Simulated Erosion and Fertilizer Effects on Winter Wheat Cropping Intermountain Dryland Area

T. W. Massee

ABSTRACT

Topsoil loss from erosion in the intermountain dry-farming area reduces crop yields. This study tested the hypothesis that the effects of erosion on water storage and wheat (*Triticum aestivum* L.) yield could be partially alleviated by applying appropriate fertilizers. Two sites were used, one on Rexburg silt loam, a coarse-silty, mixed, frigid Calcic Haploxeroll, and the other on Newdale silt loam, a coarse-silty, mixed frigid Calciorthidic Haploxeroll. Topsoil-depth treatments were +15, 0, −15, or −30 cm changes relative to the original surface. After making the soil depth changes, 54 kg P ha^{-1} were incorporated on one half of each topsoil depth plot and the other half received no P. These P or no P plots were split for applications of 0, 34 or 68 kg N ha^{-1}. Phosphorus had no effect on wheat yield. Without fertilizer N, yields on −15 and −30-cm plots were reduced 46 and 55%, respectively, but increased 69% from the addition of 15 cm of topsoil, compared with the 0-cm plot. Removing 15 and 30 cm of topsoil also reduced the upper limit of N-fertilized production to 80 and 65%, respectively, of production on undisturbed N-fertilized plots. Three kilograms fertilizer N ha^{-1} each crop year offset each centimeter of soil removed, but only to the new lower production limit. All plots had similar amounts of stored, available soil water in the spring, but a large fraction of this water remained unused at harvest on plots with 15 and 30 cm of topsoil removed because the low-yielding wheat did not use as much water. Profile water differences at harvest were no longer apparent by the next spring, following winter recharge. Unused water at harvest, which partially filled the soil profile, reduced winter infiltration and contributed to subsequent runoff from precipitation on those plots. Adding N fertilizer was only a partial solution to topsoil deficiencies.

Topsoil loss by erosion often decreases productivity and usually decreases the nutrient supply. Unfavorable physical characteristics resulting from erosion can reduce infiltration, induce crusting (Bennett, 1939), or reduce the effective root zone. Soils in the intermountain dry-farming area are predominately deep loess, with free $CaCO_3$ beginning at 25 to 100 cm below the surface (Barker et al., 1983).

A survey on the High Plains after the dust bowl of the 1930s (Finnell, 1951) and prior to the use of commercial fertilizer showed average yield reductions of 18% on fields that had lost 7 to 10 cm of topsoil. Horner et al. (1944) reported winter wheat yields after fallow averaged 1.35 Mg ha^{-1} where 15 cm of topsoil were removed, compared with normal production of 2.43 Mg ha^{-1}.

Power et al. (1981) provided uniform and adequate fertilizer to various topsoil and subsoil additions and reported that 20 cm of topsoil added on top of 1.9 m of subsoil produced top yields of wheat and other crops in North Dakota. Yields were 75% as high where no topsoil was added over the subsoil. Mielke and Schepers (1986) reported that adequately fertilized topsoil yielded 25% more than did fertilized subsoil alone in Nebraska. The authors concluded that there are beneficial characteristics of topsoil that cannot be replaced by fertilization.

Neither fertilizer nor sweetclover (*Melilotus officinalis* Lam.) grown in rotation restored a 45-cm desurfacing at Lethbridge, AB, Canada (Dormaar et al., 1986). Wheat yields from the desurfaced plots after summer fallow were reduced 59%. The reduction was 40% with sweetclover in rotation and 30% with either fertilizer alone or fertilizer and sweetclover.

Eck (1987) reported the mean (23 yr) yield losses from desurfaced plots were only partially restored by N and P fertilizer at Bushland, TX. Tanaka and Aase (1989) reported yields decreased 45% at Sidney, MT, from an 18-cm desurfacing. Nitrogen and P fertilizer restored only a portion of the yield loss. Plots desurfaced 20 cm and fertilized with twice the recommended rate usually yielded less than the control plots of Manitoba, Canada (Ives et al., 1987). Plots that were desurfaced 38 cm at Akron, CO (Black and Greb, 1968) stored 50% more water during the fallow year after removing the darker colored surface soil, which had a lower albedo. Fertilized-wheat yields on these plots increased with the additional available water. Later, when perennial grasses replaced the wheat-fallow rotation on these plots, yields were reduced stepwise with increasing topsoil removal (Greb and Smika, 1985).

Massee and Wagonner (1985) compared 32 farm-field fertilizer trials in which half were on eroded sites and half were on nearby noneroded sites in southeastern Idaho. The noneroded sites responded more to N fertilizer, partially because they contained more available stored water. Even with equal stored water, the yield increases from N were greater on the noneroded sites.

These experiments on dry-farming areas in North America demonstrate that soil fertility is closely linked to the conservation of topsoil. There is a need for more quantitative information on the specific impacts of topsoil loss on crop productivity and the role of soil water and fertilizer in the production system on eroding dryland soils. This study explores the effects of erosion in intermountain dry-farming areas on soil water regimes and wheat yield and the remedial effects of N and P fertilizer.

METHODS AND MATERIALS

Two experimental field sites representative of the intermountain dry-farming area were established near Albion, ID. Each site was a duplicate of the other, except for soil series (Table 1). The Rexburg series had 60 to 90 cm of silt loam over a nonrestricting lime layer or Bk1 horizon, and the Newdale series had only 30 to 60 cm of silt loam over a Bk1 horizon. Both sites had an A_p horizon approximately 15 cm thick and effective loessial, silt-loam root zone ex-

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Table 1. Chemical characteristics of experimental sites before soil desurfacing/addition.

Depth	pH	Organic C	$CaCO_3$	P	Exchangeable cations				Cations exchange capacity
					Ca	Mg	K	Na	
cm		g kg^{-1}		mg kg^{-1}	cmol$_c$ kg^{-1}				
				Rexburg series site					
0–15	7.3	10.0	10	16.5	14.1	3.6	1.3	0.02	22.1
15–30‡	7.1	2.4	10	8.8	14.7	2.2	1.0	0.02	17.9
30–45‡	8.0	2.2	230	5.9	13.8	2.0	0.7	0.04	16.8
				Newdale series site					
0–15	7.9	5.3	60	8.6	12.3	3.1	1.0	0.02	15.4
15–30‡	8.1	2.1	180	1.8	12.4	2.3	0.6	0.03	15.9
30–45‡	8.1	2.0	210	1.8	11.1	2.1	0.7	0.03	14.4

‡ The original 15- to 30-cm soil layer became the new 0- to 15-cm layer on plots where 15-cm was desurfaced. Likewise, the 30- to 45-cm soil layer became the new 0- to 15-cm layer on plots where 30-cm was desurfaced, etc.

tending below 1.5 m. These series, together with variants, constitute a major share of the intermountain dry-farming area.

Half of the plot area at each site was cropped and half was fallowed so that a complete set of crop and fallow data could be gathered each crop year, 1980 through 1984. Within each of these four plot areas (i.e., two soil series by crop vs. fallow), eight main plots were established, each 15 by 15 m. Topsoil thicknesses of +15, 0, −15 and −30 cm were established as main plots by removing or adding topsoil. To add 15 cm to the original profile, the upper 15 cm of a plot being desurfaced was used as material. One half of each of these topsoil depth areas received 54 kg P ha^{-1} in the triple superphosphate form and the area was disk-harrowed for incorporation. These plots were split and 0, 34, or 68 kg N ha^{-1} applied to each wheat crop. A 10:1 mix of NH_4NO_3 and $(NH_4)_2SO_4$ was used as the N source, and was broadcast by hand in the fall after planting.

Since P-fertilizer application was to be a variable, a criterion for the experimental sites was that the new 0- and 15-cm soil depth on desurfaced plots contain less than 10 mg of $NaHCO_3$-extractable P kg^{-1} Soil-profile nutrient characterization was performed on the experimental sites prior to surface-soil removal or additions, Soil sampling of each designated plot was done by 15-cm increments, indexed to the surface that would exist following topsoil-depth main plot establishment (Table 1). A year later, soil sampling was repeated on the newly established 0- to 15-cm depth to determine the new P status. These data are designated P_{fert} (Table 1).

Soil water contents were determined gravimetrically in 30-cm increments to a 1.5-m depth, three sample sets per plot. This was done after planting, at the initiation of spring crop growth, after harvest, and in the spring of the summer-fallow year. The sampling dates were 25 Sep, 25 Apr, 1 Sep, and 30 Apr. Subsamples were taken for soil NO_3–N analysis from the 0- to 30-, 30- to 60-, and 60- to 90-cm depths in the spring of the crop year, and immediately dried at 25 °C. Bulk density and water retention of the 30-cm increments were measured by the clod and pressure-plate methods, respectively (Klute, 1986) so that gravimetric measurements could be converted to millimeters of available water. Precipitation was measured with weighing rain gauges.

Summer-fallow operations consisted of subsurface tillage with a duckfoot field cultivator followed by three to four shallow operations with a rodweeder as needed to control weeds. These tillage operations provided a seedbed for fall planting of 67 kg seed ha^{-1}, 'Jeff' hard red winter wheat, using a deep-furrow drill with 36-cm opener spacing.

Broadleaf weeds were controlled by a single application of 2,4-D [(2,4-dichlorophenoxy) acetic acid] in June at the 3- to 5-tiller stage. Harvest samples were handcut from 3.47-m^2 areas near plot center and threshed with a plot thresher to measure yield and wheat-quality parameters.

Soil chemical-analysis methods used were: pH in $CaCl_2$; 0.5 *M* $NaHCO_3$-extractable P; cation-exchange capacity by NH_4OAc replacement; estimation of $CaCO_3$ equivalent by gravimetric CO_2 loss; organic C by Walkley-Black method; NO_3–N by electrode; and exchangeable Ca, Mg, K, and Na by NH_4OAc leachates (Page et al., 1982). Standard micro-Kjeldahl procedures were used to determine wheat-grain N concentration (Nelson and Sommers, 1980).

The analyses of variance (ANOVA) used considered sites as a split in space and years as a split in time. Variance from second and higher order interactions were pooled into appropriate error terms. Multiple regression, where choice of independent variables was questionable, was a combination of backward elimination and stepwise procedures (Draper and Smith, 1966).

RESULTS AND DISCUSSION

Harvest-to-Spring Precipitation and Soil Water Storage

Precipitation from harvest to spring averaged 300 mm, ranging from 222 to 356 mm. Storage in the 1.5-m profile was related to both the precipitation amount and to the quantity of available soil water at harvest. Storage regimes were similar at both sites and, therefore, the data from both locations were combined. The results of regressing millimeters of soil water storage gain ($\hat{Y}$) on millimeters of unused available profile water present at harvest (X_1) and millimeters of precipitation (X_2) was

$$\hat{Y} = 77 - 0.98X_1 + 0.51X_2,\ R^2 = 0.86^{**} \quad [1]$$

where ** shows significance at the 0.01 probability level.

Available soil water at harvest (X_1) had nearly no impact on water stored by spring. The average treatment extremes for available water at harvest were 27 mm in plots with 15 cm of soil added plus 34 kg N ha^{-1} and 93 mm in plots with 30 cm of soil removed and no N added (Table 2).

It was unlikely that available water at harvest was lost below the measured 1.5-m profile by percolation, because the 1.2- to 1.5-m segment was filled to less than 80% of field capacity when measured in the spring of the fallow year. Runoff and associated erosion during the winter are common when intermittent soil freezing occurs (Massee and Siddoway, 1969). Indi-

Table 2. Average available water (cm) in the 1.5-m soil profile for three treatments and four sample times.

Treatment soil addition/ removal	Fertilizer N	Sample time			
		Harvest	Spring fallow†	Fall planting‡	Spring crop year§
cm	kg ha^{-1}	cm			
+15	34	27	216	172	221
0	34	47	229	182	226
−30	0	93	220	175	212
LSD (0.05)		16	NS	NS	NS

† Average precipitation from harvest to initiation of fallow in the spring was 300 mm.
‡ Average precipitation from initiation of fallow to fall planting was 146 mm.
§ Average precipitation from fall planting to initiation of fallow was 264 mm.

rectly, it is likely that the available water at harvest contributed to runoff. As estimated by Regression Eq. [1], at the start of summer fallow, all plots contained approximately the same amount of available soil water, averaging 222 mm (Table 2). The over-winter soil storage/precipitation relation from plots initially having only small amounts of available water at harvest agrees with earlier data (Massee and Siddoway, 1970).

Summer-Fallow Profile Water Storage

The average 222 mm available soil water at initiation of summer fallow decreased to 178 mm by fall (Table 2). This 44-mm loss occurred despite an average of 146 mm of precipitation during the period. Causative factors were evaluated by regression, including initial soil water content (X_1), interim rainfall (X_2), and the amount of soil-surface addition/removal. The latter was not significant (Table 2) and, therefore, is not included:

$$\hat{Y} = -238 + 2.33X_1 - 0.0069X_1^2 + 0.106X_2,\ R_2 = 0.80^{**} \quad [2]$$

where $\hat{Y}$ is the estimate of the water change (mm). The statistical significance of the variables for this estimate, indicated by their probability levels, are: $P = 0.123$ for X_1, $P = 0.46$ for X_1^2, and $P = 0.063$ for X_2. The coefficient for X_2 indicates that only one-tenth of summer rainfall was stored, or alternately that the net summer loss of stored available water was reduced by one-tenth of the summer-precipitation amount. The profile water loss associated with X_1 was 0.74 mm mm^{-1} initially stored, when evaluated at the mean of 222 mm initially stored and the precipitation mean of 146 mm. This relation is in agreement with past work in the intermountain area (Massee and Siddoway, 1970), and is quite similar to the findings in the Oregon Columbia Plateau (R.E. Ramig, 1989, personal communication) and Washington Palouse Prairie (Leggett et al. ,1974) dry-farming areas.

Second Winter Soil Water Storage

From fall planting until the resumption of spring growth of winter wheat, only an average of 35 mm from 264 mm of precipitation was stored, ranging by years from 6 to 67 mm (Table 2). Stored water was not significantly related to the initial fall planting amount, precipitation, or soil addition/removal. Not even the summer-fallow loss was regained. Instead,

Table 3. Results of analysis of variance of simulated erosion experiment. The sites were considered as a split in space and the years as a further split in time. Second and greater order interaction variance was placed in appropriate error terms.

Source of error	df	F
Topsoil depth (SI)	3	209.21**
Nitrogen (N)	2	58.65**
SI × N	6	4.86**
Phosphorus (P)	1	5.29
P × SI	3	3.62
P × N	2	1.67
Error(*a*)	6	
Site (S)	1	32.10**
S × SI	3	5.81**
S × N	2	1.90
S × P	1	1.03
Error(*b*)	17	
Years (*Y*)	4	41.58**
Y × N	8	1.54
Y × SI	12	4.67**
Y × P	4	1.30
Y × S	4	9.79**
Error(*c*)	160	
Total	239	

** Significant at $P = 0.01$.

there was a net loss of 3 mm from the spring of the summer-fallow year to the spring of the crop year. Some water was used for crop transpiration from emergence until sampling the spring of the crop year, for which there is no accounting.

Regression analysis established that the first winter storage after harvest estimate was negatively related to the millimeters of available water present at the start of the storage period (X_1), and positively related to the millimeters of precipitation (X_2) (Eq. [1]). To determine if this relationship also predicted storage from the second winter after harvest, the value of 178 mm of previous storage and 264 mm of precipitation were used. The relationship predicted 37 mm storage, compared with the 35 mm measured. Thus, it seems plausible that low storage during the winter-after planting wheat partially resulted from the larger initial amount present.

Wheat Yield

Because the effects of soil addition/removal and N were highly significant in the ANOVA (Table 3), a regression of individual plot yields on these variables produced a response surface. Despite the site significance in ANOVA caused by the Rexburg site having slightly higher average yields than the Newdale site, their individual response surfaces were similar. The actual yield values are shown in Fig. 1. Curvilinear transformations of the soil addition/removal and N variables were not statistically warranted. Thus, a planar response surface resulted:

$$\hat{Y} = 1.76 + 0.036X_1^3 + 0.011X_2,\ R^2 = 0.69^{**} \quad [3]$$

where $\hat{Y}$ is the estimate of wheat yield (Mg ha^{-1}), X_1 is the positive or negative centimeters of profile depth change from topsoil addition or removal, and X_2 is the kg N ha^{-1} applied. The standard partial-regression coefficients for this relation are: $X_1 = 0.74$ and $X_2 = 0.34$, indicating that, among the data used, the soil-thickness changes were more than twice as effective in

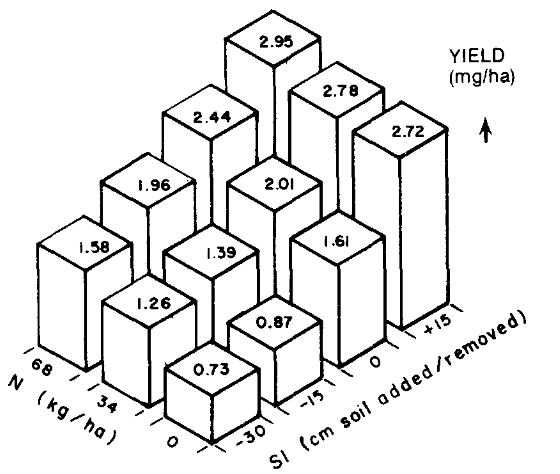

Fig. 1. Wheat yield resulting from simulated erosion and N fertilizer treatments near Albion, ID, 1980 through 1984. Values are averaged across 4 yr, two sites, and two P fertilizer levels.

predicting yield as was the N variable. A comparison of the coefficients of X_1 and X_2 showed that 3 kg N ha^{-1} each crop year offset the effect of 1 cm of topsoil loss.

A rerun of the regression with treatments averaged over years at each location gave the same regression equation, but the R^2 value increased from 0.69 to 0.92. This suggests that random yearly variation was a large contributor to the initially unexplained variation. This might have been expected from the ANOVA variance-ratio value of 41.58 for years (Table 3). The annual yield average ranged from 1.68 Mg ha^{-1} in 1984 to 2.10 in 1981. The Rexburg site had an overall average yield of 1.93 Mg ha^{-1}, while the Newdale site averaged 1.78 Mg ha^{-1}. However, in two of the five years, yields were higher on the Newdale than on the Rexburg site. These differences caused the significant site and year by site effects. The reasons for these site effects are not fully understood. It was noted, however, that snow usually melted earlier in the spring at the Newdale site, which had a westerly exposure, compared with the Rexburg site, which had an easterly exposure. The Newdale site probably benefitted at times by the earlier snow removal and expansion of the early growing season. The N by topsoil depth significance (F = 4.86, Table 3) resulted from the small N-fertilizer response where topsoil was added, compared with the better N responses for the other treatments.

Fertilizer field-test results have shown little or no response to P in the study area (Massee and Painter, 1978). This might be anticipated, since topsoils in the area usually have more than 10 mg $NaHCO_3$-extractable P kg^{-1}. Removal of 15 or 30 cm of topsoil reduced the available P to only 1.8 mg P kg^{-1} on the Newdale soil, which is very low (Table 1). Adding 54 kg ha^{-1} to the surface of the plots after topsoil was removed increased the $NaHCO_3$-extractable P values to 24.3 mg kg^{-1} where no topsoil was removed to 16.4 mg kg^{-1} where 15 cm was removed and to 1.32 mg kg^{-1} where 30 cm was removed on the Rexburg series. Respective increases for the Newdale series were to 16.1, 7.3, and 7.1 mg kg^{-1}. No visible response to P was observed on any plot.

The beneficial yield effect from adding 15 cm of topsoil to the original profile was greater than the detrimental effect of removing 15 cm (Fig. 1), occurring each year. A possible explanation is that, because surface soil dries in the summer, only the portion below remains wet enough for nitrification to proceed. Therefore in the plots having 15 cm of added topsoil, there was over twice the active topsoil present after a somewhat constant drying depth. There was no indication that yields from plots having topsoil removed were recovering with time in this 5-yr experiment.

Wheat Protein Concentration

Protein concentration paralleled yield but with smaller deviations from the mean. The overall trend estimated from regression was

$$\hat{Y} = 11.27 + 0.033\,X_1 + 0.032X_2 \qquad [4]$$

where $\hat{Y}$ is the estimate of the protein concentration (5), X_1 is the centimeter of topsoil depth change, and X_2 is the fertilizer-N application rate, kg ha^{-1}. The standard partial-regression coefficients of Y on X_1 and X_2 were 0.52 and 0.82, respectively. Compared with changes in yield caused by soil addition/removal and N fertilizer, protein concentration was more responsive over the N range applied. The coefficients of X_1 and X_2 indicate that 1 kg N ha^{-1} was needed to compensate for each centimeter of topsoil loss to maintain the same protein concentration. Equation [4] accurately predicts the protein values shown in Table 4, producing an R_2 of 0.94 for the same 5-yr means but, when using yearly individual-plot data, the R_2 value was only 0.36.

Fertilizer N Recovery

Soil NO_3–N data fluctuated widely during the experiment, and was not associated with previous precipitation or water storage at sampling time. In most years, recovered N reflected N fertilizer applied, but not soil removal/addition. These data have limited utility.

Data in Table 4 indicate that the first increment of applied N, 34 kg ha^{-1}, increased both yield and protein concentration, but the increases were not fully proportional with little effect on the grain protein concentration. Applying 68 kg N ha^{-1} produced a proportional increase in yield with a similar recovery of N per amount applied. Recovery as protein, in contrast, was usually greater from the second increment than from the first. The N recovered, which can be attributed to increased yield and to increased protein are shown in the last two columns of Table 4, respectively. These results suggest a tendency for N-deficient dryland wheat to partition a major share of absorbed N from an initial fertilizer application toward yield, rather than protein. After the N-deficiency is partially satisfied, additional increments of N will be shifted toward protein-concentration increases. This is in agreement with other dryland experiments (Jackson et al., 1983).

Table 4. Five-year-mean N uptake on soil addition/removal (SI) and fertilizer-N treatments.

SI treatment	Fertilizer N	Yield	Protein	N in grain Total	Recovery from N fertilizer† Yield	Recovery from N fertilizer† Protein	Recovery from N fertilizer† Total
cm	kg ha⁻¹	Mg ha⁻¹	%	kg ha⁻¹			
+15	0	2.72	12.1	58.0	–	–	–
	34	2.78	13.1	64.2	1.0	5.2	6.2
	68	2.95	13.8	72.4	4.8	9.6	14.4
0	0	16.1	11.4	32.0	–	–	–
	34	2.01	12.0	41.4	8.1	1.3	9.5
	68	2.44	13.3	57.4	16.8	8.5	25.4
−15	0	0.87	10.4	15.3	–	–	–
	34	1.39	11.4	27.2	8.9	3.0	11.9
	68	1.96	13.2	45.5	20.2	9.9	30.1
−30	0	0.73	10.3	12.7	–	–	–
	34	1.26	11.7	25.8	9.5	3.6	13.1
	68	1.58	12.6	34.4	15.7	6.0	21.7

† Recovered fertilizer N for yield is taken from increased yield and calculated at the same protein concentration as 0-N treatment. Thus, the recovery by protein equals the total recovery less the yield recovery.

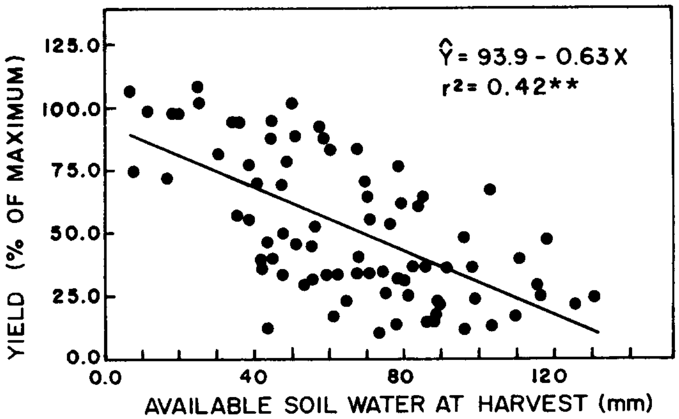

Fig. 2. Relationship of wheat grain yield and unused available soil water at harvest.

Yield and Available Soil Water at Harvest

An average of 93 mm of available, but unused, soil water was present in the 1.5-m profile at harvest in plots with 30 cm of surface soil removed and no N-fertilizer added (Table 2). Koehler (1960) found no differences in water extraction from fertilizing dryland wheat with N in Washington, but Brown (1971) increased profile water extraction by 94 mm, and more than doubled wheat yields by adding N, near Bozeman, MT.

Low wheat yields on our plots and similar soils were associated with fertility problems, as indicated by visual symptoms of poor vigor and early-season lower-leaf desiccation. The relation between relative yields and available water at harvest is shown in Fig. 2. The mean of the three highest yielding plots at each site, each crop year, was assigned a value of 100% = maximum yield, and regressed against the remaining yields giving an r^2 of 0.42. Although this indicates there is other sources of variation, a fair assessment of N deficiency in the field could be made from available soil water.

SUMMARY

Two representatives, deep loessial soils of the intermountain dry-farming area both lost significant wheat-production potential from topsoil removal. Where topsoil was added to normal profiles, production was improved, indicating there was insufficient topsoil normally present for best utilization of the limited cropping water associated with dry farming. Although all treatments had similar stored soil-water quantities during the spring of the crop year, the subsequent water extraction by wheat was largely proportional to yield. The plots with topsoil removed were low yielding and contained appreciable unused, available soil water at harvest. The unused water, in turn, reduced soil water storage from precipitation, probably adding to runoff. Adding N fertilizer each crop year was only a partial solution to inadequate topsoil. During the 5-yr experiment, there were no indications that plots with topsoil removed were becoming ameliorated, but rather they were subject to more erosion because of the increased runoff. This experiment indicates that topsoil is irreplaceable, and that intensive dryland management to fully utilize the available soil-profile water by cropping is, in itself, a conservation practice.

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