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Optimizing Wet-Dry Precipitation Probabilities For Improving Plant Establishment

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Abstract

Studies have shown that the chances of achieving successful seedling establishment in arid and semiarid regions is dependent upon the pattern of favorable wet-dry precipitation sequences. A daily rainfall simulation model based on a first-order Markov chain was used to generate wet-dry-wet precipitation sequence probabilities based on parameters estimated from 22 years of daily precipitation data in southern Arizona. These simulated data were used to indicate an optimum seeding time that maximizes the probability of a favorable wet-dry sequence following seeding. Based on a premise that a favorable sequence consists of wet periods of 1 to 3 days in length with the following dry period being 5 days or less, the results indicate that the optimum time to seed in southern Arizona is after 1 August. This is two to three weeks later than the normal start of the rainy season.

Introduction

Many guidelines for plant establishment from seeds under rainfed conditions provide only general information concerning water requirements for seedling establishment. Stoddard (1946) recommended seeding only in areas where the annual precipitation exceeds a predefined amount based upon species requirements. Information on new plant species frequently refers to adaptability in specific annual rainfall zones, (Stevens et al. 1985). These guidelines do not take into account the effect of the timing of available soil moisture on

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plant establishment. Cox and Jordan, (1983), reported that the frequency and quantity of precipitation events at the time of seeding are much more critical to successful seedling establishment than the total annual precipitation. The timing of the precipitation events is especially important in arid and semiarid regions where seeding successes may only occur once in 5 to 10 years (Cox et al. 1982).

There are two critical periods of water availability in the initial stages of seedling establishment; (1) the initial wet period when seeds germinate and (2) the subsequent dry period (Frasier et al. 1985). Some seeding guidelines have been concerned with only the length and timing of the wet period. Parker and McGinnies (1940) recommended that, for southwestern ranges, seeds be planted prior to the start of the summer rainy season. Very little information is available on the effect of the inevitable dry period which always follows the wet period (Cox 1984). With a wet period of suitable length, the seeds germinate and seedlings develop to a physiological stage capable of surviving the following dry period. However, if the dry period exceeds some critical length, the seedling will die (Frasier 1986). Frasier et al. (1987) found that 3 wet days were sufficient to produce viable seedlings of five warm season grasses that could survive subsequent dry periods up to five days duration. When the dry period following the initial 3 wet days was extended to 7 days, seedling survival was significantly reduced.

To maximize the probability for achieving successful seedling establishment, the seeding must occur at the time of the year when there is a maximum joint probability that the wet period exceeds the time required for seed germination and initial seedling root development and that the following dry period is shorter than the critical length which kills the germinated seeds or seedlings. This paper discusses an approach for estimating the time of year in southern Arizona that has the highest probability of favorable wet-dry sequences for seedling establishment that meet the 3 wet day, 5 days or less dry, plant survival characteristics.

Methods

A simulation model was developed to estimate the number of various wet-dry precipitation sequences during the year. The model has two components; (1) the occurrence process of wet-dry daily rainfall sequences which is modeled using a first-order Markov chain and (2) a distribution of daily amounts which is modeled using a mixed exponential distribution. The parameters for these models were estimated using twenty-two years, (1955 through 1976), of daily precipitation data from a raingage on the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona.

Woolhiser and Roldan (1986) described the dependence between wet and dry occurrences using a first-order Markov chain:

$$p_{ij}(n) = P\{X_\gamma(n) = j \mid X_\gamma(n-1) = i\} \text{ for } n > 1, \qquad (1)$$

and

$$p_{ij}(1) = P\{X_\gamma(1) = j \mid X_{\gamma-1}(365) = i\} \qquad (2)$$

where p_{ij} is the transition probability, $i = 0, 1$ and $j = 0, 1$, X_γ is the occurrence, and γ is the year of the occurrence. $X_\gamma(n)$ is 0 if day n is dry or 1 if day n is wet. The necessary seasonal variations of the transition probabilities were approximated using Fourier series.

Smith and Schreiber (1974) showed that daily precipitation amounts in southern Arizona could be described by a mixed exponential distribution:

$$f_n(P) = \frac{\alpha(n) \exp[-P/\beta(n)]}{\beta(n)} + \frac{[1 - \alpha(n)]\exp[-P/\delta(n)]}{\delta(n)} \qquad (3)$$

where f_n is a probability density function and (P) is the amount of rainfall minus some threshold value. The variable $\alpha(n)$ is a weighing parameter whose values range between 0 and 1. The variable $\beta(n)$ represents the mean of the smaller precipitation distribution; and $\delta(n)$, the mean of the larger precipitation distribution. The seasonal variations of these parameters were approximated by Fourier series. The necessary means, amplitudes and phase angles of the Fourier series were computed using a program, MCMELOG, which computes a numerical maximization of the log likelihood function (Woolhiser and Roldan 1986). The Akaike (1974) information criterion was used to select significant harmonics.

Before simulation begins, the transition probabilities, the probability of rain and the amount of rain for an entire year were computed using the Fourier coefficients obtained by program MCMELOG. The simulation program then asked the user to enter a starting day, n.

Simulation began by first sampling from a uniform distribution, U(0,1), using a random number generator. The dry-dry transition probability for day n,

$p_{00}(n)$, was compared with the number. If this number was less than $p_{00}(n)$, then the day was dry.

When the number was greater than $p_{00}(n)$ the day was wet. If the day was wet, a second number was taken from U(0,1) and used to determine which exponential distribution to use to compute the rainfall amount.

After, the exponential distribution was selected, a third number was drawn from U(0,1). This number was used to generate the amount of rain for day n. This amount was compared to the threshold selected for the start of a wet sequence. If the amount exceeded the threshold, then the first day of the wet sequence had occurred. If the amount was not greater than the threshold, then the day was wet but did not meet the minimum amount criterion and the day was considered dry.

This is the cycle used to simulate an occurrence. However, once a wet sequence was started the first number drawn was compared against $p_{10}(n)$ and the rainfall amounts were compared against the threshold for subsequent wet days. At the end of each cycle, n is incremented. The cycle terminated when a second wet sequence occurred or when n had reached the maximum length for a sequence specified by the user.

The number of days in the wet sequence and the following dry sequence were used to compute the joint probabilities. The procedure was repeated until a thousand years of data had been simulated and the number of wet days and following dry days tabulated for each starting date.

The following joint probabilities were calculated from the simulated data:

$$P\{ n = 1,2,3 \mid m \le 5 \} \tag{4}$$

$$P\{ n = 2,3 \mid m \le 5 \} \tag{5}$$

$$P\{ n = 1,2,3 \mid m > 5 \} \tag{6}$$

$$P\{ n = 2,3 \mid m > 5 \} \tag{7}$$

where n is the number of wet days in the sequence and m is the following number of dry days in the sequence. Four pairs of thresholds (initial day and subsequent wet days) were studied: 6.4 and 0.25 mm; 6.4 and 6.4 mm; 2.5 and 0.25 mm; and 2.5 and 2.5 mm.

Results and Discussion

The historical daily average rainfall and the theoretical average daily rainfall as described by a Fourier Series are presented in Figure 1.

The data show that the mean daily rainfall peaks during the period from the middle of July to the middle of August. There are of course, large variations in the historical average daily amounts on adjacent dates. The model sampling smooths the daily extremes which is intuitively satisfying because we would not expect erratic behavior in the rainfall process.

The probabilities of: (1) no rain, (2) 1-3 wet days followed by 1-5 days dry; and (3) 1-3 wet days followed by a dry period of greater than 5 days during the 30 day period starting on the first of each month with initial and subsequent rainfall thresholds of 0.25 mm are shown in Figure 2.

Results of plant survival studies (Frasier et al. 1987), suggest that the best time for seeding occurs when the joint probabilities of 1-3 wet days followed by 1-5 dry days is greater than the probabilities of the same 1-3 wet days but with the dry period > 5 days. The results indicate that this condition occurs during the month of August. This period is two to three weeks after the assumed start of the rainy season in the area (Schreiber and Sutter 1972). This is also the period with the lowest probability of not having any rain.

This assessment does not quantify the effect of the size of the storm. There is a disproportionate number of the storms (45% of the total number of wet days) when the rainfall would be too low for practical benefit (Figure 3). A threshold rainfall amount of 2.5 mm or more is more appropriate for seeding requirements than the 0.25 mm used in the previous discussion.

Table 1 presents the probabilities of: (1) 1-3 wet days, 1-5 dry days; (2) 1-3 wet, >5 dry; (3) 2-3 wet, 1-5 dry; (4) 2-3 wet, > 5 dry; and (5) no rain, for initial and subsequent rainfall thresholds of 0.25, 2.5 and 6.4 mm. The results show the same general pattern as previously discussed in Figure 2. The probability magnitudes become lower as the rainfall threshold levels increases. In all combinations, the best time to seed remains about the first of August when there is a greater probability of the dry period being 5 or less days than the probability of the dry periods being greater than 5 days.

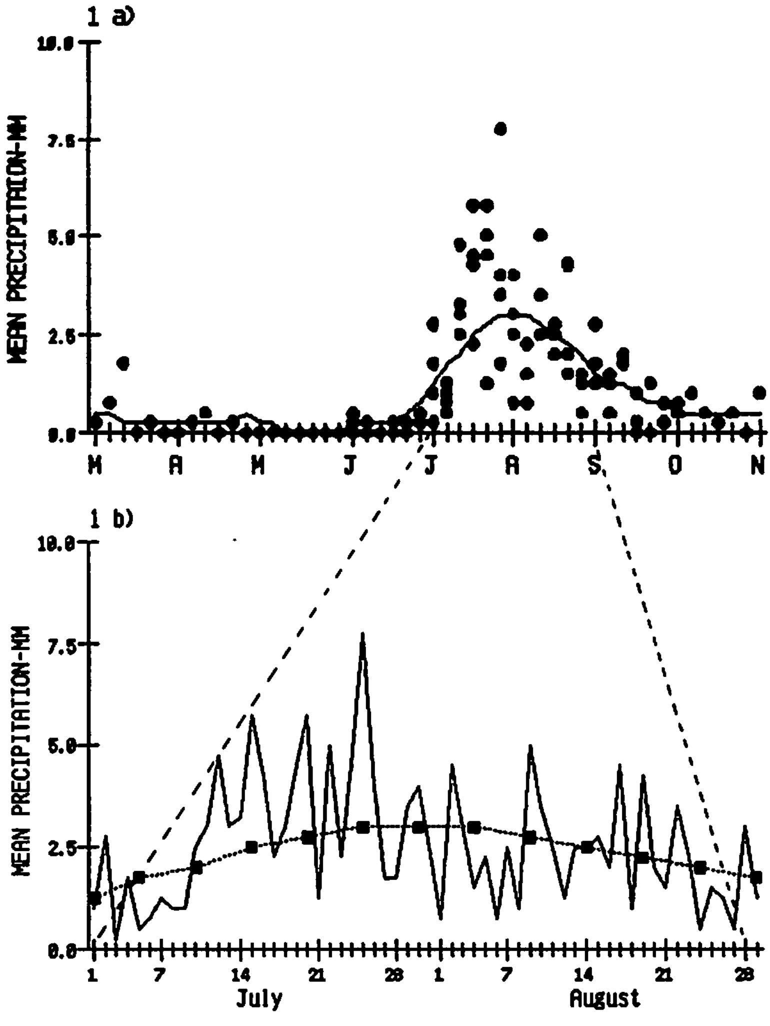

Figure 1. a) Historical 20 year average daily and modeled average rainfall quantities for the spring-summer rainfall season (March-October) at the Walnut Gulch Experimental Watershed near Tombstone, Arizona; b) the historical and modeled daily rainfall averages for the period of 1 July through 30 August.

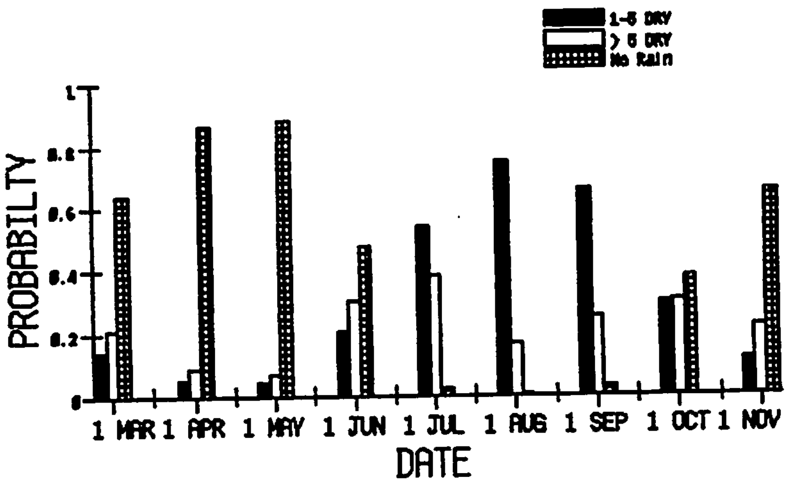

Figure 2. Probability of: (1) no rain; (2) 1-3 days wet, 1-5 days dry; and (3) 1-3 days wet, > 5 days dry during the a 30 day period starting on the first of each month with initial and subsequent rainfall thresholds of 0.25 mm at the Walnut Gulch Experimental Watershed.

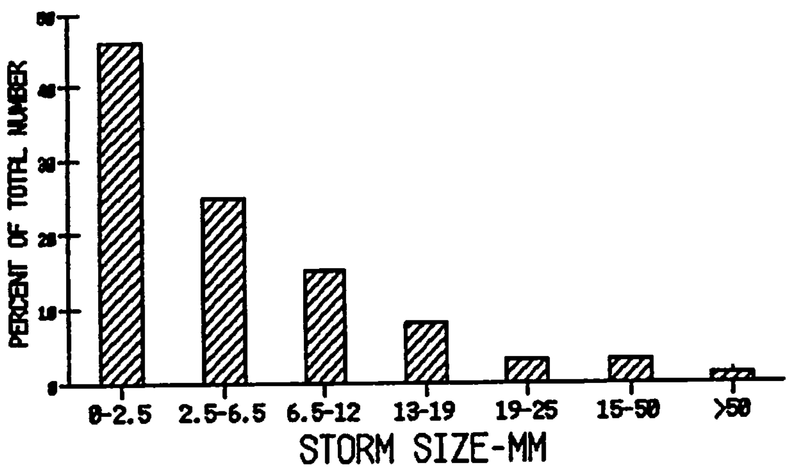

Figure 3. Storm size distribution from a single raingage on the Walnut Gulch Experimental watershed was used to generate parameters for the simulation model.

Table 1. Probabilites of wet-dry sequences: (a) 1-3 days wet, 1-5 days dry; (b) 1-3 wet, >5 dry; (c) 2-3 wet, 1-5 dry; (d) 2-3 wet, >5 dry and probability of no rain for five initial and subsequent rainfall thresholds for nine 30 day periods starting on the first of each month during the summer at the Walnut Gulch Experimental Watershed near Tombstone, AZ.

THRESHOLD		WATER SEQUENCE		DATE								
INITIAL	SUBSEQ.	WET	DRY	1 MAR	1 APR	1 MAY	1 JUN	1 JUL	1 AUG	1 SEP	1 OCT	1 NOV
(mm)	(mm)	(days)	(days)									
0.25	0.25	1-3	1-5	0.14	0.05	0.05	0.21	0.54	0.75	0.66	0.30	0.12
			>5	0.21	0.09	0.07	0.30	0.38	0.17	0.25	0.30	0.22
		2-3	1-5	0.03	0.02	0.01	0.06	0.20	0.30	0.23	0.10	0.03
			>5	0.06	0.01	0.01	0.09	0.11	0.08	0.10	0.09	0.07
		NO RAIN		0.64	0.87	0.89	0.47	0.02	<.01	0.03	0.38	0.65
2.5	0.25	1-3	1-5	0.06	0.02	0.01	0.12	0.40	0.57	0.44	0.13	0.07
			>5	0.09	0.03	0.04	0.20	0.43	0.31	0.35	0.22	0.11
		2-3	1-5	0.01	<.01	<.01	0.04	0.16	0.20	0.16	0.04	0.02
			>5	0.02	<.01	0.01	0.05	0.15	0.11	0.14	0.06	0.03
		NO RAIN		0.86	0.96	0.95	0.68	0.12	0.04	0.16	0.63	0.81
2.5	2.5	1-3	1-5	0.07	0.02	0.02	0.14	0.44	0.63	0.48	0.16	0.09
			>5	0.09	0.03	0.04	0.20	0.43	0.32	0.37	0.23	0.11
		2-3	1-5	0.01	<.01	<.01	0.03	0.09	0.16	0.10	0.03	0.01
			>5	0.01	<.01	<.01	0.02	0.08	0.07	0.10	0.03	0.02
		NO RAIN		0.85	0.95	0.94	0.67	0.12	0.03	0.15	0.61	0.80
6.4	0.25	1-3	1-5	0.01	0.01	0.01	0.05	0.25	0.39	0.27	0.06	0.03
			>5	0.03	0.01	0.01	0.09	0.33	0.37	0.31	0.12	0.04
		2-3	1-5	<.01	<.01	0.00	0.01	0.09	0.15	0.08	0.02	0.01
			>5	0.01	<.01	<.01	0.03	0.10	0.13	0.11	0.04	0.02
		NO RAIN		0.96	0.99	0.98	0.86	0.38	0.17	0.40	0.80	0.93
6.4	6.4	1-3	1-5	0.02	0.01	0.01	0.06	0.27	0.45	0.28	0.08	0.04
			>5	0.03	0.01	0.01	0.09	0.36	0.39	0.33	0.14	0.04
		2-3	1-5	0.00	<.01	0.00	<.01	0.03	0.07	0.03	0.01	<.01
			>5	<.01	0.00	<.01	0.01	0.03	0.04	0.06	0.01	0.01
		NO RAIN		0.95	0.99	0.98	0.85	0.37	0.16	0.39	0.79	0.92

By using two thresholds, one for the start of the wet sequence and the other for the subsequent wet days in the wet sequence, the sequences were dissociated. The probability of getting 1 to 3 wet days followed by 1 to 5 dry days was higher when both thresholds were set to 6.4 mm than when they were set to 6.4 and 0.25 mm for the initial and subsequent wet days, respectively. By lowering the threshold for subsequent wet days in a sequence, the wet sequence was extended. Further evidence of dissociation is indicated when the rainfall thresholds for the initial and subsequent days are equal (ie. 2.5 and 2.5 mm) the probabilities for 2 to 3 wet days followed by 1 to 5 dry days are considerably less than the probabilities for the 1 to 3 wet day followed by 1 to 5 dry days. When lower thresholds are used, the number of wet sequences increases and the probability of not having rain decreases.

Conclusion

The occurrence of specific wet-dry day sequences is of major significance in the development of seeding procedures for arid and semi-arid regions. Short-term precipitation records are frequently highly variable and it is difficult to know if the means are representative of the local climate. A first-order Markov chain simulation model was used to generate a 1000 record years of wet-dry day sequences based on a 22 year data set in southern Arizona. The program computed the daily joint probability for different wet-dry day combinations at various threshold rainfalls.

For effective seedling establishment, the optimum time to seed is the time of year when the probability of a wet period followed by a short dry period is greater than the wet period followed by a long dry period. The results showed that for southern Arizona, the optimum time for seeding is in August. This is in contrast to common seeding practice which recommends planting prior to the start of the summer rainy season in July.

References

Akaike, H. (1974). "A New Look at the Statistical Model Identification." IEEE Trans, Autom. Control, 19(6):716-723.

Cox, J.R. (1984). "Temperature, Timing of Precipitation and Soil Texture Effects On Germination, Emergence and Seedling Survival of South African Lovegrasses", J. South Africa Botany, 2(2):159-170.

Cox, J.R., and Jordan, G.L. (1983). "Density and Production of Seeded Range Grasses in Southeastern Arizona (1970-1982)." J. Range Manage., 36:649-652.

Cox, J.R., Morton, H.L., Johnsen Jr., T.N., Jordan, G.L., Martin, S.C., and Fierro, L.C. (1982). "Vegetation Restoration in the Chihuahuan and Sonoran Deserts of North America." United States Department of Agriculture, Agricultural Research Service, Agricultural Reviews and Manuals, ARM-W-28, 37 pgs.

Frasier, G.W. (1986). "Water Requirements for Range Plant Establishment." Water Forum '86: World Water Issues in Evolution, Vol. 1, ASCE, pp. 839-846.

Frasier, G.W., Cox, J.R., and Woolhiser, D.A. (1985). "Emergence and Survival Response of Seven Grasses for Six Wet-Dry Sequences." J. Range Manage., 38:372-377.

Frasier, G.W., Cox, J.R., and Woolhiser, D.A. (1987). "Wet-dry Cycle Effects on Warm-season Grass Seedling Establishment." J. Range Manage., 40(1):2-6.

Parker, K.W., and McGinnies, W.G. (1940). "Reseeding Southwestern Ranges." Southwestern Forest and Range Experiment Station Research Note No. 86, 5 pgs.

Schreiber, H.A., and Sutter, N.G. (1972). "Available Soil Water: Time-Distribution in a Warm Season Rangeland." J. Hydrology, 15:285-300.

Smith, R.E., and Schreiber, H.A. (1974). "Point Processes of Seasonal Thunderstorm Rainfall 2. Rainfall Depth Probabilities." Water Resources Research, 10(3): 418-423.

Stevens, R., Jorgensen, K.R., McArthur, E.D., and Davis, J.D. (1985). "'Immigrant' Forage Kochia." Rangelands, 7(1):22-23.

Stoddard, L.A. (1946). "Seeding Arid Ranges to Grass with Specific Reference to Precipitation." Circular 122, Agricultural Experiment Station, Utah State University, Logan, Utah.

Woolhiser, D.A., and Roldan, Jose. (1986). "Seasonal and Regional Variability of Parameters for Stochastic Daily Precipitation Model: South Dakota, U.S.A." Water Resources Research, 22(6):965-978.