Effects of Soil Physical Properties, Rainfall Characteristics, and Wind Velocity on Clod Disintegration by Simulated Rainfall[1]

LEON LYLES, L. A. DISRUD, AND N. P. WOODRUFF[2]

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Effects of Soil Physical Properties, Rainfall Characteristics, and Wind Velocity on Clod Disintegration by Simulated Rainfall[1]

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ABSTRACT

The effects of clod size and density, rainfall intensity and duration, and wind velocity on clod disintegration by simulated rainfall were studied in a laboratory wind tunnel-raintower facility. Significant interactions (including those of higher order) were found among the variables studied. Clod bulk density had a minor effect on disintegration. For a specific clod size and wind velocity, 10-min rains at 5.61 cm/hour were about as destructive as 90-min rains at 1.60 cm/hour, even though the total volume of rainfall was 2.5 times larger in the latter case.

Wind-driven rain was very effective in clod disintegration. Up to 66% more soil was lost from clods exposed to 13.4-m/sec winds than from those exposed to no wind for the same rain intensity, duration of exposure, and clod size. Mean drop size striking the clods probably increases with wind velocity and would account for some of the wind effects. Small clods were more susceptible to disintegration by raindrop impact than large clods. Multiple regression analyses indicate about 80 and 89% of the soil detachment variance was accounted for by linear and curvilinear procedures respectively.

Additional Key Words for Indexing: **soil erosion, wind-driven rain, cloddiness, liquid limit.**

SOIL CLODDINESS is an important factor in controlling both wind and water erosion. A rough, cloddy surface readily receives rainfall and is less wind erodible than smoother surfaces (3).

Soil cloddiness is transient and depends on numerous soil, climatic, and mechanical factors (4, 5, 7, 8). Clods formed by tillage are subsequently disintegrated by other mechanical manipulation and climatic influences. Notable climatic factors affecting surface clod disintegration are rainfall intensity and duration. The impact of raindrops plus water entry cause soil fragments or clods to "melt" and run together (1).

Physical soil factors affecting the persistence of clods exposed to beating and wetting action of rainfall have not been studied extensively. Excluding soil texture, clod size, and clod density are soil physical properties that should influence resistance to breakdown by rainfall.

Although many rainfall events are accompanied by strong winds, the effect of wind-driven rainfall on clod disintegration, as opposed to rainfall without wind, is largely unknown.

This paper examines the combined effects of clod size, clod density, rainfall intensity, rainfall duration, and wind velocity on disintegration of soil fragments or clods.

DESIGN AND DESCRIPTION OF EXPERIMENT

For ease of reference and identification, the experimental variables are summarized in Table 1. The study was a factorial experiment in a completely random design with three replications of each combination.

Field clods were formed by chisel tillage of a silt loam soil for which certain physical properties are given in Table 2. Moisture contents are on a weight basis. Samples were collected and air-dried, and the size ranges for study were obtained by rotary sieving.

The various clod sizes were placed on 38.1- by 45.7-cm trays whose bottoms were 6.4- or 2.0-mm screens (Fig. 1), and exposed to simulated rainfall in the 1.52-m-wide by 3.05-m-long raintower section of the low-velocity wind tunnel facility at Kansas State University. Three replications were exposed during each rainfall event. Vertical dividers were used between trays

Table 1—Identification and magnitude of experimental variables

Variable	Symbol	Values
Clod size 1	C_1	2.0 - 6.4 mm in diameter
Clod size 2	C_2	6.4 - 12.7 mm in diameter
Clod size 3	C_3	12.7 - 38.0 mm in diameter
Clod size 4	C_4	50.8 - 76.2 mm in diameter
Soil bulk density no. 1	D_1	1.25 g/cm³ (avg of 15 samples)
Soil buil density no. 2	D_2	1.51 g/cm³ (avg of 15 samples)
Duration of exposure no. 1	T_1	30 minutes
Duration of exposure no. 2	T_2	90 minutes
Rainfall intensity no. 1	I_1	1.60 cm/hour (avg over 3 wind velocities)
Rainfall intensity no. 2	I_2	2.84 cm/hour (avg over 3 wind velocities)
Rainfall intensity no. 3	I_3	5.61 cm/hour (avg over 3 wind velocities)
Wind velocity no. 1	V_1	0 m/sec
Wind velocity no. 2	V_2	6.7 m/sec
Wind velocity no. 3	V_3	13.4 m/sec

Table 2—Some physical characteristics of soil studied

Sand, %	14.5
Silt, %	63.6
Clay, %	21.9
Liquid limit, % moisture	32.85
Optimum moisture for compaction, standard Proctor, %	18.58
1/3 atmosphere, % moisture	23.36
15 atmospheres, % mosture	9.90
Maximum density, standard Proctor, g/cm³	1.64
Moisture content at time of tillage, 0-10.2 cm, density 1, %	18.01
Moisture content at time of tillage, 0-10.2 cm, density 2, %	20.77

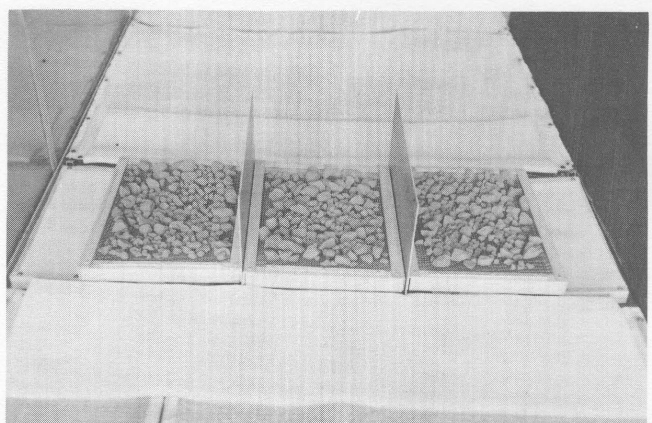

Fig. 1—Photograph of 12.7- to 38-mm clods placed in raintower section of wind tunnel before exposure to wind and rainfall.

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[2] Agricultural Engineer, Agricultural Engineer Research Assistant, and Research Investigations Leader, Soil Erosion, respectively, USDA, Manhattan, Kan.

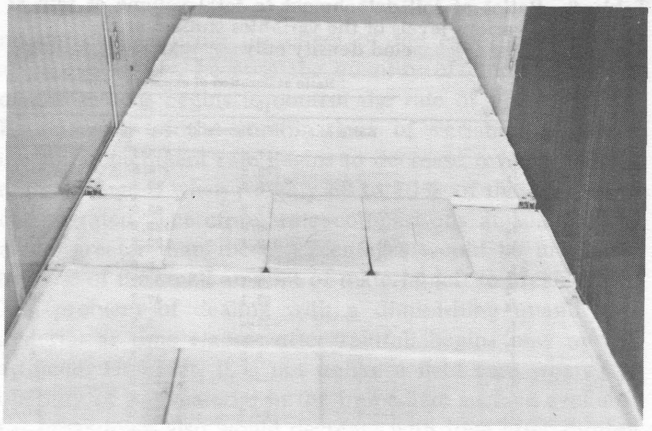

Fig. 2—Metal trays filled with polyurethane foam material to measure wind-driven rainfall.

to prevent interchange of soil splash. The trays plus clods were weighed, exposed to rainfall and wind, air-dried (313K), and reweighed to determine the quantity of soil material detached and passed through the screens.

Simulated rainfall was applied with full jet nozzles (14WSQ or 35WSQ Spraying Systems, Inc. Use of this product does not imply endorsement by the USDA or that it is superior to other competing products.) operated at 0.14 to 0.18 kg/cm² about 10.4 m above the soil samples. Size distribution of the simulated raindrops at each intensity was determined by the flour method (2, 6, 9).

Difficulties in accurately measuring rainfall when exposed to wind were overcome by exposing shallow metal trays containing a water-absorbing polyurethane foam material of known area for definite times and weighing it before and after exposure (Fig. 2). The trays were placed at the same height as the trays that held exposed clods. The concrete floor of the raintower

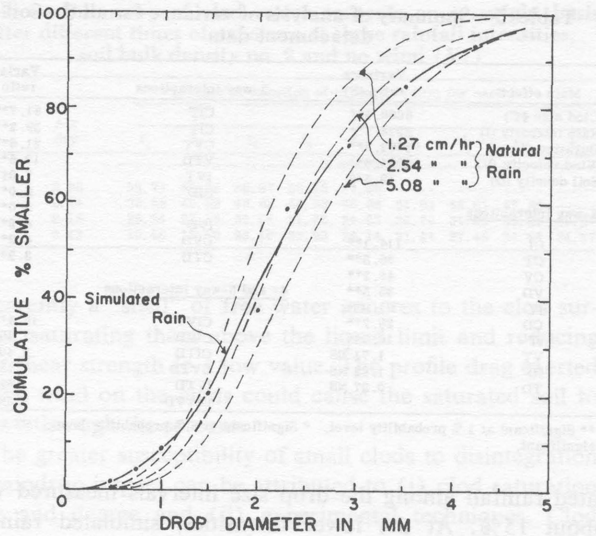

Fig. 3—Comparison of drop size distribution between natural and simulated rainfall. Natural rainfall data taken from Laws and Parsons (6).

was covered with the foam material near the trays and fly screen at a 2.54-cm height to suppress raindrop splash.

Reference wind velocities were measured in the center of the 1.52-m-wide by 2.44-m-high wind tunnel immediately upwind from the test samples.

EXPERIMENTAL DATA AND OBSERVATIONS

Raindrop size distribution between natural and simulated rainfall near the study intensities was fairly similar (Fig. 3) The largest difference between natural and simu-

Table 3—Average soil detachment at each level of the variables studied

			Clod size											
			C$_1$			C$_2$			C$_3$			C$_4$		
Clod density	Rainfall duration	Wind velocity	I$_1$	I$_2$	I$_3$	I$_1$	I$_2$	I$_3$	I$_1$	I$_2$	I$_3$	I$_1$	I$_2$	I$_3$
g/cm³	minutes	m/sec	% soil detached											
1.25 (D$_1$)	30 (T$_1$)	0 (V$_1$)	56	93	97	24	67	96	4	9	36	1	3	9
		6.7 (V$_2$)	95	98	100	34	94	99	8	25	51	2	9	15
		13.4 (V$_3$)	97	100	100	75	98	100	27	64	97	5	29	77
	90 (T$_2$)	0	97	98	100	56	96	100	11	38	91	3	6	45
		6.7	99	100	100	97	98	100	30	78	91	11	45	52
		13.4	99	100	100	99	100	100	51	98	100	23	72	100
1.50 (D$_2$)	30	0	66	97	99	20	66	99	2	12	52	1	2	9
		6.7	96	99	100	20	66	100	2	12	52	3	4	16
		13.4	97	100	100	51	95	100	10	40	90	4	8	39
	90	0	97	99	100	47	97	100	9	41	87	3	6	22
		6.7	100	100	100	96	100	100	44	77	91	5	27	39
		13.4	100	100	100	98	100	100	63	91	100	13	48	88

Table 4—Average soil detachment for selected combinations of variables at 5- and 10-min exposures

			Clod size											
			C$_1$			C$_2$			C$_3$			C$_4$		
Clod density	Rainfall duration	Wind velocity	I$_1$	I$_2$	I$_3$	I$_1$	I$_2$	I$_3$	I$_1$	I$_2$	I$_3$	I$_1$	I$_2$	I$_3$
g/cm	minutes	m/sec	% soil detached											
1.25	5	0			69									
		6.7												
		13.4			95			78						
	10	0	15	49	92			70	2	3	13			
		6.7		76	95		30	81			25			
		13.4			99			97			45			27
1.5	5	0						30						
		6.7												
		13.4			97			61						
	10	0	15		98	5	16	77	1	2	12	1	1	3
		6.7		75	97		50				25			
		13.4			99			97			45			11

Table 5—Summary of analysis of variance for all the soil detachment data

Main effect	Variance ratio (F)	3-way interactions	Variance ratio
Clod size (C)	5660.1**	CIT	61.7**
Rain intensity (I)	2228.7**	CIV	39.2**
Duration (T)	1962.3**	CVT	21.6**
Wind velocity (V)	1094.6**	VTD	12.6**
Soil density (D)	19.5**	IVT	7.04**
		CID	6.0**
2-way interactions			5.0**
		IVD	4.9**
CI	114.1**	CVD	4.2**
CT	86.3**	CTD	3.2**
CV	48.3**		
VD	35.5**	4- and 5-way interactions	
IV	31.9**		
CD	29.7**	CIVT	16.4**
IT	16.1**	CIVD	3.30**
VT	1.71 NS	CITD	2.40*
ID	1.62 NS	CVTD	1.45 NS
TD	0.37 NS	IVTD	.62 NS
		CITVD	2.59**

** Significant at 1 % probability level. * Significant at 5 % probability level. NS - Nonsignificant.

lated rainfall among the drop size intervals measured was about 15%. At the lower intensities, simulated rainfall contained a higher percentage of large drops than natural rainfall. However, the reverse was observed at the highest rainfall intensity. That result was expected because the percentage of large drops increases with increasing natural rainfall intensity (up to about 10.16 cm/hour), whereas for a specific nozzle and operating pressure the drop size remains constant.

The average soil detachment in percentage of original weight at each level of the variables studies is presented in Table 3. Results from longer exposure prompted other tests of selected combinations of variables at 5- and 10-min exposure times (Table 4).

A summary of the variance ratios for the variables and their interactions is given in Table 5. They were obtained through an arcsin transformation of the soil detachment data. The 5- and 10-min exposure times are not included. The significance of the interactions, especially higher order ones, restricts interpretation of the main variable effects.

To assist in answering meaningful questions, certain portions of the soil detachment data were divided by the total volume of rain received to give interpretable ratios on a unit of rainfall basis (Table 6).

Both multiple linear and curvilinear regression procedures were used that included: (i) all the data, (ii) soil detachment greater than 95% omitted, and (iii) soil detachment greater than 80% omitted. Both untransformed and transformed soil detachment data were used. From the analyses, estimating equations, variance accounted for, and relative importance of independent variables were determined (Tables 7, 8).

Table 6—Ratios of soil detachment to total volume of rain at the various levels of the variables studied at D_2 clod density only

	Intensity	Ratio at duration of exposure, min			
		5	10	30	90
		Ratio of soil detachment to total volume of rain			
$C_1V_1D_2$	I_1	-----	147.5	216.4	106.0
	I_2	-----	272.2	179.6	61.1
	I_3	379.7	270.0	90.8	30.6
$C_2V_1D_2$	I_1	-----	49.2	65.6	51.4
	I_2	-----	88.9	122.2	59.9
	I_3	165.1	212.1	90.8	30.6
$C_3V_1D_2$	I_1	-----	-----	6.6	9.8
	I_2	-----	11.1	22.2	25.3
	I_3	-----	33.1	47.7	26.6
$C_4V_1D_2$	I_1	-----	-----	3.3	3.3
	I_2	-----	-----	3.7	3.7
	I_3	-----	8.3	8.3	6.7
$C_3V_2D_2$	I_1	-----	-----	25.8	47.3
	I_2	-----	-----	43.9	41.7
	I_3	-----	67.2	55.6	27.2
$C_3V_3D_2$	I_1	-----	-----	30.3	63.6
	I_2	-----	-----	76.9	58.3
	I_3	-----	122.3	81.4	30.2

INTERPRETATIONS AND DISCUSSION

Significant interactions among the variables restrict conclusions about factor effects; namely, that to examine the influence of one variable (factor) on clod disintegration, one must specify the level of the other variables. This is vividly illustrated by considering clod size, a variable of primary interest and one that was highly significant in its effect on clod breakdown (Table 5). The soil detachment for the $D_1T_2V_1I_1$ combination was 97, 56, 11, and 3% for clod size 1, 2, 3, and 4, respectively, which agrees with the statistical evidence. However, examination of the $D_1T_2V_3I_3$ combination reveals an identical soil detachment (100%) for all clod sizes. Although that result is not unexpected, indications are that if any variable is of sufficient "strength," increases in levels of other specific variables are superfluous; i.e., a 5-kg hammer is not needed if a 1-g hammer will do the job.

Table 7—Effect of transformations and omissions of certain data on the soil detachment variance

Identification of data †	R^2 Untransformed	R^2 Arcsin transformed	Order of variables*
Linear:			
All data	.764	.8022	2-5-3-4-6
Data > .95 omitted	.6689	.7125	2-3-5-4-6
Data > .80 omitted	-----	.6570	2-4-3-5-6
Curvilinear:			
All data	.838	.8875	2-5-3-4-8-11-9
Data > .95 omitted	.791	.8397	2-3-5-4-8-11-9
Data > .80 omitted	-----	.7986	2-4-3-5-8-11-9

* Brought in based on maximum increase to sum of squares due to regression. † Refers to soil detachment data.

Variables

2 - Clod size
3 - Rain intensity
4 - Wind velocity
5 - Duration of exposure
6 - Soil Density
8 - Clod size squared
9 - Rain intensity squared
11 - Duration squared

Table 8—Effect of including additional variables on the soil detachment variance

Variable added	R^2	R	ΔR^2 †
			%
Clod size	.445	.667	
Duration	.570	.755	8.8**
Intensity	.719	.848	9.3**
Wind velocity	.802	.896	4.8**
Clod size squared	.860	.927	3.1**
Duration squared	.880	.938	1.1**
Intensity squared	.887	.942	0.4**
Soil density	.888	.942	0.03 NS

† Percentage of variance of soil detachment accounted for by adding variables indicated after each preceding variable has been considered.

Linear regression equation : $\hat{SD} = \{\sin(27.3085 - 0.8961C + 20.6310T + 6.1828I + 1.5281V)\}^2 \cdot R^2 = .802.$

Curvilinear regression equation: $\hat{SD} = \sin(7.9058 - 2.456C + 71.3801T + 18.8613I + 1.4387V + .0222C^2 - 28.0871T^2 - 1.6387I^2)^2 \cdot R^2 = .888.$

100 $\hat{SD}$ - soil detachment in %
C - clod size in millimeters
I - rainfall intensity in centimeters/hour
V - wind velocity in meters/second
T - exposure in hours.

Above a certain percentage of soil detachment we are no longer measuring the effect of the experimental variables exclusively, because the quantity of clods remaining on the screens begins to control the rate of disintegration. Examination of the combinations of variables at which the soil detachment rate begins to decrease reveals that the critical range is when roughly 60 to 70% of the clods have disintegrated. Therefore, rate comparisons at soil detachments greater than those percentages would be unreliable because of the small amount of material left to break down. The problem of dealing with a diminishing quantity of material as time elapses after rainfall begins may appear artificial. However, it is not unlike a field case where the quantity of soil material in the immediate surface available for breakdown also would decrease with time after rainfall starts.

Except for the I_1V_1 combinations, the 90-min exposure was too long for the two smaller clod sizes. All clods had disintegrated regardless of density, wind velocity, or rainfall intensity. High-intensity rain (I_3) driven by 13.4-m/sec wind had disintegrated 95 to 97% of the small clods (C_1) in 5 min (Table 4).

Except for individual cases, largely confined to the largest clod size (C_4), soil density effects were small, inconsistent, and apparently obscured by other factors. The lower density large clods (C_4) showed about 15% more soil detachment than the denser clods at high levels of the other variables.

The effect of storm intensity can be determined by comparing ratios, before decreasing disintegration rates begin, for different times for each clod size (Table 6). For example, a 5-min rain on C_1 at V_1I_3 is severer than a 30-min rain at V_1I_1. Also, a 10-min rain on C_3 at V_1I_3 is severer than a 90-min rain at V_1I_2. The same is true for C_3 with V_2 and V_3 winds. Those comparisons are based on soil detachment per unit of rainfall.

Wind-driven rain was more effective in clod breakdown than anticipated. Up to 66% more soil detachment occurred at 13.4-m/sec wind velocity than for no wind at the same rainfall intensity, duration of exposure, and clod size (Table 3) Comparisons at different wind velocities for the same clod size (C_3) indicate that a low-intensity rain (I_1) for 90 min driven by 6.7- or 13.4-m/sec wind is severer than a high-intensity (I_3), 10-min rain with no wind. A precise explanation for such large differences in clod disintegration between the wind and no wind conditions is not available. Disrud, Skidmore, and Lyles (unpublished data) determined that waterdrop resultant velocities in the wind tunnel-raintower were lower under wind than no wind conditions and thus cannot account for the large differences obtained. Probably mean drop size striking clods increases with wind velocity. As wind velocity increases, the smaller drops would be deflected farther downwind and might not reach the exposed soil surface at all. This hypothesis was supported by the necessity to provide extra or larger nozzles to maintain equal intensities as wind velocity was increased. Another likely factor involved is clod moisture content. Moisture data show that the clods reach moisture contents above the liquid limit (Table 9).

Table 9—Summary of clod water contents on a weight basis after different times of exposure at three rainfall intensities, soil bulk density no. 2 and no wind (V_1)

Clod size	Air dry	% water at duration of exposure (min) for each I								
		10			30			90		
		I_1	I_2	I_3	I_1	I_2	I_3	I_1	I_2	I_3
		% moisture								
C_1	2.30	56.71	56.24	60.97	56.63	54.66	-----	-----	-----	-----
C_2	2.14	39.22	45.23	48.88	44.43	46.34	51.01	43.61	47.38	-----
C_3	2.18	22.34	27.18	34.61	31.73	34.65	39.70	34.65	38.22	39.37
C_4	2.43	10.48	11.80	23.46	23.93	24.14	31.31	27.45	34.68	34.57

Apparently a "shell" of free water adheres to the clod surfaces, saturating them above the liquid limit and reducing their shear strength to a low value. The profile drag exerted by the wind on the clods could cause the saturated soil to "flow" through the screens.

The greater susceptibility of small clods to disintegration by raindrop impact can be attributed to (i) clod saturation time and degree and (ii) experimental techniques. Clod moisture content is related to clod size, rainfall intensity, and time (Table 9). The two smaller clods reached moisture contents well above the liquid limit within 10 min after rainfall began, even at the lowest intensity; whereas about 30 min were required for clod size 3 and the largest (C_4) had not reached the liquid limit in 90 min (at I_1). Therefore, the breakdown of large clods should be slower than small clods.

The experimental techniques used tended to favor breakdown of the smaller clods. The smaller clods could pass through the screens with smaller amounts of detached soil per clod than the larger clods. Some measure of this effect was determined by placing the 6.4- to 12.7-mm clods (C_2) on 2-mm screens and comparing the soil detachment to that of the same clod size placed on 6.4-mm screens. Soil detachment ranged from about 1% more at the lowest intensity to 10% more at the highest intensity for the larger screen size. Although not measured, the effect of screen size should be less for larger clods.

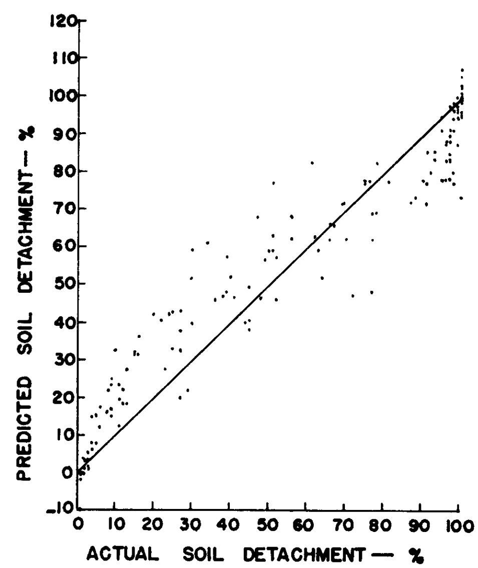

Fig. 4—Comparison between actual average soil detachment and that predicted by the curvilinear regression equation (Table 8).

For the untransformed case, about 76% of the variation in soil detachment was accounted for by assuming the relationship between soil detachment and the variables studied to be linear. Including quadratic terms increased the explained variance to about 84% (Table 8). Those values correspond to 80% and 89%, respectively, for the transformed case. In general, the estimating equation overpredicted low soil detachment events and underpredicted the high soil detachment events (Fig. 4). As soil detachment data were omitted, the percentage of variance accounted for decreased (Table 7). Omission of the larger soil detachment percentages changed the order in which the variables were brought into the stepwise regression procedure based on maximum increase to the sum of squares due to regression (Table 7). As the larger soil detachment values were omitted ($> .80\%$), duration of exposure and wind velocity exchanged positions in occupying second place in the order. This logically suggests that the influence of wind velocity on soil detachment becomes more discernible as rainfall duration decreases.

Soil bulk density did not account for a significant percentage of the variance in soil detachment after the other variables, including the quadratic terms, were considered (Table 8). The same was true for the quadratic term on wind velocity. Consequently, those terms are not included in the curvilinear regression equation.

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