alternative harvesting methods, and sediment production under different objective functions for a linear programming model.

The forest model now is linked to the agricultural model. The agricultural model has 14 endogenous commodities: barley, corn grain, corn silage, cotton, legume hay, nonlegume hay, oats, pasture, sorghum grain, sorghum silage, soybeans, sugar beets, and wheat. The nation is delineated into the 105 producing areas shown in Figure 5 and crop activities are defined for each producing area. Each producing area has nine land classes which serve as restraints on production. Crops can be grown under three tillage practices: conventional tillage - residue removed, conventional tillage - residue left, and minimum tillage - residue left. They also can be grown under four conservation practices: straight row cropping, contouring, strip cropping, and terracing. Soil loss in tons per acre per year is measured for each combination of crops, tillage practices, and conservation practice for each soil type in each producing area. A linear programming model is then specified with the land classes in each producing area, water in each water supply area, and regional commodity demands serving as restraints. The crops produced under alternative tillage methods and conservation practices serve, along with transportation routes, as activities. The model assumes a competitive equilibrium and has an objective of minimizing total costs of producing and transporting the endogenous agricultural commodities. It assumes all resources receive their market rate of return, except land where rent is determined endogenously. The details of the model are explained in Meister and Nicol [53].

Nitrogen fertilizer equivalent wastes are produced by all classes of livestock. These wastes are transferred to the nitrogen fertilizer balance system or as potential inputs into the crop production system.

The general objective behind the linkage of the agriculture model and the forest model is to determine potential trade-offs between the two sectors with respect to production patterns and sediment generation. Cropland and forest land both contribute to nonpoint pollution in the nation's public waterways. The potential for trade-off exists between the forest and agriculture sectors when restrictions are placed upon the sediment levels of a river system. In several of the river basins, agriculture constitutes less than 15 percent of the land area. Therefore, the addition of the forest land as endogenous activities provides model flexibility and a mechanism for expanded internal control of the nonpoint sources of sediment produced across the nation.

The intent of the linkage was to determine whether forestry and/or agriculture activities shift more in response to the imposed restrictions on sedimentation.

Alternatives analyzed

The linkage between the agriculture and forestry models was simulated with three solutions: an unrestricted alternative, an 80 percent river basin restriction alternative, and an alternative incorporating the historic pattern of forest harvest practices. Each solution utilized the same assumptions for population, demand and export levels for the agriculture and forestry models in the year 1985. Moderate levels were selected for each of these parameters.

Unrestricted minimum cost

The alternative refers only to the absence of restrictions for sediment production and transport. The objective was to minimize the cost of producing the desired mix of commodities by optimizing the spatial location of crop production activities. The optimization process yields production patterns for agriculture and forestry that satisfy the demand levels subject to historic agriculture cropping patterns and the moderate fixed demands. The suspended sediment levels were not restricted in any manner, except that they must adhere to the river basin's hydrology.

80 percent river basin restriction

This alternative restricts the level of sediment leaving the river basins. Sediment production must be reduced to 80 percent of the unrestricted level; the intent was to determine the optimal mix of forestry and agricultural activities that concurrently meet the national product demands as well as satisfying the environmental restrictions imposed for the river basins. The solution was undertaken to determine if the degree of trade-off between the nonpoint sources of suspended sediment. Would the 80 percent restriction be met by changes in cropping patterns within agriculture or changes in harvest patterns within forestry or some combination of both?

The historic pattern

This alternative required that 75 percent of forest harvesting must be done by historic methods in each PA. It also required that sediment leaving U.S. river basins must be reduced to 80 percent of the sediment level generated under the Unrestricted Minimum Cost alternative. The purpose of this solution was to determine if additional restrictions on the forest sector alone would cause shifts in the cropping pattern and sediment generation of the agriculture sector. The historic pattern of harvest methods produced higher sediment levels. These, in turn, may be counteracted by shifts to less erosive agricultural practices or by shifts in the location of both crop production and forest harvesting.

The Unrestricted Minimum Cost alternative simulates the normative position for both the forest and agricultural land areas in the sense that no restrictions were placed upon sediment production, delivery, or transport. The unrestricted alternative determined the optimal activities and their spatial locations for the minimum cost objective. The river network simply functioned as a receiver of the residuals produced during the production activities of both the forest and agriculture sectors. No restriction was placed on the amount of suspended sediment that is permitted to move through the nation's public waterways. The minimum cost solution obtained acts as the base of comparison with the other alternatives.

The acreages of the endogenous crops produced in the continental United States under the three alternatives are presented in Table 23. The commodity production pattern was influenced by resource availability, national demand levels, regional comparative advantages, and historic patterns of production. The Unrestricted Minimum Cost solution used less land to meet the commodity demands than did the other two alternatives. The restriction on sediment production increases the acreage of agricultural commodities by shifting some productive but highly erosive land out of crop production. Additional acres of lower land classes were brought into the solution to meet the national demands. The Unrestricted Minimum Cost solution allowed high yielding but highly erosive lands and tillage practices to be used. Hence, less land was needed to meet commodity demands.

Table 23. Total acreage of major crops for the forest and agriculture model link alternatives

Endogenous commodities	Unrestricted minimum cost (000 acres)	80% river basin limit (000 acres)	Historic forestry and 80% river basin limit (000 acres)
Barley	9,563	10,881	10,881
Corn grain	65,250	68,596	68,596
Corn silage	5,799	8,391	8,391
Cotton	8,722	10,604	10,604
Legume hay	21,558	26,002	26,002
Nonlegume hay	28,193	30,293	30,293
Fallow	30,774	21,360	21,360
Oats	15,423	17,316	17,316
Pasture	1,978	2,134	2,134
Sorghum grain	16,988	16,834	16,834
Sorghum silage	3,637	926	926
Soybeans	54,377	54,046	54,046
Sugar beets	0	0	0
Wheat	64,454	71,788	71,788

Table 24 displays the major crop types and the acreage disaggregation by river basins for the Unrestricted Minimum Cost solution. About 48 percent of the agriculture land area in production was in row crops. Close-grown, hay crops, and summer fallow covered 28, 15, and 9 percent, respectively, of cropland. Table 24 provides a good base for comparison with alternative solutions; the composition of the major crop types are indicated for each river basin.

The pattern of conservation and tillage practices helps explain the increased acreage generated in the restricted solution. Shifts to

Table 24. Cropland use by crop type and river basin for the Unrestricted Minimum Cost alternative

River basin	Row crop[a]		Close grown crops[b]		All hay crops[c]		Summer fallow	
	Acreage (000 acres)	Percent of total	Acreage (000 acres)	Percent of total	Acreage (000 acres)	Percent of total	Acreage (000 acres)	Percent of total
New England	182	15	76	6	987	79	0	0
Mid Atlantic	2,384	28	2,888	34	3,221	38	0	0
South Atlantic-Gulf	8,852	46	8,978	46	1,526	8	0	0
Great Lakes	16,563	77	1,458	7	3,424	16	0	0
Ohio	20,884	73	3,156	11	4,561	16	0	0
Tennessee	2,588	93	145	5	41	2	0	0
Upper Mississippi	43,593	74	6,214	10	9,360	16	0	0
Lower Mississippi	4,986	27	11,072	60	2,276	13	0	0
Souris-Red-Rainy	303	2	10,496	66	0	0	5,174	32
Missouri	24,560	33	22,574	31	11,306	15	15,527	21
Arkansas-White-Red	18,055	48	10,901	29	4,475	12	3,924	11
Texas-Gulf	8,362	63	2,120	16	1,808	14	979	7
Rio Grande	1,030	72	72	5	324	23	0	0
Upper Colorado	244	26	320	34	254	27	122	13
Lower Colorado	209	31	107	16	309	46	51	7
Great Basin	0	0	367	28.5	793	61.5	131	10
Columbia-North Pacific	808	6	6,083	42	2,871	20	4,690	32
California	1,145	19	2,394	41	2,199	37	172	3
U.S. Total[d]	154,773	48	89,440	28	49,751	15	30,774	9

[a] Row crops are corn, cotton, sorghum, soybeans, and sugar beets.

[b] Close grown crops are barley, oats, and wheat.

[c] All hay crops are rotation legume and nonlegume hays.

[d] Totals may not add because of computer rounding.

conservation practices of terracing, strip cropping, and contour cropping lessen straight-row cropping and thus reduce erosion and sedimentation. However, land use shifts among regions also can reduce erosion. Lands in the Southeast which have ample rainfall and do not freeze in the winter are fairly erosive. Solutions causing reduced erosion require less intensive cropping in these regions and greater proportions of crops to be produced in the Great Plains where there was more level land and less rainfall. These national shifts in land use also cause average national yields to decline.

The combination of the four conservation and the three tillage practices allow 12 management options for each endogenous crop. Table 25 shows the national amount of each of the 12 management practices in the three alternatives. Sediment produced per acre was at a maximum with straight-row farming with residue removed in the fall under conventional tillage.

Tables 26 and 27 show the acres of cropland used and sediment losses by river basins under the various environmental alternatives included in the analysis. Considerable difference exists in cropping patterns under the various alternatives. The 80 Percent River Basin Limit had the largest acreage devoted to conservation tillage methods. Also, it had more of the endogenous row crops produced in regions where erosion is less severe.

The forest sector of unrestricted solution

Agriculture is the largest sediment contributor per acre while forest land occupies the largest number of acres. The linkage of the

Table 25. National total acres and percent of total cropland in conservation and tillage treatments for the three alternatives

Land use	Unrestricted minimum cost		80% river basin limit		Historic forestry and 80% river basin limit	
	(000 acres)	Percent	(000 acres)	Percent	(000 acres)	Percent
Straight Row[a]	103,559	26.2	81,350	20.6	81,350	20.6
Con. til.[b] residue removed	25,433	6.4	18,054	4.6	18,054	4.6
Con. til. residue left	44,819	11.3	30,036	7.6	30,026	7.6
Reduced tillage	33,307	8.4	33,270	8.4	33,270	8.4
Contour Cropping[a]	164,685	41.7	170,694	43.3	170,694	43.3
Con. til. residue removed	19,566	5.0	19,133	4.8	19,133	4.8
Con. til. residue left	72,314	18.3	85,736	21.7	85,736	21.7
Reduced tillage	72,805	18.4	65,825	16.7	65,825	16.7
Strip Cropping[a]	35,245	8.9	25,656	6.5	25,656	6.5
Con. til. residue removed	6,919	1.7	5,350	1.4	5,350	1.4
Con. til. residue left	6,792	1.7	4,756	1.2	4,756	1.2
Reduced tillage	21,534	5.4	15,550	3.9	15,550	3.9
Terracing[a]	21,249	5.4	59,337	15.0	59,337	15.0
Con. til. residue removed	237	.1	8,266	2.1	8,266	2.1
Con. til. residue left	20,499	5.2	41,487	10.5	41,487	10.5
Reduced tillage	477	.1	9,584	2.4	9,584	2.4
Total Cropland[a]	324,738	82.3	337,037	85.4	337,037	85.4

[a] Totals may not add because of computer rounding.

[b] Con. til. is an abbreviation for conventional tillage.

Table 26. Total cropland and sediment loss by conservation practice and river basin for the Unrestricted Minimum Cost alternative

	Unrestricted minimum cost			
River basin	Straight row	Contour farming	Strip cropping	Terraces
New England				
Acreage (000 acres)	338	719	187	0
Sediment (000 tons)	1,461	322	325	0
Mid Atlantic				
Acreage (000 acres)	2,618	5,019	806	48
Sediment (000 tons)	29,449	9,659	4,965	5
South Atlantic-Gulf				
Acreage (000 acres)	9,146	7,718	2,476	0
Sediment (000 tons)	114,173	50,896	14,848	0
Great Lakes				
Acreage (000 acres)	4,554	14,556	2,335	0
Sediment (000 tons)	11,985	21,430	6,964	0
Ohio				
Acreage (000 acres)	7,879	16,737	3,850	136
Sediment (000 tons)	51,288	60,513	31,073	47
Tennessee				
Acreage (000 acres)	605	1,436	441	292
Sediment (000 tons)	3,701	13,289	4,938	330
Upper Mississippi				
Acreage (000 acres)	18,951	31,825	8,393	0
Sediment (000 tons)	186,178	98,817	65,701	0
Lower Mississippi				
Acreage (000 acres)	7,931	9,513	519	372
Sediment (000 tons)	91,730	75,356	2,203	822
Souris-Red-Rainy				
Acreage (000 acres)	1,212	14,760	0	0
Sediment (000 tons)	3,359	12,398	0	0
Missouri				
Acreage (000 acres)	17,181	38,065	10,209	8,513
Sediment (000 tons)	231,695	90,310	46,700	2,487
Arkansas-White-Red				
Acreage (000 acres)	7,906	17,387	1,402	10,661
Sediment (000 tons)	53,727	68,050	2,509	5,866

Table 26. (Continued)

River basin	Unrestricted minimum cost			
	Straight row	Contour farming	Strip cropping	Terraces
Texas-Gulf				
Acreage (000 acres)	9,813	2,235	0	12,225
Sediment (000 tons)	142,830	9,032	0	282
Rio Grande				
Acreage (000 acres)	1,063	365	0	0
Sediment (000 tons)	5,520	420	0	0
Upper Colorado				
Acreage (000 acres)	438	504	0	0
Sediment (000 tons)	570	1,029	0	0
Lower Colorado				
Acreage (000 acres)	576	102	0	0
Sediment (000 tons)	225	51	0	0
Great Basin				
Acreage (000 acres)	684	607	0	0
Sediment (000 tons)	1,250	595	0	0
Columbia-North Pacific				
Acreage (000 acres)	7,288	2,870	4,296	0
Sediment (000 tons)	18,319	2,422	17,436	0
California				
Acreage (000 acres)	5,340	250	322	0
Sediment (000 tons)	3,375	91	111	0

two sectors in the Unrestricted Minimum Cost alternative produced few changes in the forest sector as compared to the Minimum Cost solution presented in Tables 18 and 19 when the solution was for the forest sector alone.

The 80 Percent River Basin Restriction

The river basin restriction described the optimal forest and agriculture production pattern when national demands are met with a reduced

Table 27. Total cropland and sediment loss by conservation practice and river basin for the 80 Percent River Basin Restriction alternative

River basin	Straight row	Contour farming	Strip cropping	Terraces
New England				
Acreage (000 acres)	456	720	72	0
Sediment (000 tons)	3,432	132	54	0
Mid Atlantic				
Acreage (000 acres)	1,914	4,379	531	792
Sediment (000 tons)	17,816	7,350	4,410	538
South Atlantic-Gulf				
Acreage (000 acres)	2,413	7,707	778	1,738
Sediment (000 tons)	15,561	45,325	11,922	4,687
Great Lakes				
Acreage (000 acres)	4,066	13,193	805	1,442
Sediment (000 tons)	7,568	17,718	782	876
Ohio				
Acreage (000 acres)	7,816	16,737	2,290	2,405
Sediment (000 tons)	38,298	61,358	9,172	6,579
Tennessee				
Acreage (000 acres)	1,131	1,436	0	836
Sediment (000 tons)	12,314	10,165	0	3,835
Upper Mississippi				
Acreage (000 acres)	17,409	31,825	6,861	5,079
Sediment (000 tons)	30,415	123,251	40,084	7,453
Lower Mississippi				
Acreage (000 acres)	6,929	10,718	235	1,107
Sediment (000 tons)	70,142	83,995	2,044	1,987
Souris-Red-Rainy				
Acreage (000 acres)	1,212	14,760	0	2,168
Sediment (000 tons)	1,183	10,316	0	522
Missouri				
Acreage (000 acres)	14,346	42,392	8,544	24,045
Sediment (000 tons)	80,603	97,210	22,117	19,243
Arkansas-White-Red				
Acreage (000 acres)	6,920	18,029	1,409	12,220
Sediment (000 tons)	30,861	70,864	2,509	6,765

Table 27. (Continued)

River basin	Unrestricted minimum cost: Straight row	Contour farming	Strip cropping	Terraces
Texas-Gulf				
Acreage (000 acres)	6,961	3,950	0	6,529
Sediment (000 tons)	76,834	19,266	0	5,115
Rio Grande				
Acreage (000 acres)	8,132	424	0	27
Sediment (000 tons)	3,564	277	0	12
Upper Colorado				
Acreage (000 acres)	740	5	0	18
Sediment (000 tons)	1,623	24	0	22
Lower Colorado				
Acreage (000 acres)	278	0	0	0
Sediment (000 tons)	55	0	0	0
Great Basin				
Acreage (000 acres)	369	51	0	243
Sediment (000 tons)	186	51	0	60
Columbia-North Pacific				
Acreage (000 acres)	5,166	4,198	4,130	646
Sediment (000 tons)	8,378	2,010	12,232	196
California				
Acreage (000 acres)	2,026	155	0	0
Sediment (000 tons)	1,302	54	0	0

negative impact on the environment. The 80 Percent River Basin alternative requires the sediment leaving the river basins of the continental United States be reduced to 80 percent of the unrestricted totals. The 80 Percent River Basin Restriction simulates environmental policy that is uniformly administered across the United States, but with each basin being allowed to accomplish the necessary changes depending upon its own unique characteristics.

Agriculture changes

Tables 24 and 28 allow a comparison of cropping pattern between the 80 Percent River Basin Limit and the Unrestricted Minimum Cost alternative. In comparison with the latter, the River Basin Limit caused a slight reduction in row crops and fallow for the nation. More interesting shifts were at the river basin level. Only the Missouri river basin had an increase in row crops under the River Basin Limit. It also had an increase in close-grown crops but a decrease in fallow land. Only the Texas Gulf basin had a decrease in hay crops. It also decreased row and fallow crops but increased close-grown crops. The Souris-Red-Rainy basin increased fallow land at the expense of row crops. The Mid-Atlantic, Upper Colorado, Lower Colorado, and California basins decreased close-grown crops and fallow and increased hay crops. The New England, Ohio, Upper Mississippi, Lower Mississippi, and Arkansas-White-Red basins remained basically unaffected in crop changes under the River Basin Limit.

Basins that experienced the greatest reduction in row crops under the River Basin Limit were located in the South (Atlantic Gulf, Tennessee, Rio Grande, Lower Colorado, and California). The erosion potential for agriculture cropland generally was the greatest in the southern portion of the United States for reasons mentioned previously.

Within the straight-row conservation treatment (Table 25), the major reductions between solutions were in the conventional tillage practices. Reduced tillage acreage increased under the restricted solution because of its protection of the soil mantle relative to the

Table 28. Cropland use by crop type by river basin for the 80 Percent River Basin Restriction

River basin	Row crop[a]		Close grown crops[b]		All hay crops[c]		Summer fallow	
	Acreage (000 acres)	Percent of total	Acreage (000 acres)	Percent of total	Acreage (000 acres)	Percent of total	Acreage (000 acres)	Percent of total
New England	200	16	62	5	987	79	0	0
Mid Atlantic	2,309	30	1,366	18	3,943	52	0	0
South Atlantic-Gulf	3,956	31	6,285	50	2,397	19	0	0
Great Lakes	13,789	71	2,605	13	3,110	16	0	0
Ohio	21,222	72	3,468	12	4,606	16	0	0
Tennessee	2,483	72.5	150	4.5	797	23	0	0
Upper Mississippi	47,259	77	5,582	9	8,333	14	0	0
Lower Mississippi	5,236	28	12,220	64	1,532	8	0	0
Souris-Red-Rainy	0	0	1,848	65.5	2,947	16	3,345	18.5
Missouri	32,245	36	31,165	35	13,243	15	12,674	14
Arkansas-White-Red	19,123	50	11,250	29	4,766	12	3,434	9
Texas-Gulf	10,259	59	4,948	28	1,991	11.5	240	1.5
Rio Grande	832	53	236	15	513	32	0	0
Upper Colorado	111	14.5	210	27.5	441	58	0	0
Lower Colorado	17	6	0	0	260	94	0	0
Great Basin	0	0	110	17	553	83	0	0
Columbia-North Pacific	216	2	8,378	59	3,879	27	1,665	12
California	116	5	81	4	1,982	91	0	0
U.S. Total[d]	159,397	47	99,985	30	56,295	17	21,360	6

[a] Row crops are corn, cotton, sorghum, soybeans, and sugar beets.

[b] Close grown crops are barley, oats, and wheat.

[c] All hay crops are rotation legume and nonlegume hays.

[d] Totals may not add because of computer rounding.

other tillage options for straight-row conservation practices. Contour cropping gained in acres sightly because of the large increase in conventional tillage with the residue left in the fields. Strip cropping and related tillage practices decreased across-the-board as a result of the large increase in terracing. Terracing increased primarily on the more erosive lands which were previously strip cropped or fallowed.

The combined figures on crop acres suggest the complex nature of intra- and interbasin shifts to attain sedimentation goals (Table 26). In the Ohio basin the acres of straight-row conservation practices remained relatively constant but there was still a considerable reduction in sediment loss under the restricted solutions. The reduction was caused by greater acreage of close-grown crops and the use of erosion control tillage practices.

Table 29 shows the shadow prices for the endogenous crops of the agriculture sector for both the Unrestricted Minimum Cost and the 80 Percent River Basin Restriction solution. As expected, the shadow price of corn increased under the latter because production was shifted to more marginal producing areas where yields and soil loss are low because of less rainfall and a greater amount of level land. This shift also explains increases in shadow prices of other row crops such as sorghum and cotton. Silage shadow price increased because of the more extensive use of a minimum tillage with more residue left in the fields.

The forest sector with 80 percent restriction

The 80 Percent River Basin limit caused some major shifts of production patterns in the agriculture sector of the combined forest and agriculture model. Shifts again were away from row cropping regions with erosion problems to regions with less rainfall and erosion. The forest sector also shifted toward environmentally sensitive harvest practices.

Table 29. Average shadow prices for endogenous crops in the continental United States for the agriculture sector of the Unrestricted Minimum Cost and 80 Percent River Basin Restriction Alternatives in 1985

Endogenous commodity	Unit	Unrestricted Minimum Cost	80 Percent River Basin Restriction	Percent change
			(in dollars)	
Corn	bu.	1.49	2.33	+56
Sorghum	bu.	1.40	1.70	+21
Barley	bu.	1.32	1.96	+48
Oats	bu.	1.01	.80	-21
Wheat	bu.	2.11	3.36	+59
Oilmeals	cwt.	7.01	5.43	-22
Legume hay	tons	37.47	45.66	+22
Nonlegume hay	tons	44.90	46.00	+2
Silage	tons	9.94	14.42	+45
Pasture	tons	39.95	50.77	+27
Cotton	bales	143.74	176.18	+23

The Minimum Cost solution for the forest model closely paralleled the Unrestricted Minimum Cost solution of the combined forest and agriculture model. The parallel nature allowed comparisons of the solution for the forest sector of the linked model with the forest sector as a separate model. One basic fact was evident in both: the river basins with the greatest portion of agricultural land (e.g., the Ohio, Upper Mississippi, Lower Mississippi, Souris-Red-Rainy, Missouri, Arkansas-White-Red, Texas Gulf, and Rio Grande) had modest or no shifts toward environmentally sensitive forest harvest methods. This result was caused by the small amount of forest acres in these basins and also the shifts within the agricultural sector of the model as a means of sedimentation control. River basins with the greatest shift toward conservative harvest technology were all in the southern portion of the United States (e.g., the California South Pacific, Great Basin, Lower Colorado, and the South Atlantic Gulf).

The river basin restrictions caused a large acreage decrease in PA 14 of the South Atlantic Gulf. This river basin has been singled out by both the forest model and the combined forest and agriculture model, as priorities are requiring increased environmental measures. Only three PAs experience shifts both to environmentally oriented forest harvest methods and decreases in the acreage of forest harvests: PA 2 of the New England basin, PA 70 of the Texas Gulf basin, and PA 97 of the Columbia North Pacific basin. Table 31 indicates the pattern of harvesting methods for the two restricted solutions.

Table 30 indicates sediment losses and production costs for the major river basins under the environmental alternatives for the combined model. The most significant reductions from sediment control programs occurred in the southeast and southwest basins. The major

Table 30. Sediment loss and production costs by river basin under the combined forest and agricultural model

River basin	Unrestricted Minimum Cost Solution	80 Percent River Basin Restriction	80 Percent Historic Pattern with Restriction
		(in million tons)	
New England	4.22	3.23	3.48
Mid Atlantic	4.95	3.91	4.18
South Atlantic-Gulf	52.78	46.12	47.58
Great Lakes	2.36	2.11	2.16
Ohio	6.64	6.32	5.77
Tennessee	3.84	3.84	3.13
Upper Mississippi	2.29	2.29	2.25
Lower Mississippi	1.87	1.87	1.47
Souris-Red-Rainy	.04	.04	.04
Missouri	1.08	1.10	1.08
Arkansas-White-Red	2.03	2.03	1.88
Texas-Gulf	2.20	2.14	2.12
Rio Grande	1.75	1.75	1.74
Upper Colorado	.84	.76	.78
Lower Colorado	.36	.34	.34
Great Basin	1.14	1.11	1.12
Columbia North Pacific	4.58	4.45	4.05
California	47.30	37.60	40.90
Total Sediment (Million tons)	140.25	121.04	124.07
Total Cost[a] (Billion dollars)	2.65	3.49	3.24

[a] Cost of producing and transporting endogenous crops and forest harvesting.

Table 31. Forest acreage and harvest method by river basin for alternative models when the forest and agriculture sectors are linked into a comprehensive model

	80 Percent River Basin Restriction		80 Percent Restriction plus Historic Pattern	
River basin	Method of harvest	Commercial acres harvested	Method of harvest	Commercial acres harvested
New England	Helicopter	304,855	Tractor	234,536
			Helicopter	74,191
Mid Atlantic	Helicopter	373,739	Tractor	280,303
	Skyline	7,900	Skyline	5,114
			Helicopter	96,222
South Atlantic-Gulf	High lead	209,275	Tractor	1,176,627
	Helicopter	161,544	High lead	44,077
			Helicopter	12,725
Ohio	High lead	347,462	Tractor	327,170
	Helicopter	178,430	High lead	44,007
			Helicopter	12,725
Tennessee	High lead	229,234	Tractor	171,926
			High lead	57,308
Upper Mississippi	High lead	136,149	Tractor	102,165
			High lead	32,724
Lower Mississippi	High lead	634,776	Tractor	476,082
			High lead	157,120
Souris-Red-Rainy	High lead	65,737	Tractor	49,303
			High lead	16,434
Missouri	High lead	79,824	Tractor	72,604
	Skyline	4,662	High lead	26,530
			Skyline	6,565
			Balloon	61,475
			Helicopter	549
Arkansas-White-Red	High lead	304,923	Tractor	227,703
	Helicopter	2,789	High lead	76,726
			Skyline	714
			Helicopter	2,789

Table 31. (Continued)

River basin	80 Percent River Basin Restriction		80 Percent Restriction plus Historic Pattern	
	Method of harvest	Commercial acres harvested	Method of harvest	Commercial acres harvested
Texas-Gulf	High lead	102,311	Tractor	108,355
	Helicopter	29,843	High lead	25,577
Rio Grande	High lead	18,475	Tractor	13,718
	Skyline	625	High lead	4,741
			Skyline	641
			Helicopter	41,000
Upper Colorado	High lead	36,198	Tractor	51,766
	Helicopter	43,154	High lead	10,463
			Skyline	1,414
			Helicopter	13,764
Lower Colorado	Helicopter	61,337	Tractor	45,542
			High lead	230
			Skyline	230
			Helicopter	15,335
Great Basin	Helicopter	22,286	Tractor	14,566
			High lead	527
			Skyline	527
			Helicopter	7,780
Columbia North Pacific	High lead	839,964	Tractor	232,466
	Helicopter	68,785	High lead	426,792
			Skyline	216,797
			Helicopter	55,162
California-South Pacific	Helicopter	175,059	Tractor	69,623
			High lead	31,280
			Skyline	31,280
			Helicopter	43,878

agricultural or crop regions had very modest reductions in sediment. The 80 Percent River Basin Restriction is effective in environmental improvement when the forest sector in the combined model is compared to separate forest model (Table 20).

Under the 80 Percent River Basin Restriction shifts in both the forest and agriculture sectors alleviate sedimentation. These shifts result from absolute and comparative advantage changes in cropping activities among regions, use of more conservation and tillage practices, and changes in forest harvest methods. Agriculture and forest sectors are not good substitutes in lessening sedimentation. River basins with large areas in agricultural crops meet environmental restrictions by shifts in agricultural practices and forested basins shift to advanced harvesting technologies to achieve environmental restraints.

Historic Pattern with 80 Percent River Basin Restriction

Table 31 presents the forest sector impact of the Historic Pattern with 80 Percent River Basin Restriction. In this alternative, forest harvest methods were restrained according to their historic pattern of occurrence. The total cost for the nation was reduced, compared to the case when the historic pattern was not forced into solution, from 3.49 to 3.24 billion dollars (Table 30). This was caused by a movement away from the most expensive harvest method, helicopter logging. Helicopter logging entered the solution to meet the 80 Percent River Basin Restriction without the historic pattern. Increased sediment production from the forest sector with the introduction of the historical pattern of harvesting was expected to be counteracted by shifts in the agricul tural sector towards greater soil protection activities. However, these shifts did not occur and infeasibilities developed indicating that the agricultural sector had reached its most environmentally efficient production pattern for meeting the national commodity demand levels.

CHAPTER IX. SUMMARY OF RESULTS AND IMPLICATIONS

Deterioration of water quality emerged as a prime public concern in the environmentally conscious decade of the 1970s. Research results indicate that significant national improvements in the environment can be attained by adopting certain soil protecting management options. These options include the type of crops planted, the conservation activities, and tillage practices actually implemented. Although cropland generates the largest nonpoint contribution per acre, it occupies less than 15 percent of the total United States acreage. Forest land, which comprises over 614 million acres in the continental states, is also identified as a potential source of nonpoint pollution.

This study was initiated to develop models, which could analyze the potential effect of certain policies directed toward reducing stream sedimentation from forest lands. A major objective of this study is to develop a model of the forest economy that interacts with the agricultural sector via the river basin network. Possible policy alternatives that restrict erosion or sediment may then be tested to determine the degree of trade-off between production requirements and pollution for both the agricultural and forested land areas.

The Forest Model

Regression techniques first are used to estimate the underlying relationships between site characteristics and the undisturbed rate of suspended sediment production from forests. The impacts of forest fires and mass erosion events also are estimated with respect to their contributions to suspended sediment rates. The key management decision variables for the forest sector are the methods employed in harvesting. The alternative methods of forest harvesting require various amounts of road construction and result in widely varying degrees of site disturbance. The extent of the forest site that is disturbed in turn affects the quantities of sediment that are delivered to the nation's public water system. Thus, the forest ecosystem is a flexible resource that is capable of being managed for timber products and, simultaneously, reducing the sediment loads carried in the nation's rivers.

The study explored four possible objectives relating production and pollution while concurrently fulfilling the nation's need for forest products. The four options examined for the forest model were:

(a) The Minimum Cost alternative. This solution allowed least cost production to occur with no activity bounds or Spatial Predesignation incorporating 1985 demand levels. The amount and spatial location of sediment production under this alternative was used as a basis for comparison with alternative solutions.

(b) The Minimum Sediment alternative. This was an extreme environmentalist position that was designed to achieve the national demand levels for forest products but with the minimum level of environmental deterioration.

(c) The Sediment/Cost alternative. This solution was intended to locate alternative optima if a trough in the production surface exists. The solution minimized sediment production subject to the cost level attained in the Minimum Cost alternative.

(d) The Cost/Sediment alternative. This is a "reverse concept" in the sense that alternative cost positions were examined subject to the minimum sediment level attained in the Minimum Sediment solution.

On-site erosion and resultant instream suspended sediment were determined under each model alternative. The goal of the analysis was to determine the physical as well as economic changes which would take place in agriculture and the forest sector when different means to reduce major river sedimentation were implemented.

Each alternative solution depicted a different scenario of harvest methods and acreages for the 105 producing areas (PAs) of the continental United States. Except for a few PAs in the western states, the minimum cost solution advocated high lead logging, as did the Cost/Sediment Solution. The Minimum Sediment solution supported helicopter logging as the method of least disturbance while the Sediment/Cost solution selected a mixture of all harvesting alternatives except tractor logging. Tractor logging is the most widely used practice in the forest industry at the present time, but when road construction costs are included internally in the harvest methods, the tractor method creates the greatest soil disturbance but is only average in terms of total harvest cost per acre.

The Combined Forest and Agriculture Model

The encompassing objective behind the linkage of the agricultural model and the forest model was to determine the extent of trade-off between the two sectors with respect to possibilities in reducing sedimentation. The intent of the linkage was to determine if forestry and/or agricultural harvesting and production technologies shift in response to imposed environmental restrictions. The linkage between the models and the trade-off was simulated with three alternative solutions:

(a) The Unrestricted Minimum Cost alternative. No restrictions were placed upon the sediment production patterns or transport mechanism. However, the quantity of suspended sediment was monitored in the free market solution to compare with the other alternatives.

(b) The 80 Percent River Basin Restriction. This alternative was designed to determine the degree of trade-off occurring between the sectors as nonpoint sources of sediment when environmental restrictions of 80 percent of the Minimum Cost sediment pattern was imposed upon the river basins.

(c) The Historic Pattern with 80 Percent River Basin Restriction. This alternative restrained forest harvesting to historic methods while requiring the 80 Percent River Basins reduction in sedimentation. The intent was to determine if the imposed solution for the forest sector, which has higher sediment production rates, would be counteracted by shifts to more conservation-oriented practices in the agricultural sector.

The agriculture sector results

The 80 Percent River Basin Restriction caused crop acreage to shift from basins in the South which have high rainfall and are erosive. Crop acreage shifts to regions such as the Great Plains where there was more level land, less rainfall, and less erosion. Because yields were lower per acre with the less intensive agriculture, an additional 12.3 million acres of the endogenous crops were produced under the 80 percent restriction. There was a decrease in both the erosive row crop, tillage methods, and fallow land under the 80 Percent River Basin Restrictions. The greatest reduction of row crops was in the South, because the most erosive lands are located in the southern river basins.

The 80 Percent River Basin Restriction included shifts to conservation practices and tillage methods that provided additional soil protection. Movement was away from erosive straight-row practices and slightly away from strip cropping, toward the protective practices of contour cropping and terraces. As expected, conventional tillage with residue removed from the field is abandoned in favor of the more conventional tillage with the residue left in the field and the minimum tillage options.

The forest sector results

Under the combined model, the main change in the forest sector was to harvest methods such as helicopter and skyline logging. The greatest portion of these shifts occurred in the southern river basins. A second type of change in the forest sector was a change in acreage under the 80 Percent River Basin Restriction. The acreage shifts were also mainly located in the southern river basins. Forest harvesting trends were away from the southern areas to areas of less erosion potential.

The imposition of the historical pattern of forest harvesting practices indicates limited trade-off possibilities between the agriculture and forest sectors. In other words, reduced sedimentation from agriculture did not serve well as a substitute for reduced sedimentation from the forest sector. River basins with large areas in agricultural crops meet environmental restrictions primarily by shifts to soil-protecting agriculture practices. Heavily forested river basins shift toward advanced harvesting technologies to attain reduced sediment production rates.

Although the modeling solutions indicated that forest land and cropland were poor substitutes in terms of reducing instream sedimentation, it was very evident that policies directed toward environmental enhancements had exceptionally high opportunity costs. If sediment minimization was a national goal, it could be achieved at the cost of nearly a thousand dollars per ton by shifting to advanced technologies rather than the conventional tillage and harvest methods currently being employed.

The applicability of the research results presented here must be tempered by the abstractions from reality that were necessary for the development and linkage. In this study all forest types and products were aggregated; this has obvious implications on changing the specified rotation lengths, the product mixes, and the transportation requirements of each type. The concentration was exclusively oriented to the commercial forest land acreage; noncommercial and productive deferred uses might also be included as national production shifts to include fuelwood, posts, wildlings, and other less traditional uses.

Additional detail could be included to incorporate alternative machinery within the harvest methods, varying road widths and quality of construction, different road locations, species compositions, and end product mixes. Refinements of this nature would allow the forest sector to enjoy the high level of sophistication that is currently built into the agricultural sector.

The orientation presented also didn't allow for forest land to be converted into cropland or for abandoned cropland to be reverted back to productive forest land. Flexibility of this nature would most surely change the degree of substitutability between the two sectors.

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