A METHOD TO QUANTIFY TOPOGRAPHIC EFFECTS ON WATER REDISTRIBUTION AND SPRING WHEAT YIELDS[1]

by

Gary A. Halvorson
and
Eugene C. Doll[2]

Abstract. Spring wheat yields and water use were monitored at two locations for five years. At each location, soil series were selected that were representative of different topographic positions in the landscape. The objective of this study was to quantify how topography affects wheat yields and water use. Topographic (topo) factors were calculated at each site by measuring the slope in four directions, 90 degrees apart and adding the slopes together. If a slope was downward toward a site it was considered positive. If the slope was upward toward a site it was considered negative. The topo factor, if positive, would indicate that runon water would be added to a site and if negative, water would be lost from the site due to runoff. When the topo factor was added in to the regression of yield versus water use, the coefficient of determination (R^2) increased in the first three years. The last two years of the study were drought years and the topo factor accurately reflected the lack of water redistribution in those years. Measurements of actual soil water content following rainfall events showed that the topo factor did accurately reflect the actual redistribution of water in the landscape. Topo factors were calculated for measurements 3, 6, 15 and 30 m from each site. Topo factors measured 15 m from the site gave the highest R^2 values in the regression of yield versus water use. The topo factor can be used to help determine the successful reestablishment of productivity on mined-land in a complex landscape.

Additional Key Words: productivity, landscape, slope, wheat, water use.

Introduction

Topographic position in the landscape has been shown to influence crop yields (Ciha, 1984; Simmons et al, 1989; Stone et al, 1985; and Douglas et al, 1985). Some studies have emphasized how erosional losses in productivity are landscape-dependent (Stone et al, 1985; Jones et al, 1989; and Daniels et al, 1985). Hanna et al (1982), among others, have documented how topography redistributes water in the landscape. In a semi-arid area such as the northern Great Plains this becomes important because water is so limiting to crop production. Bauer (1972) showed that stored water at planting or soil-water loss during the growing season plus the growing season precipitation are well correlated with yield of small grains. Because of runoff and runon of precipitation as well as saturated and unsaturated flow in the soil profile, water is not evenly distributed in the landscape.

Regulations in North Dakota require that land disturbed by mining be reclaimed to productivity equal to or greater than the pre-mine land. Since the landscape is severely disrupted during mining, it is difficult to compare land productivity before and after mining without a good understanding of how topography affects crop yields. Doll et al (1984) summarized several studies in North Dakota where landscape position had an important influence on crop production on mined land. Wollenhaupt and Richardson (1982) presented evidence that even microtopographic differences can be an important

[1]Paper presented at the conference 'Reclamation 2000: Technologies for Success', Durango, Colorado, May 14-17, 1991. Publication in this proceedings does not preclude the authors from publishing this manuscript, whole or in part, in other publication outlets.

[2]G. A. Halvorson and E. C. Doll, Soil Scientists, Land Reclamation Research Center, North Dakota State University, P. O. Box 459, Mandan, ND 58554.

Proceedings America Society of Mining and Reclamation, 1991 pp 35-42
DOI: 10.21000/JASMR91010035
https://doi.org/10.21000/JASMR91010035

factor in determining crop yields on reclaimed land.

In general, the studies of the influence of topography have been quantitative in nature and have categorized sites only by their morphologic landscape position. Very few have attempted to quantify the landscape effects on crop production. Sinai et al (1981) calculated a soil surface curvature factor that correlated very well with soil moisture content. Simmons et al (1989) used a modification of this method to calculate curvature and slope, which was then found to be significantly related to crop yields.

A study was undertaken to quantify the relationships of landscape to water distribution and crop yields. The ultimate goal of this research is to model and to predict crop yields on unmined and reclaimed land based on such factors as soil water and landscape position which are important to crop production in the northern Great Plains.

Methods and Materials

Two locations were selected for this study. The first was located 5 km west of the town of Underwood, North Dakota. Some preliminary yield data was collected in 1984 and a more intense study began in 1985. The location consisted of 3 fields that encompassed about a half-section, or 130 ha. The second location was about 10 km north of Beulah, North Dakota. Detailed measurements at this site began in 1985. This location consisted of 2 fields which, in total, consisted of about 65 ha.

Soils at both sites were derived from glacial till. At the Underwood site, soil series were identified which represented different topographic positions in the landscape. The Zahl soil (fine-loamy, mixed Entic Haploboroll) is located on hilltops and shoulder positions in the landscape. The Williams soil (fine-loamy, mixed Typic Argiboroll) is located on hilltops and sideslopes. The Bowbells soil (fine-loamy, mixed Pachic Haploboroll) is found in footslope or toeslope positions. The Tonka soil (fine-montmorillonitic, frigid Argiaquic Argialboll) is located in small depressional areas. The Tonka soil series was not present at the Beulah location. Four sites of each soil series were located in each field. In 1986 1 to 3 additional sites of each soil series were located in each field.

Soil water was determined gravimetrically from core samples to a depth of 1.2 m in 0.3 m increments taken approximately every 3 weeks during the growing seasons of 1985-1988. Wheat grain yields were determined from 5 subsamples taken at each site. Each subsample consisted of wheat from two drill rows, 0.91 m long.

The topographic (topo) factor was determined at each site. The slope was measured in four directions, 90 degrees apart from each other. If the slope in any one direction was downward away from the site, it was designated as negative. If the slope was upward from the site, it was designated as positive. Slope measurements from four directions were then added together to give one number, designated as the topo factor. This topo factor should be positive in landscape positions where a net increase in water would be expected from runon water or movement downslope within the soil profile. The topo factor should be negative in landscape positions where a net loss of water should occur from runoff and downslope movement of water in the soil profile. Topo factors were determined for measurements made at distances of 3, 6, 15 and 30 m from the site.

Water use was calculated from the difference in available soil water to a depth of 1.2 m at planting and at harvest plus the total precipitation. Wheat yields were regressed against water use. The topo factor was used to adjust the water use for topographic effects using the equation:

$$AWU = WU\ [(\text{Topo factor} \times CH) + 1] + b \qquad (1)$$

where WU = water use, AWU = adjusted water use, CH is %CH + 100 where % CH is the percent change in water use caused by topo factor of $\pm$ 1 at a given site. The % CH which gave the highest R^2 value was selected for the calculation of AWU. The calculated AWU was identical to the AWU which would have been calculated if the topo factor had been added into the WU equation using multiple regression techniques. The additional constraint that the intercept of the AWU equation had to be negative was also imposed on the regression.

Results and Discussion

Highest mean yield of spring wheat was obtained from the Tonka soil sites at the Underwood location (see Table 1). These yields were not significantly different from the spring wheat yields on Bowbells sites. Yields from the Zahl soil sites were lowest of the soils studied and were significantly lower than yields from the Tonka in all years except 1989. Mean yields from the Williams soil were intermediate

Table 1. Yield of spring wheat from the Underwood and Beulah, ND locations.

Soil Series	Wheat Yield 1985	1986	1987	1988	1989
			---Mg ha^{-1}---		
			Underwood		
Bowbells	3.9a⁺	2.9a	1.7ab	----	0.7a
Tonka	5.0a	3.0a	2.2a	----	1.4a
Williams	3.1ab	2.4ab	1.2b	----	0.6a
Zahl	2.6b	2.0b	1.0b	----	0.7a
			Beulah		
Bowbells	5.1a	3.0a	3.9a	1.4a	2.5a
Williams	4.7ab	2.7ab	3.2a	1.6a	2.1a
Zahl	3.6b	1.8b	2.0b	1.3a	1.7a

⁺Mean values in the same column within each location followed by the same letter are not significantly different at the (.05) level according to Tukey's honestly significant difference test.

between Bowbells and Zahl. Spring wheat yields from the Beulah location followed the same pattern between soils. Wheat yields from the Beulah location were higher and did not vary as much from year to year as they did at Underwood. This is probably due to higher stored soil water in the fallowed fields at Beulah compared to the continuously cropped fields at Underwood. Significant differences between soils existed for all growing seasons except 1988 and 1989 which were very hot and were considered drought years. No yields were taken from the Underwood location in 1988 because of a total crop loss due to drought.

Water use was not consistently different between soils at both locations (see Table 2). At the Underwood location, highest water use was recorded at sites with Tonka soils for the years 1985-1987. In a semi-arid climate water use by a growing crop can be considered a measure of water availability. Water use at the Beulah location was generally higher than at the Underwood location. Again this is probably a result of the additional stored water in the fallowed fields at Beulah.

Topo factors varied considerably with the distance the measurement was taken from a given site (see Table 3). The Tonka soils would be expected to have a positive topo factor, since they are located in depressional areas. Similarly, the Bowbells soils located on footslope or toeslope positions would be expected to have positive topo factors. With one exception topo factors for Tonka soils were positive at all measuring distances. Bowbells soils had numerous negative topo factors measured at 3 and 6 m from the site. All topo factors measured at 15 to 30 m were positive for Bowbells soils. The Zahl soils would be expected to have all negative topo factors because of their location on hilltops and shoulders. Surprisingly, topo factors measured at a distance of 3 m were all positive in this field, while those measured at 15 m were all negative. The Williams soils which are located on sideslopes should be intermediate between Bowbells and Zahl. Some of the topo factors for the Williams soils were positive and some were negative when measured 15 or 30 m from the site. Overall, topo factors measured at 15 m from the site seem to give the best values qualitatively matching their topographic position. Topo factors measured at 30 m were almost as good. Just why 15 m worked out best is not clear, but was probably related to the scale of the topographic features in this landscape. A landscape with different topographic characteristics could produce optimum topo factors at other distances.

Table 2. Water use calculated from the difference in soil water content at the beginning of the growing season minus the soil water content at the end of the growing season to a depth of 1.2 m.

Soil Series	Wheat Yield 1985	1986	1987	1988	1989
			---------------mm-----------		
			Underwood		
Bowbells	151a[+]	60a	23b	----	52a
Tonka	155a	90a	140a	----	----
Williams	107a	65a	28b	----	43a
Zahl	93a	71a	39b	----	61a
Precipitation	93	139	260	----	191
			Beulah		
Bowbells	----	100a	52a	108a	165a
Williams	----	88a	93a	152a	150a
Zahl	----	64a	64a	130a	108b
Precipitation	----	109	220	101	213

[+]Values in the same column within each location followed by the same letter are not significantly different at the (.05) level according to Tukey's honestly significant difference test.

The relationship between wheat yield and water use varied considerably, and overall was only fair (see Table 4). At Underwood the coefficient of determination (R^2) in 1985 was 0.70, while the R^2 at Beulah in 1987 was only 0.04. The topo factor increased the R^2 values for both locations for the years 1985-1987 when added into the regression equations. For example, the R^2 from Underwood in 1985 increased from 0.70 to 0.80. The R^2 at Beulah in 1987 increased from 0.04 to 0.62.

Wheat yields on different soils were not significantly different in 1988 and 1989 and the topo factor correctly reflected this (Table 4). Inclusion of the topo factor in the yield versus water use regression at the Beulah location in 1988 and at the Underwood location in 1989 did not improve the regression. At Beulah in 1989 the topo factor increased the regression only slightly.

The 1988 and 1989 growing seasons were unusually hot and dry. That rainfall which did fall usually fell in amounts of 0.015 m or less. Under these conditions very little chance for rainfall redistribution in the landscape occurred.

Soil water content data was analyzed to determine the actual redistribution of water in the landscape following specific rainfall events. Most rainfall events were not of sufficient magnitude for any redistribution to occur or else evaporation and transpiration were too great by the time the measurements were made for the data to be useful. However, reasonably good data was obtained from the rainfall events in the period July 7 - July 28, 1987 (see Table 5). A regression of the topo factor versus change in soil water content produced a poor correlation at the Underwood location and a significant correlation at the Beulah location. Based on these correlations, a change in topo factor of ±1 would cause a change in water content of 24.3 mm at the Underwood location and 7.2 mm at the Beulah location. This represents a 7.7% change in total water use at the Underwood location and a 2.5% change at the Beulah location, which is very similar to the percent change of 7% and 3% calculated in Table 4.

Table 3. Topo factors for slopes measured 3, 5, 15, and 30 meters in a field at the Underwood station.

Soil series	Site	Distance from site (m) 3	6	15	30
Bowbells	1	-0.30	-1.10	0.68	0.58
	2	-1.20	0.40	0.98	1.73
	3	2.50	-0.70	1.60	3.61
	4	4.90	0.20	0.80	1.28
	5	-0.60	-2.60	0.28	1.00
	6	3.40	1.05	2.26	2.97
Tonka	1	2.00	-0.50	1.06	1.99
	2	0.80	2.20	2.02	1.76
	3	5.20	5.20	6.08	5.94
	4	2.80	0.70	1.68	1.12
Williams	1	-1.00	0.55	1.90	1.46
	2	-0.30	-0.60	-1.38	-6.07
	3	-2.90	-4.10	-2.90	-3.96
	4	-1.00	-2.40	0.90	0.40
	5	-0.50	-1.05	-1.26	-1.56
	6	-1.80	-1.35	-0.65	-2.13
Zahl	1	1.10	-1.25	-0.92	-1.33
	2	0.30	-0.25	-3.20	-0.74
	3	0.30	-1.50	-1.58	-3.02
	4	3.20	-0.45	-2.22	0.69
	5	0.20	1.00	-4.02	-4.33
	6	0.30	-2.15	-2.08	-2.82

Conclusions

Yields of spring wheat were higher on soils in lower slope and depressional areas than on hilltops or shoulder positions. In the semi-arid climate of the Northern Great Plains, an important factor causing these topographic differences in yield is the redistribution of water in the landscape. The topo factor was developed to quantify this redistribution of water. Adding the topo factor into the regression of yield versus water use improved the regression in 3 years of the study. In the other 2 years, which were considered drought years, the topo factor correctly reflected the lack of water redistribution in the landscape. Measurement of actual water redistribution in the field following a rainfall event in 1987 provided evidence that the topo factor correctly estimated water redistribution in the landscape. The optimum distance for the slope measurements for the topo factors seemed to be 15 m from a given site.

Table 4. Regression equations of the form yield = a(WU) +b where WU is water use.

Year	Location	a	b	R^2	% change in WU for a topo factor of ± 1.0
			Unadjusted		
1985	Underwood	0.024	-1.49	0.70*	
	Beulah	-----	-----	-----	
1986	Underwood	0.013	-0.43	0.23	
	Beulah	0.019	-1.08	0.62*	
1987	Underwood	0.007	-0.79	0.43*	
	Beulah	0.007	0.96	0.04	
1988	Underwood	-----	-----	----	
	Beulah	0.004	0.60	0.12	
1989	Underwood	0.006	-0.95	0.17	
	Beulah	0.007	-0.33	0.22	
			Adjusted for Topo Factor		
1985	Underwood	0.017	-0.12	0.80**	5
	Beulah	-----	-----	----	
1986	Underwood	0.015	-0.63	0.58**	4
	Beulah	0.014	-0.13	0.68*	3
1987	Underwood	0.005	-0.05	0.61**	7
	Beulah	0.014	-0.62	0.62*	3
1988	Underwood	-----	-----	----	-
	Beulah	0.004	0.60	0.12	0
1989	Underwood	0.006	-0.95	0.17	0
	Beulah	0.007	-0.17	0.40	1

* Significant at the .05 level.
** Significant at the .01 level.

Table 5. Relationship between redistribution of rainfall in the landscape during the period July 7 - July 28, 1987, and topo factors using the regression: Topo factor = a (Δ water content) + b.

Location	Rainfall	a	b	R^2	Δ water content / ± 1 topo factor
	(mm)				(mm)
Underwood	126	-0.041	-3.13	0.17	24.3
Beulah	129	-0.137	-8.48	0.85**	7.2

Literature Cited

Bauer, A. 1972. Effect of water supply and seasonal distribution on spring wheat yields. North Dakota Agricultural Experiment Station Bulletin 490.

Ciha, A. J. 1984. Slope position and grain yield of soft white winter wheat. Agronomy Journal 76:193-196.
http://dx.doi.org/10.2134/agronj1984.00021962007600020006x

Daniels, R. B., J. W. Gilliam, D. K. Cassel, and L. A. Nelson. 1985. Soil erosion class and landscape position in the North Carolina Piedmont. Soil Science Society Journal. 49:991-995.
http://dx.doi.org/10.2136/sssaj1985.03615995004900040040x

Doll, E. C., S. D. Merrill, and G. A. Halvorson. 1984. Soil replacement for reclamation of stripmined lands in North Dakota. North Dakota Agricultural Experiment Station Bulletin No. 514. 24 p.

Douglas, C. L., R. R. Allmaras, and P. E. Rasmussen. 1984. Soil productivity on different landscape positions in the Columbia Plateau of Oregon and Washington. Agronomy Abstracts p. 247.

Hanna, A. Y., P. W. Harlan, and D. T. Lewis. 1982. Soil available water as influenced by landscape position and aspect. Agronomy Journal. 74:999-1004.
http://dx.doi.org/10.2134/agronj1982.00021962007400060016x

Jones, A. J., L. N. Mielke, C. A. Bartles, and C. A. Miller. 1989. Relationship of landscape position and properties to crop production. Journal of Soil and Water Conservation. 44:328-332.

Simmons, F. W., D. K. Cassel, and R. B. Daniels. 1989. Landscape and soil property effects on corn grain yield response to tillage. Soil Science Society of America Journal. 53:534-539.
http://dx.doi.org/10.2136/sssaj1989.03615995005300020038x

Sinai, G., D. Zaslavsky, and P. Golany. 1981. The effect of soil surface curvature on moisture and yield - Beer Sheba observation, Soil Science 132:367-375.
http://dx.doi.org/10.1097/00010694-198111000-00007

Stone, J. R., J. W. Gilliam, D. K. Cassel, R. B. Daniels, L. A. Nelson, H. J. Kleiss. 1985. Effect of erosion and landscape position on the productivity of Piedmont soils. Soil Science Society of America Journal. 49:987-991.
http://dx.doi.org/10.2136/sssaj1985.03615995004900040039x

Wollenhaupt, N. C. and J. L. Richardson. 1982. The role of topography in revegetation of disturbed lands. In: Mining and Reclamation of Coal Mined Lands in the Northern Great Plains, Proceedings, Montana Agricultural Experiment Station Research Report. 1984.