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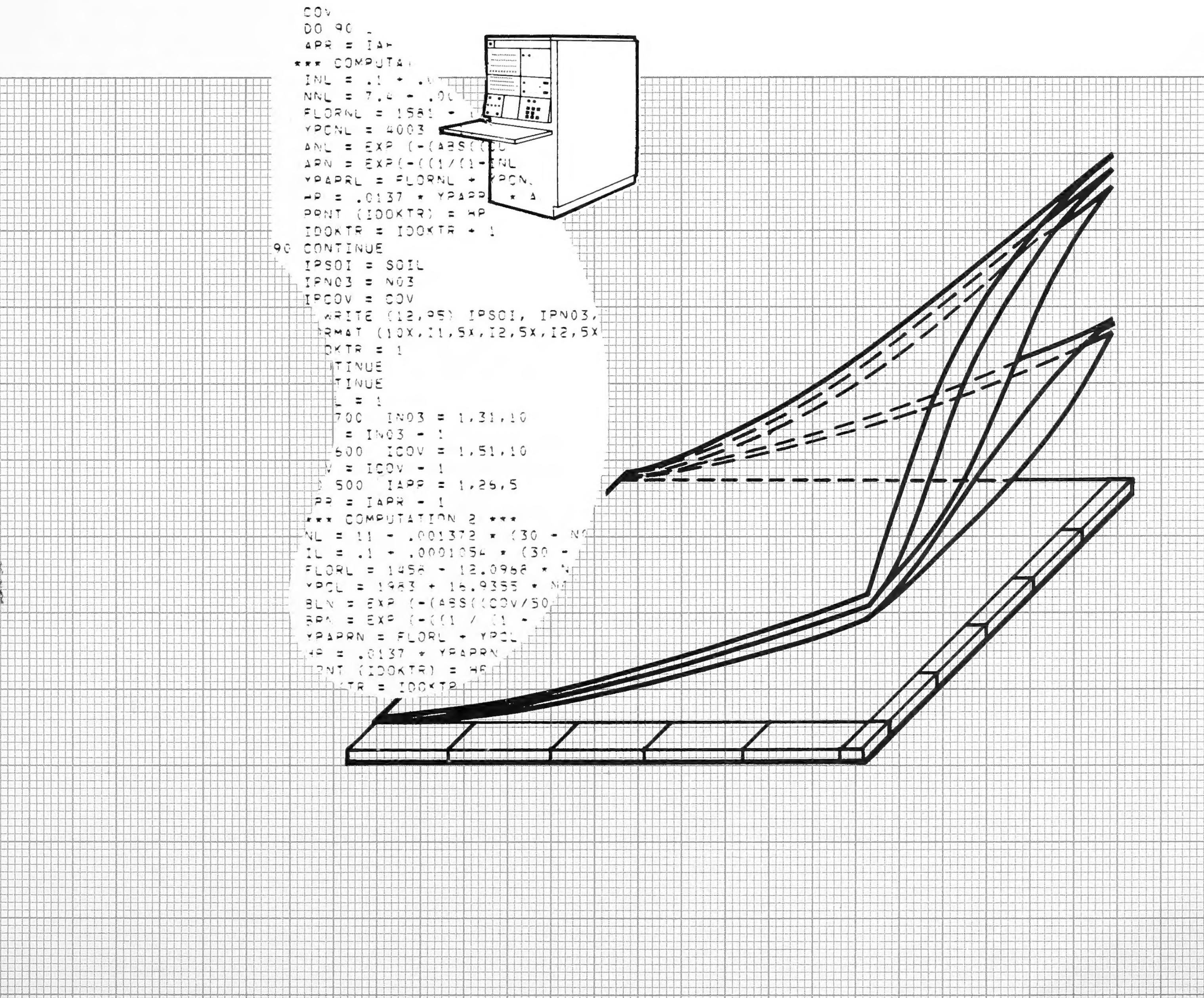
**Intermountain
Forest and Range
Experiment Station**

Research Paper
INT-279

July 1981

Mathematical Hypothesis for Herbage Production Potential on Pinyon - Juniper Areas

**Warren P. Clary
and
Chester E. Jensen**



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CHESTER E. JENSEN, retired, served as principal statistician for the Intermountain Forest and Range Experiment Station from 1967-1980. He held the same position at the Northeastern and Central States Forest Experiment Stations prior to coming to the Intermountain Station. Mr. Jensen, who holds a Master of Forestry degree from Michigan State University, received graduate training in statistics at Iowa State University.

RESEARCH SUMMARY

Herbage production potential of clearcut pinyon-juniper areas can be of critical interest to land managers. Published information is the basis for the theorized form of the relation between such potential and annual precipitation, original tree cover, soil nitrification level, and presence or absence of limestone soil. The fundamental expected effects appear to exist in a small data set from north-central Arizona. Estimates of specific forms and scales of the effects are made from data trends, within the constraints of expectation. Validation or at least rescaling (refitting) of the resulting interactive mathematical model to data from areas of application is recommended as a precondition for interim field use. A Fortran IV computer program for table output from the model is included.

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INTRODUCTION

Our concern here is the estimation of herbage production potential on wooded sites being considered for conversion to grassland. The relation between such production potential and four major variables affecting it is discussed. A mathematical model for the relation is presented along with a Fortran IV program to produce tabled model output. Some empirical inputs to the model were derived from data collected in the pinyon-juniper type of north-central Arizona.

The general form of the relationship is expected to apply to pinyon-juniper areas of the West and may have conceptual relevance to other woody plant communities. Testing or refitting of the mathematical model to data from other woodland or shrub communities may result in suitable prediction models for use by local land managers.

HYPOTHESIS--COMPONENT SOURCES

Herbage production values for 19 clearcut pinyon-juniper sites in north-central Arizona were subjected to regression screening processes for the simple additive effects of a variety of independent variables measured on these same sites (Clary and Jameson 1981). These simple hypotheses were regarded as having some theoretical basis and as being generally meaningful. The most useful of the effects appeared to be annual precipitation, tree cover, soil nitrates, and presence or absence of limestone soils.

We attempt in this paper to develop a model more rigorously tuned to the interactive nature of the relation wherein the effects of some or all of the independent variables change, depending on the levels of others. This model is proposed as a reasonable approximation of the true relation. The basic model structure was developed from information available in the literature, but specific coefficients were estimated from the Arizona data set.

DISCUSSION OF HYPOTHESIS COMPONENTS

Annual precipitation (APR) is the source of soil moisture needed for plant growth on most terrestrial sites. Also, as is known, regional differences in the capacity of land to produce plant matter are strongly and positively related to APR (Coe and others 1976; Sims and Singh 1978; Webb and others 1978). These circumstances, along with the widespread availability of APR information,[1] have led to its inclusion in the model as a prime and convenient indicator of regional differences in productivity.

Within a region of limited APR-range, gross differences in soil parent material can be expected to have a major effect on plant response to APR. In particular, reduced plant production on limestone-derived soils compared to that on many other soils is evidently a worldwide phenomenon (Whittaker and Niering 1968), although some variations to this can occur (Ffolliott and Clary 1975). This reduced production seems to be most likely to occur in areas where soils are poorly developed and are derived from relatively pure limestone parent material. It is least likely to occur where soils are highly developed from soil parent material with substantial amounts of impurities (Jenny 1941). Generally, the trend across arid and humid climates is for natural plant communities supported by limestone soils to exhibit a more xeric character than adjacent communities on other soils. This xeric nature is often characterized by reduced plant densities, different species composition, or changes in community physiognomy. Thus, we expect herbage yields to be generally lower on the limestone soils than on many nearby soils.

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[1] Climatological data. National Oceanic and Atmosphere Administration, National Climatic Center, Asheville, N.C.

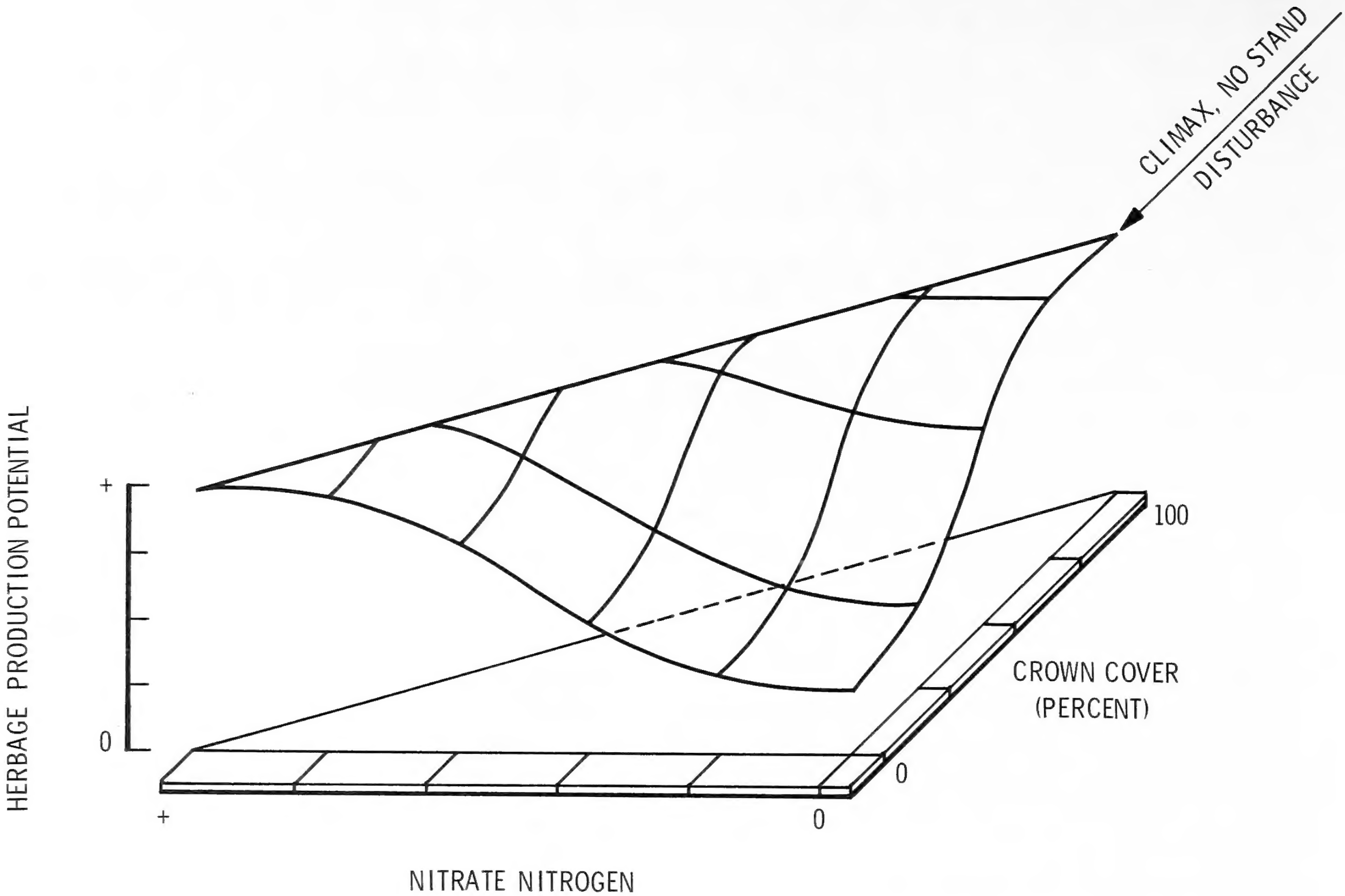

Figure 1.--The hypothesized relation between herbage production potential, nitrate-nitrogen level, and crown cover percent.

Within a region of limited APR-range and soil parent material (limestone versus other), site productivity can be expected to vary by reason of local differences in such environmental factors as topography and microclimate. The long-term integrated effects of these factors are reflected in the amount of tree cover developed for climax stands; so cover constitutes an excellent within-region index to site quality. Cable (1975), Clary and others (1966), and Pechanec and others (1954), have documented the positive relation between the amount of original woody-plant cover and, subsequent to removal of this cover, the amount of herbaceous plant growth in semiarid ecosystems. The hypothesized herbage production/cover relation is pictured at the right edge of figure 1. When climax cover is scant, the site is expected to be poor and potential herbage production low. As cover increases, both site and potential herbage production improve, the latter possibly reaching the asymptote shown over the upper range of cover.

When cutting, catastrophic fires, and other recent disturbances have decimated the climax cover to a greater or lesser extent, cover is no longer an uncompromised measure of site productivity. Under these circumstances, a supplementary index to productivity is needed. Studies conducted in both grassland and forest ecosystems suggest that ecosystems at the climax stage inhibit nitrification (Rice and Pancholy 1972, 1973). Release of a site, through disturbance of the climax overstory, could be expected to result in conditions again favorable to the accumulation of nitrates (model acronym NO3) in the soil to the extent permitted by residual climax trees (Vitousek and Melillo 1979).

With no residual trees, the opportunity exists for the accumulation of NO3 to a level determined by the characteristics of the site (Jenny 1941). The level of accumulation will of course differ among sites because each is unique in its exact combination of characteristics. Accumulation could vary as indicated by the full range of NO3 at zero cover in figure 1. The sigmoidal form for herbage production over NO3 was assumed to be approximately correct because experience in the agronomic field has shown diminishing returns from higher nutrient levels (Black 1957) and results in semiarid natural ecosystems have shown that only very modest nutrient levels can be effectively utilized by such systems (Hyder and others 1975).

It is assumed that when climax cover reaches a maximum virtually no nitrification takes place. Thus, the surface shown in figure 1 is truncated on the diagonal at the rear because maximum soil nitrates and maximum tree cover are not expected to occur simultaneously. The interactive nature of NO3 and climax cover is apparent in that herbage production potential varies differently over NO3, depending on the level of climax overstory.

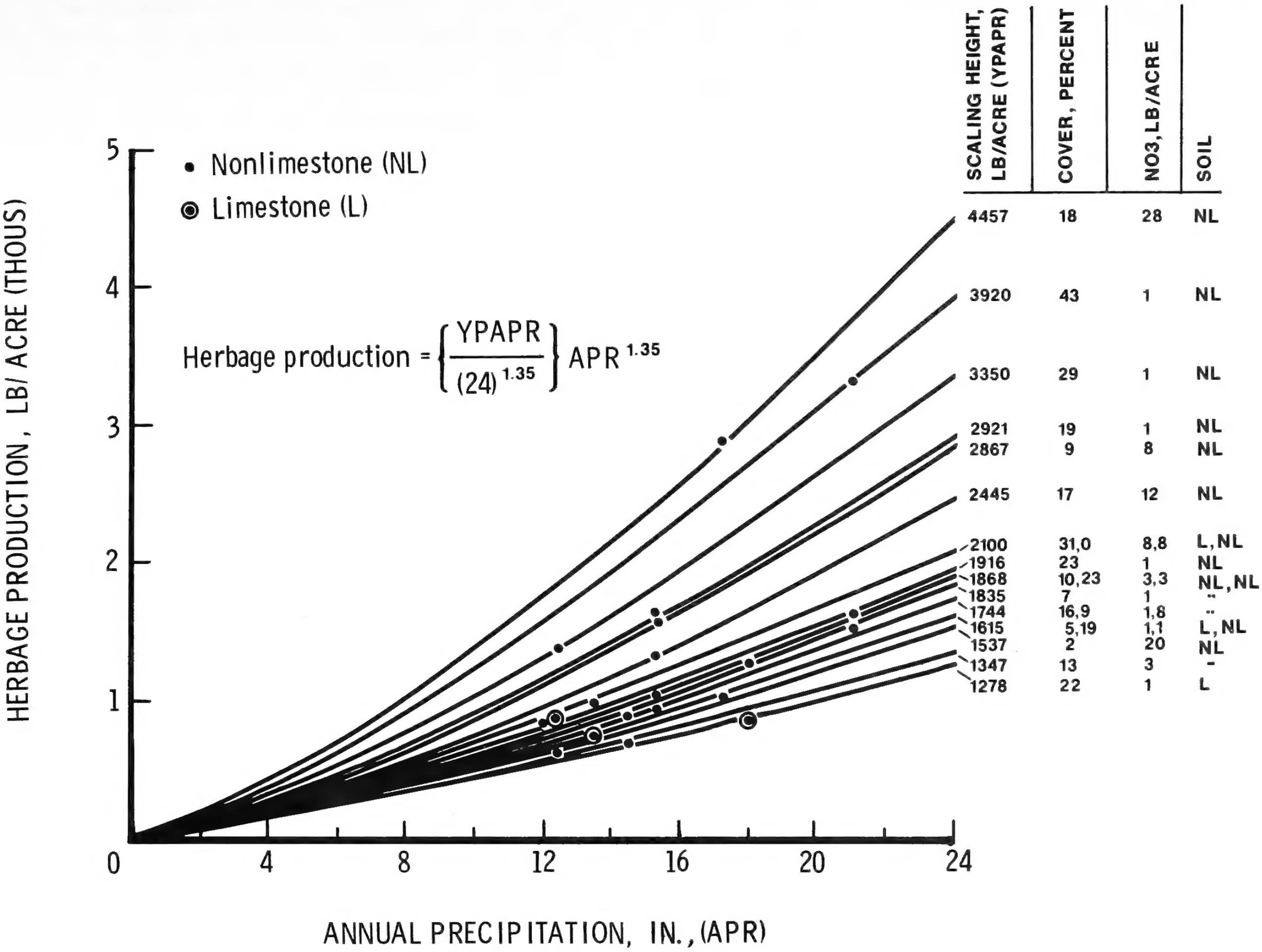

Figure 2.--Family of annual precipitation curves relating to individual data points.

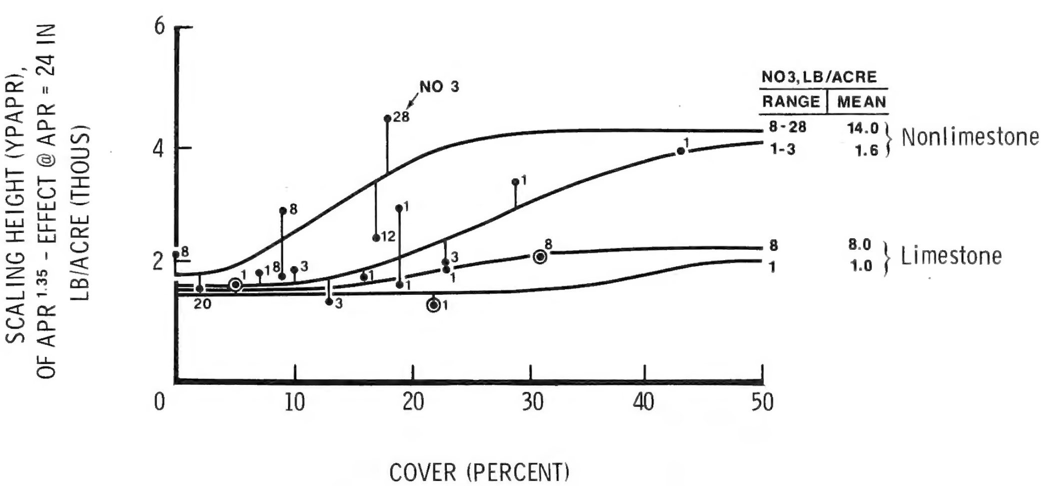

Figure 3.--Scaling height for the annual precipitation effect in relation to cover percent, nitrate-nitrogen, and limestone soils (presence or absence).

HYPOTHESIS DEVELOPMENT AND ASSOCIATED HERBAGE PRODUCTION POTENTIALS

Estimates of specific forms and scales for the effects of the independent variables were made from data trends, within the general constraints of the hypothesized model. In the modeling process, APR-effects were quantified first, followed in order by cover, nitrification, and limestone. The form of the relation was described mathematically according to Jensen and Homeyer (1970, 1971) and Jensen (1973, 1976, 1979). This modeling process was used since it is highly sensitive to curvilinear interaction, characteristic of the expected relation. Some procedural detail is presented for those who may be interested in validating the form and internal scales of the model with data from new areas. Methods are also shown for simple rescaling (refitting) of the existing model in its entirety, to data from new areas.

The expected effect for APR on biomass production is, of course, positive. Experience in the 5- to 25-inch (13- to 64-cm) precipitation zones of the Intermountain Area of the West (Packer and others 1979, Stevens and others 1974) suggests a flat to slightly concave-upward curve form. APR to the 1.35 power ($APR^{1.35}$) appeared to be appropriate for the Arizona data (Jensen and Homeyer 1971). Forced through both zero and each herbage production value, APR-effects were extended to APR=24 inches (61 cm) (fig. 2) The APR-effect was scaled at that point to the scaling height (YPAPR) for the Arizona data. YPAPR was then explored for expected limestone-, sigmoidal cover-, and N-effects (fig. 3) (Some steps in the model development [fig. 2 and 3, and the Fortran IV program] are illustrated in English units only. Model output [fig. 4 and table 1] is shown in both English and SI units.)

The expected negative limestone effect appeared to be at least supported by the very few observations available on limestone soils, and the expected cover- and NO3-effects were also fairly well expressed (fig. 3). The rather strong trend indicated by the six data points of the upper line (NL, NO3 = 14.0), together with experience-based knowledge that average-high productivity is not likely to exceed 4,500 lb/acre (5 040 kg/ha) (Stevens and others 1974), resulted in specification of a sigmoid that asymptotes conservatively at 4,200 lb/acre (4 704 kg/ha). It is possible that the asymptote could be higher. The complete sigmoid is reasonably well portrayed by the 10 data points for the second line from the top (NL, NO3 = 1.6).

The sigmoids of the two bottom lines (L, NO3 = 8.0 and 1.0) are highly conjectural, but the greatly reduced scale of these effects is one of the more important features of the model. In general, the sigmoidal forms shown in figure 3 can be visualized as representing sections of figure 1 at different NO3 levels and with different scaling factors.

The sigmoidal forms over cover were described using e^{-k} (Jensen and Homeyer 1970, Jensen 1979). Associated intercepts (FLORNL, FLORL), changing power (NNL, NL), inflection points (INL, IL), and scaling heights (YPCNL, YPCL) were all expressed as power functions of NO3 (Jensen and Homeyer 1971; Jensen 1973, 1976). Note that separate equations are developed for limestone and nonlimestone soils with each being displayed at two or three NO3 levels in figure 4.

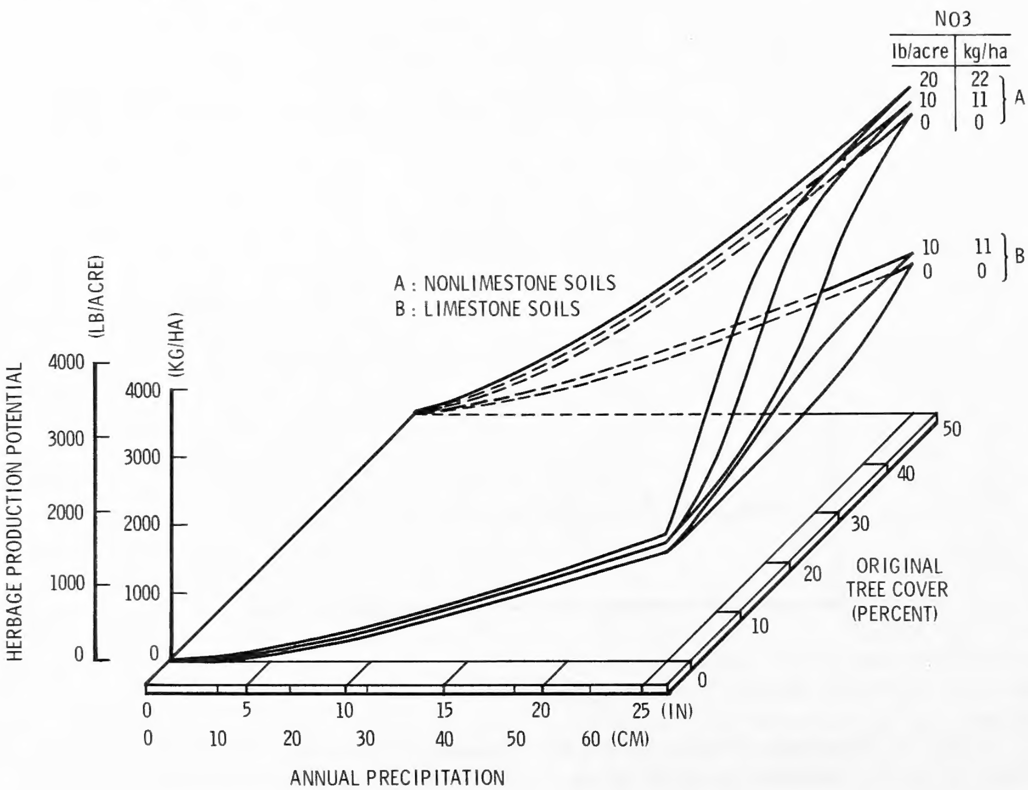

Figure 4.--Herbage production potential: the hypothesized interactive relation involving annual precipitation, presence or absence of limestone soils, tree crown cover, and nitrate nitrogen in the soil.

Table 1.--Modeled herbage production potentials for selected combinations of annual precipitation, presence or absence of limestone soils, tree crown cover, and nitrate-nitrogen in the soil

Soil	NO3	Cover	Annual precipitation, inches (cm)									
			5	(13)	10	(25)	15	(38)	20	(51)	25	(64)
	Lb/acre (kg/ha)[1]	*Percent*	*Forage production, lb/acre (kg/ha)*									
Lime	0 (0)	0	169	(189)	430	(482)	744	(833)	1,096	(1 228)	1,482	(1 660)
		10	169	(189)	430	(482)	744	(833)	1,096	(1 228)	1,482	(1 660)
		20	169	(189)	430	(482)	744	(833)	1,097	(1 229)	1,483	(1 661)
		30	170	(190)	434	(486)	751	(841)	1,107	(1 240)	1,496	(1 676)
		40	186	(208)	473	(530)	818	(916)	1,207	(1 351)	1,631	(1 827)
		50	229	(256)	585	(655)	1,011	(1 132)	1,491	(1 670)	2,015	(2 257)
	10 (11)	0	183	(205)	466	(522)	805	(902)	1,187	(1 329)	1,605	(1 798)
		10	183	(205)	467	(523)	807	(904)	1,190	(1 333)	1,608	(1 801)
		20	220	(246)	562	(629)	971	(1 088)	1,431	(1 603)	1,935	(2 167)
		30	247	(277)	631	(707)	1,090	(1 221)	1,608	(1 801)	2,173	(2 437)
		[2]40	249	(279)	635	(711)	1,098	(1 230)	1,618	(1 813)	2,187	(2 449)
Nonlime	0 (0)	0	183	(205)	466	(522)	806	(903)	1,189	(1 332)	1,606	(1 799)
		10	195	(218)	497	(557)	859	(962)	1,266	(1 418)	1,712	(1 917)
		20	233	(261)	593	(664)	1,026	(1 149)	1,513	(1 695)	2,045	(2 270)
		30	312	(349)	796	(892)	1,376	(1 541)	2,029	(2 272)	2,742	(3 071)
		40	413	(463)	1,052	(1 178)	1,818	(2 036)	2,681	(3 003)	3,623	(4 058)
		50	463	(519)	1,181	(1 323)	2,041	(2 286)	3,010	(3 371)	4,068	(4 556)
	10 (11)	0	197	(221)	502	(562)	868	(972)	1,280	(1 434)	1,730	(1 938)
		10	233	(261)	593	(664)	1,029	(1 152)	1,517	(1 699)	2,050	(2 296)
		20	377	(422)	960	(1 075)	1,660	(1 859)	2,448	(2 742)	3,308	(3 705)
		30	467	(523)	1,190	(1 333)	2,058	(2 305)	3,034	(3 398)	4,101	(4 593)
		40	482	(540)	1,230	(1 378)	2,126	(2 381)	3,135	(3 511)	4,237	(4 745)
	20 (22)	0	211	(236)	538	(603)	930	(1 042)	1,371	(1 536)	1,853	(2 075)
		10	352	(394)	897	(1 005)	1,552	(1 738)	2,288	(2 563)	3,092	(3 463)
		20	475	(532)	1,212	(1 357)	2,095	(2 346)	3,089	(3 460)	4,175	(4 676)
		30	501	(561)	1,276	(1 429)	2,207	(2 472)	3,254	(3 645)	4,398	(4 926)
	30 (34)	0	225	(252)	573	(642)	991	(1 110)	1,462	(1 637)	1,976	(2 213)
		10	408	(457)	1,039	(1 164)	1,796	(2 012)	2,648	(2 966)	3,579	(4 008)
		20	506	(567)	1,289	(1 444)	2,229	(2 496)	3,287	(3 681)	4,442	(4 975)

[1]SI units in parentheses.
[2]The table is asymmetric because maximum values of NO3 and cover are not expected to occur simultaneously (see fig. 1).

For each model then, we are able to specify the basic APR-effect as:

$$HP = \left\{ \frac{YPAPR}{(24)^{1.35}} \right\} * (APR)^{1.35}$$

where:

YPAPR = INTERCEPT + SCALAR FOR THE SIGMOIDS* SIGMOIDS OVER COVER.

YPAPRL is used in the model for lime soils.

YPAPRN is used in the model for nonlime soils.

INTERCEPTS:

NON-LIME: FLORNL = 1581 + 12.0968 * NO3

LIME: FLORL = 1458 + 12.0968 * NO3

SCALARS FOR SIGMOIDS:

NON-LIME: YPCNL = 4003 + 16.9355 * NO3 - FLORNL

LIME: YPCL = 1983 + 16.9355 * NO3 - FLORL

SIGMOIDS OVER COVER:

$$\left(\frac{e^{-\left|\frac{\frac{COVER}{50} - 1}{1 - INFL}\right|^{N}} - e^{-\left\{\frac{1}{1-INFL}\right\}^{N}}}{1 - e^{-\left\{\frac{1}{1-INFL}\right\}^{N}}} \right)$$

INFLECTION POINTS (INFL):

NON-LIME: INL = 0.1 + 0.0006869 * $(30\text{-}NO3)^{1.9}$

LIME: IL = 0.1 + 0.0001054 * $(30\text{-}NO3)^{2.6}$

SIGMOIDAL POWER (N):

NON-LIME: NNL = 7.4 - 0.003067 * $(30\text{-}NO3)^{2.2}$

LIME: NL = 11.0 - 0.001372 * $(30\text{-}NO3)^{2.6}$

LIMITS:

$0 \leq$ cover ≤ 50, IF cover >50, HP = HP @ cover = 50

$0 \leq APR \leq 25$

$0 \leq NO3 \leq 30$, IF NO3 >30, HP = HP @ NO3 = 30

After derivation from both prior knowledge and the data at hand, the model was mathematically readjusted to the data with a relatively simple coefficient that forces the fitted model through zero,

$$b = \Sigma XY / \Sigma X^2$$

where X = the model herbage production value for specified levels of APR, cover, and NO3; and Y = the related observed value of herbage production. A weighting factor of $1/Y^n$ was evaluated and discarded since it was poorly related to the variance about the least-squares fitted model ($R^2 = 0.03$). The b-value for the 19 observations was 0.9618 or, in other words, the initially derived model was about 4 percent high with respect to the least-squares fit. For the final model R^2 is 0.84 and $s_{y.x}$ is about 287 lb/acre (321 kg/ha). Values for the relation are given in table 1.

Note that $s_{y.x}$ is likely to be underestimated here since unknown degrees of freedom are sacrificed in exploiting the data as explained. Models developed in this way are probably best used as advanced hypotheses, to be tested and scaled ($b = \Sigma XY / \Sigma X^2$) to new data sets. In the absence of better information such models can, of course, be used as interim predictors with suitable caution.

A Fortran IV computer program for table output from the model follows:

```
; DGC FORTRAN IV REV 05.52NS

; C     ***  PROGRAM NAME = CHET
; C     ***  PERFORM CALCULATIONS FOR LIME AND NON-LIME SOIL
; C     ***  USEING VARIABLES NO3, COVER AND APR
;         DIMENSION PRNT(6)
;         REAL NNL, INL, NL, IL, NO3
;         IPSOI = 0
;         IPNO3 = 0
;         IPCOV = 0
;         IDOKTR = 1
;         SOIL = 0
;         WRITE (12,5)
;       5 FORMAT (46X,"ANNUAL PRECIPITATION")
;         WRITE (12,10)
;      10 FORMAT (8X,"SOIL",3X,"NO3",3X,"COVER",10X,"0",7X,"5",6X,"10",6X,"1
;        -5",6X,"20",6X,"25")
;         WRITE (12,15)
;      15 FORMAT (1X,"-----------------------------------------------------
;        ----------------------------------------")
;         DO 200 INO3 = 1,31,10
;         NO3 = INO3 - 1
;         DO 100 ICOV = 1,51,10
;         COV = ICOV - 1
;         DO 90 IAPR = 1,26,5
;         APR = IAPR - 1
; C      *** COMPUTATION 1
;         INL = .1 + .0006869 * (30 - NO3) ** 1.9
;         NNL = 7.4 - .003067 * (30 - NO3) ** 2.2
;         FLORNL = 1581 + 12.0968 * NO3
;         YPCNL = 4003 + 16.9355 * NO3 - FLORNL
;         ANL = EXP (-(ABS((COV/50-1) / (1-INL))**NNL))
;         ARN = EXP(-((1/(1-INL))**NNL))
;         YPAPR = FLORNL + YPCNL * ((ANL - ARN) / (1-ARN))
;         HP = .0137 * YPAPR * APR ** 1.35 * .9618
;         PRNT (IDOKTR) = HP
;         IDOKTR = IDOKTR + 1
;      90 CONTINUE
;         IPSOI = SOIL
;         IPNO3 = NO3
;         IPCOV = COV
;           WRITE (12,95) IPSOI, IPNO3, IPCOV, PRNT
;      95 FORMAT (10X,I1,5X,I2,5X,I2,5X,6F8.0)
;         IDOKTR = 1
;     100 CONTINUE
;     200 CONTINUE
;         SOIL = 1
;         DO 700  INO3 = 1,31,10
;         NO3 = INO3 - 1
;         DO 600  ICOV = 1,51,10
;         COV = ICOV - 1
;         DO 500  IAPR = 1,26,5
;         APR = IAPR - 1
; C       *** COMPUTATION 2 ***
;         NL = 11 - .001372 * (30 - NO3) ** 2.6
;         IL = .1 + .0001054 * (30 - NO3) ** 2.6
;         FLORL = 1458 + 12.0968 * NO3
;         YPCL = 1983 + 16.9355 * NO3 - FLORL
;         BLN = EXP (-(ABS((COV/50-1) / (1 - IL)) ** NL))
;         BRN = EXP (-((1 / (1 - IL)) ** NL))
;         YPL = FLORL + YPCL * ((BLN - BRN) / (1 - BRN))
;         HP = .0137 * YPL * APR ** 1.35
;         PRNT (IDOKTR) = HP * .9618


;         IDOKTR = IDOKTR + 1
;     500 CONTINUE
;         IPSOI = SOIL
;         IPNO3 = NO3
;         IPCOV = COV
;         WRITE (12,95) IPSOI, IPNO3, IPCOV, PRNT
;         IDOKTR = 1
;     600 CONTINUE
;     700 CONTINUE
;         STOP
;         END
```

Note that all statements within the brackets comprise the Fortran IV program necessary to output of tables values presented in the paper. This should run on any computer subject to minor changes to accommodate programing peculiarities of the system: e.g., "PRINT" in place of "WRITE" is appropriate for IBM systems.

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Herbage production potential of clearcut pinyon-juniper areas can be of critical interest to land managers. Published information is the basis for the theorized form of the relation between such potential and annual precipitation, original tree cover, soil nitrification level, and presence or absence of limestone soil. The fundamental expected effects appear to exist in a small data set from north-central Arizona. Estimates of specific forms and scales of the effects are made from data trends, within the constraints of expectation. Validation or at least rescaling (refitting) of the resulting interactive mathematical model to data from areas of application is recommended as a precondition for interim field use. A Fortran IV computer program for table output from the model is included.

KEYWORDS: hypothesis, mathematical model, herbage production, pinyon-juniper, precipitation, cover, nitrate, soil type

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The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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