# Furrow Irrigation Erosion Lowers Soil Productivity

By D. L. Carter[1]

**Abstract:** Recent research efforts have shown that soil erosion decreases soil productivity. Erosion-caused crop production decreases of 15–40% are commonly reported with some values over 50%. Furrow erosion on irrigated land in Idaho decreases topsoil depth on the upslope approximately 33% of the field area and may increase topsoil depth on the downslope 50–55%. Crop yields are generally decreased where topsoil depths are decreased, but yields are not generally increased where topsoil depths are increased beyond a critical depth. Crops vary in their sensitivity to decreases in topsoil depth, but all crops studied exhibited lower yields on the eroded areas. Soil productivity potential of one area representing several million ha of furrow irrigated land was reduced at least 25% by furrow erosion over 80 irrigation seasons. Technology is not available to restore soil productivity potential to the level that would exist had there been no erosion except for returning topsoil to eroded areas. Research and technology applications are needed to reduce or eliminate topsoil loss and redistribution by irrigation erosion.

## INTRODUCTION

Soil erosion has challenged mankind for centuries. Some historians believe that soil erosion reduced the abilities of some early civilizations to produce food, and therefore these civilizations declined until they were conquered or relocated (Wolman 1985). Although these claims may be speculative, recent reports of 40% fertility loss from erosion of some former Union of Soviet Socialist Republics soils, 25–50% yield loss from erosion of some U.S. soils, 30% less production on eroded than on noneroded Haiti soils, and 50% yield decline from erosion of 5 cm of surface soil from some Nigeria soils (Wolman 1985), provide some indirect support to them. There is no question that erosion is a serious problem. We are only recently beginning to understand its impact on soil productivity and crop yield potential.

Most reports of the detrimental impact of soil erosion on crop production have been published in the last 10 years, and they represent all regions of the United States, as well as some other countries. White et al. (1985) reported that crop yields on severely eroded soils in the southern Piedmont were only 50% as great as those on noneroded soil. They found that with severe erosion, surface horizons were thinner, had higher clay contents, were redder in color, less fertile, more acid, and had lower infiltration rates. McDaniel and Hajek (1985) reported that crop yields were reduced on moderately eroded sites in 65% of the fields studied in Alabama, and the average yield decrease was 22%. Erosion reduced corn yields 12% on Maury soil and 21% on Cridder soil in Kentucky. Yields of rye, crimson clover, big flower vetch and hairy vetch were reduced 17, 30, 36, and 27%, respectively, on eroded Maury soil (Frye et al. 1985). Papendick et al. (1985) reviewed research results for the northwestern U.S. and reported both linear

[1]Supervisory Soil Scientist, USDA-Agricultural Research Service, Soil and Water Management Research Unit, 3793 North 3600 East, Kimberly, Idaho 83341.

Note. Dscussion open until May 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 26, 1992. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 119, No. 6, November/December, 1993. ©ASCE, ISSN 0733-9437/93/0006-0964/$1.00 + $.15 per page. Paper No. 4143.

and curvilinear reductions in wheat yield with decreasing topsoil depth. They concluded that the deeper the topsoil, the less was the effect of an increment of topsoil loss. Krauss and Allmaras (1982) reported that the loss of 13 cm of topsoil over a 90-year period at a site in Whitman County, Washington, decreased wheat yields 50%. Busacca et al. (1985) reported yields of four soil series had been reduced up to 25% on sites severely eroded for over 50 years.

Erosion has the same soil productivity-lowering effect as artificially removing topsoil. Engelstad and Shrader (1961) found that corn yields were reduced more than 50% by artificially exposing subsoil. Eck (1969) also reported reduced yield from mechanically removing topsoil on the Texas High Plains. The deceptive aspect of erosion is that it continues year after year, almost unnoticed, until irreversible, serious damage has been done. Pierce et al. (1983) properly called the process the erosion of soil productivity in their report on the long-term effects of erosion on soil productivity.

A number of attempts have been made to relate changes in soil properties as topsoil is lost to erosion. Schertz et al. (1985) reported organic matter and phosphorus decreases and clay content increases in the upper 15 cm of soil as erosion occurs. White et al. (1985) reported decreased infiltration and Frye et al. (1982) reported decreased water holding capacity. Nawak et al. (1985) observed these same changes in soil properties along with increased bulk density and decreased structural stability as erosion reduces topsoil depth.

Most research conducted to date on the effect of erosion on soil productivity has been on nonirrigated soils. Recent reports indicate that furrow irrigation erosion reduces crop yields on irrigated land (Carter 1985; Carter et al. 1985). The purpose of this paper is to present available information of the effects of furrow irrigation erosion on soil productivity. Furrow irrigation erosion impacts will be the primary topic. Erosion can occur under sprinkler irrigation, but a properly designed sprinkler irrigation system can eliminate that erosion. Generally, fields suitable for border and basin irrigation are not subject to serious erosion.

## EFFECTS OF IRRIGATION FURROW EROSION ON TOPSOIL DEPTH

The irrigation furrow has two purposes. First, it is the infiltrating surface for water to enter the soil to replenish the supply to meet crop evapotranspiration requirements. Second, it is the conveyance channel to supply water for infiltration over the entire furrow length. Meeting the requirements of the second purpose gives rise to erosion because the furrow stream size at the upper end of the furrow is generally sufficient to detach and move soil particles. Hence, the furrow stream erodes soil along the upper reaches of furrows and transports it downslope. As the stream size diminishes downslope from infiltration, a point is reached where the stream size becomes small enough that it is no longer erosive and erosion ceases. Further down slope, the stream size becomes still smaller and no longer has sufficient energy to transport the sediment load it accumulated from upslope erosion. At that point, sedimentation begins and continues as the stream size continues to decrease. The process continues until all sediment has settled, or until the lower furrow end is reached, and the remaining suspended soil is carried from the field in tailwater. The end result is removal of surface soil from the upper reaches of fields, deposition of part of it on downslope portions, and usually loss of some topsoil from the fields. With continuing erosion, the topsoil depth decreases near the head ditch and for a distance downslope depending upon the slope, stream size used, and irrigation and cultural practice. Topsoil depth increases along that portion of the field where deposition occurs, but significant quantities of soil are lost from fields by furrow erosion because runoff streams from furrows usually carry a sediment load (Berg and Carter 1980).

The erosion and sedimentation process is complex and many factors alter where and when erosion and sedimentation occur. For example, a recently cultivated field is more erosive than one that has not been tilled since the previous irrigation. Therefore, a large sediment load accumulates in a short length of furrow following cultivation. As a result, sedimentation may begin closer to the head of the field than if the field had not been recently cultivated. Another factor that alters where erosion and sedimentation occur is that leaves and stems from growing plants may hang or fall into the furrow stream late in the season, and dissipate some of the energy that would otherwise be available to erode and transport soil. The inflow stream size is also an important factor. Applying a larger stream for a subsequent irrigation may alter the pattern set by the previous irrigation, and move sediment further down slope.

A detailed study of fields in a large irrigated tract in southern Idaho has shown that furrow erosion has caused extensive redistribution of topsoil (Carter et al. 1985). Measurements made on noncropped, native soils adjacent to the cropped areas showed that the topsoil depth averaged approximately 38 cm. There was no evidence of erosion in these noncropped, native areas. Therefore, the 38-cm topsoil depth was assumed to be the original topsoil depth when irrigation was initiated. The subsoil is nearly white, high in lime, and much less fertile than the topsoil. Where subsoils have been exposed by erosion and tillage, the field surface becomes whitish in contrast to the gray topsoil color. This is readily observed from ground level (Fig. 1) but is more easily seen in an aerial view (Fig. 2). A survey indicated that 75% of the fields in the study area now have whitish upper ends.

Individual field studies were made to determine topsoil depth over the fields. Soil augers were used to bore holes and measure topsoil depth at

**FIG. 1. Whitish Area in Foreground Illustrates Area Eroded Sufficiently to Allow Tillage to Mix Topsoil and Subsoil; Background Shows Normal Topsoil Color**

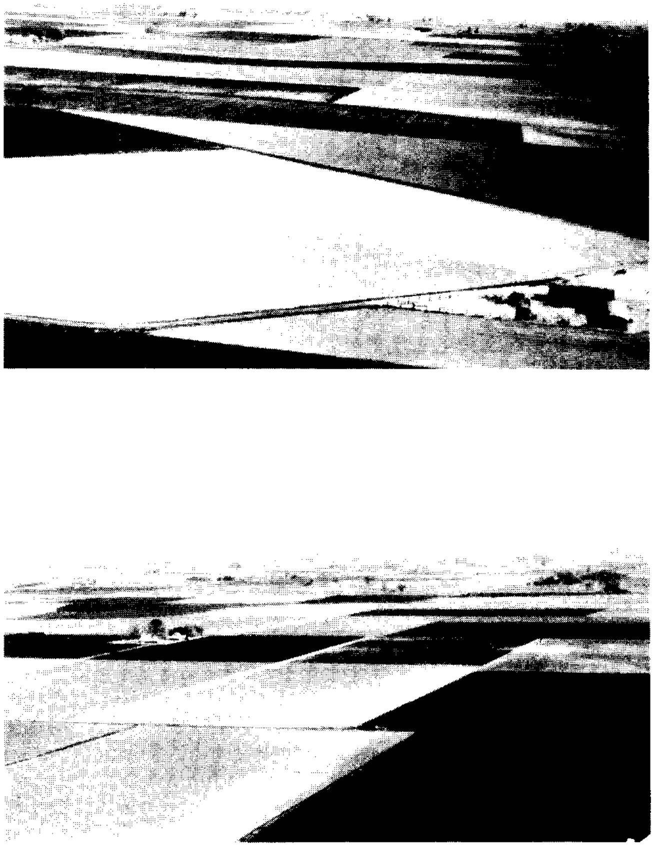

**FIG. 2. Aerial View Showing Whitish, Eroded Areas along Upslope Field Ends**

points on a grid that would show topsoil depth patterns on each field. Several conclusions were drawn from these surveys. Some fields had lost 75 cm of soil from near the head ditch, and most fields had lost more than 20 cm. Topsoil depths up to 150 cm were found on the downslope portions of a few fields with depths of 60 cm frequently encountered. These deep topsoil areas are brought about by deposition of topsoil eroded from upslope areas. Buried topsoil zones were evident in some fields. This resulted from eroding mixed topsoil and subsoil from upper ends of furrows and depositing it over topsoil.

The 75% of the fields with whitish upper ends exhibited the following average patterns: approximately 33% of each field area was whitish, an additional 10% or more of the field area had less than the original 38 cm of topsoil, and the remainder had 38 cm or more of topsoil. The typical pattern found on many fields is illustrated in Fig. 3. The figure shows that there is not much topsoil left 3 m from the head ditch and that the elevation there has decreased about 30 cm from furrow erosion. At 70 m from the

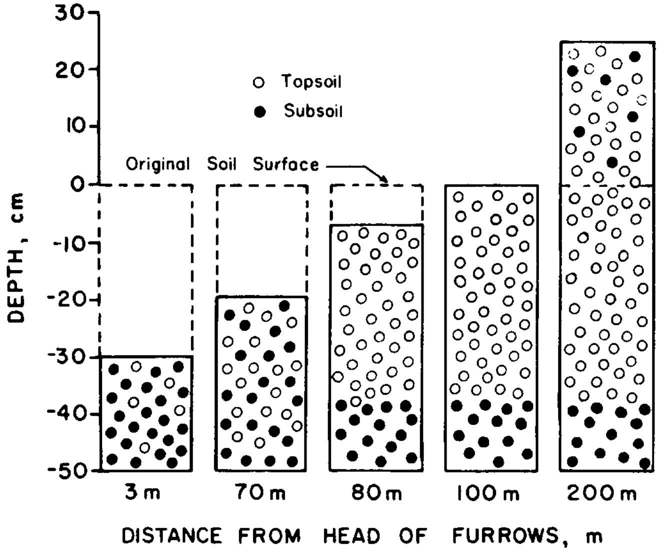


**FIG. 3. Illustration of Soil Mixing Caused by Furrow Erosion**

head of the furrows, the plow layer is about 50% topsoil and about 50% subsoil, and the surface elevation has decreased about 19 cm. At 80 m downslope, the topsoil depth is less than the original, but not yet shallow enough for the moldboard plow to reach into the subsoil and mix some of it with the topsoil. At 100 m from the head, the elevation and the topsoil depth are the same as they were originally. This represents a zone where furrow streams normally do not erode because they do not have sufficient energy as well as a zone upslope from where sedimentation begins. At 200 m from the head, considerable deposition has taken place. At first all of the deposited material was topsoil. However, because the head end 70 m has become a mixture of topsoil and subsoil, some of that mixture has been eroded away and deposited in this deposition area. Moldboard plowing has mixed some of the deposited topsoil-subsoil mixture into plow layer. As a result some subsoil is now present in the deposition area. If the erosion and sedimentation process is allowed to continue, and more and more subsoil is deposited in the deposition area, that area will also become whitish in color and crop yields may be decreased.

## RELATIONSHIPS BETWEEN TOPSOIL DEPTH AND CROP YIELD

Crop yields were reduced on all whitish areas in comparison to yields on the same field where normal topsoil color remained. Fig. 4 shows a winter wheat crop on the field illustrated in Fig. 1. The wheat yield from the whitish area in the foreground was only 35% of the yield from normal-colored soil area in the background.

Crop yields were measured at locations in 14 fields where topsoil depths had been measured, representing a range of topsoil depths from near 0 to 150 cm. Replicated measurements were made at each site by harvesting square meter yield areas for grain crops or row length segments for row and alfalfa crops. In addition to these fields, plots having a mechanically

**FIG. 4. Poor Wheat Growth on Whitish, Eroded Area Compared to Good Growth on Normal Colored Area; Wheat in Foreground Yielded Only 35% as Much as Wheat in Background**

created topsoil depth range of 10–66 cm were studied for three growing seasons. The crops studied for yield effects were alfalfa, barley, wheat, dry beans, sweet corn, and sugarbeets. Data from both fields and plots were combined and relationships between crop yields and topsoil depth were developed. To enable including all yield data in the same relationship, the highest yielding plot or location in the field was rated 100% yield, and yields on all other plots or field positions were expressed as a percentage of that yield.

Curvilinear relationships based upon the equation $y = a + b \ln x$, where $y$ = yield, $x$ = topsoil depth and $a$ and $b$ are constants, and linear relationships for two depth ranges have been reported (Carter 1985; Carter et al. 1985). The third approach reported herein is with the general asymptotic equation $y = a + b(1 - e^{-cx})$, where $y$ = yield and $x$ = topsoil depth, and $a$, $b$, and $c$ are constants. This type of equation is often used to express crop production in relation to the availability of a yield controlling factor, and has become known as the Mitscherlich-Spillman relationship (Christensen and McElyea 1985). The relationships for six crops are illustrated in Fig. 5.

The shape of the relationship between topsoil depth and crop yield depends upon the crop, the total topsoil depth, the difference in productivity potential of the topsoil and the subsoil, and other factors. Generally the relationship is curvilinear as reported in many of the studies previously cited. Relating actual yields rather than percent of maximum yield to topsoil depth generally gives the same shape of relationship, but curves are displaced on the vertical axis for different soils and crops (Papendick et al. 1985).

One problem with the asymptotic relationships is that it is difficult to ascertain the point on the relationship above which topsoil depth has no significant impact on yield. We had previously used linear regression for two portions of the data representing yield on topsoils less than and greater than the original topsoil depth, and concluded that adding topsoil to give depths greater than the original would be of no benefit. Our decision was made arbitrarily at the original depth. Applying asymptotic relationships

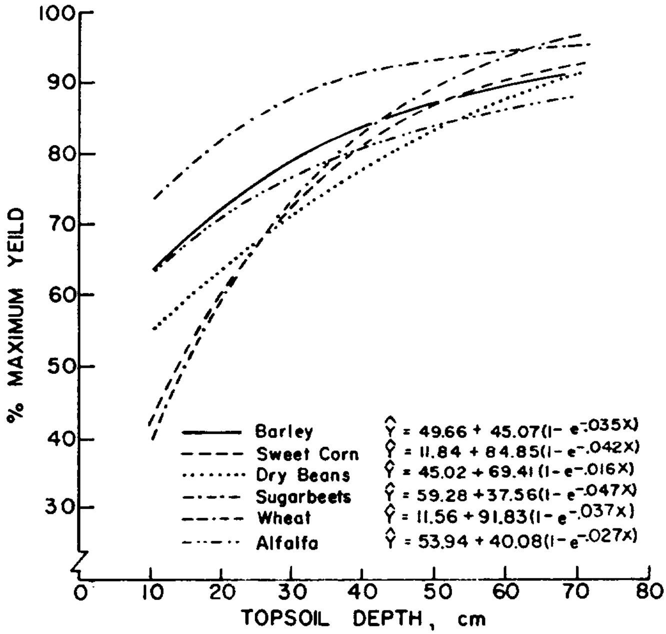


**FIG. 5. Yield Response of Six Crops in Relation to Topsoil Depth**

may lead to a slightly different conclusion suggesting a small benefit of a little added topsoil depth, depending upon the crop.

Some authors have suggested that an "S" shaped Mitscherlich-Spillman relationship (Christensen and McElyea 1985) more accurately fits the data for yields of some crops in relation to topsoil depth. However, in most cases, the part of the relationship giving the lower tail of the "S" near the *y*-axis represents such low yields that they are below levels of economic production, and therefore not important.

Some crops are less sensitive than others to changes in topsoil depth (Fig. 5). Knowing the relative sensitivity of crops is important in making management decisions. For example, a farmer who produces sugarbeets, wheat, and dry beans and has lost topsoil from erosion could expect greater relative production from growing sugarbeets more frequently on the severely eroded fields, and wheat and dry beans more frequently on the less eroded fields. Another example is that a farmer producing wheat and dry beans as cash crops on severely eroded soil may enhance his economic success by changing to producing barley and sugarbeets as his cash crops, depending upon relative crop prices.

## EROSION EFFECTS ON CROP PRODUCTION POTENTIAL

Applying the relationships in Fig. 5 and the distribution of these crops grown in the study area provided some alarming conclusions. Our field data had shown that 75% of the fields exhibited whitish upper ends. The average portion of the field area that exhibited exposed subsoil was 33%. We estimated that an additional 10% of the field area had a topsoil depth less than the original 38 cm, but was not yet exhibiting whitish color. The application of these data to all fields in the study area indicated an overall yield decrease of approximately 25% resulting from 80 seasons of irrigation furrow erosion. In other words, as a result of furrow irrigation erosion over the past 80 years on the entire study area, crop production is only 75% of what it could have been had there been no erosion.

Some assumptions were necessary to make these estimates of the impact of furrow irrigation erosion on crop yield. These assumptions were based upon information we obtained from detailed studies of some fields and involved the depth of topsoil remaining on whitish areas. In some cases we assumed 10 cm of topsoil remaining for one-third of the distance between the head ditch and the downslope end of the whitish soil area, 15 cm of topsoil in the next one-third of that distance, and 20 cm for the downslope one-third of that distance. In other fields where the whitish soil portion did not extend as far from the head ditch, we assumed 10 cm of topsoil in the upslope one-half of the distance and 20 cm for the downslope one-half. We assumed a topsoil depth of 25 cm for 10% of the field area downslope from the lower end of the whitish area.

These estimates are conservative for several reasons. The first is that fields not yet exhibiting whitish areas likely have shallower topsoils where crop yields are reduced near the head ditch. We did not measure topsoil depth and production on those areas. The 10% of the field area we estimated where whitish soils are not yet evident but where considerable topsoil has been lost is conservative.

## FACTORS CHANGED BY EROSION THAT REDUCE CROP YIELD

Earlier in this paper factors most commonly changed by soil erosion that are associated with crop yield decreases were listed. These will be discussed in relation to our results. The organic matter content of topsoils in the study area is low, ranging between 1.0 and 1.3%. The subsoils contain 0.3–0.9%. Such a small difference in soils so low in organic matter probably would not have much impact on crop yields. Soils in the study area are silt loams. The silt content ranges from 62 to 67% in the topsoil, 65 to 70% in the hardpan and generally is 70% or more below the hardpan. The remaining portion is about equally divided between sand and clay. These small differences in soil texture would not likely affect yield. The bulk density of topsoil does not differ from that of the topsoil-subsoil mixture in whitish areas. The infiltration rate does not differ significantly where subsoils have been exposed from other areas, and adequate water was added in our studies to avoid plant water stress. This is also generally the case at the upper ends of farmer's fields. Therefore, soil moisture differences were small if they existed at all.

Technology is not available to increase soil productivity potential on these eroded areas to the original status. Soil tests in the whitish areas indicated adequate available nutrients, and a screening program of foliar application of nutrients has given no indication of crop response. We also tried soil applications of manure, a commercial tree bark amendment, and unusually high rates of nitrogen, phosphorus, and potassium without positive response toward restoring yields on whitish areas. There is a possibility that subsoils contain an unidentified toxic substance that reduces crop yield.

All of the information gathered indicated that yield reductions caused by furrow erosion are permanent. Subsoils simply are not as productive as topsoils, and we do not have available technology to restore productivity on eroded areas, without adding topsoil. Topsoil hauled back to eroded areas from deposition areas restored soil productivity on five fields where this process was evaluated. This action may be economically beneficial, but further economic analysis will be required to reach a definite conclusion. Results obtained for irrigated soils are similar to results of studies from nonirrigated soils cited earlier. Wolman (1985) reported that the effectiveness of fertilizer on eroded soils was less than on noneroded soils. He stated that nitrogen may be only one-third to one-fifth as effective on eroded as on noneroded soils. Burnett et al. (1985) stated that nutrient deficiencies can be corrected by applying fertilizer to eroded areas, but generally that did not restore the soil productivity.

As erosion reduces the topsoil depth, the remaining soil gradually changes to a different soil with a lower potential productivity. This really should not be surprising because we have known for decades that soils differ in productivity. Reason alone tells us that as we lose the best part of a soil we should expect a lower productivity potential. When we develop the technology to improve productivity potential of eroded soils, we will likely be able to apply that same technology to improve productivity of noneroded soils. I do not expect that technology to be developed rapidly. Therefore, we should do everything we can to protect the existing soil productivity by reducing erosion and sediment loss.

## APPLICABILITY OF RESULTS TO OTHER FURROW IRRIGATED AREAS

Earlier in this paper, results of research on nonirrigated land were reviewed indicating that erosion reduced crop yields on most nonirrigated soils. Similar results should be expected for furrow irrigated soils. The seriousness of these yield reductions caused by furrow erosion depends upon the relative productivity of the topsoil and subsoil. If the subsoil is nearly as productive as the topsoil, negative impacts of furrow erosion may not be serious. In contrast, if subsoil productivity is much lower than topsoil productivity, the negative impact of furrow erosion may render farming seriously eroded areas unprofitable.

Furrow erosion effects become serious more rapidly where soil erosivity is high. In our study area on highly erosive soils, crop production potential has been reduced to 75% or less of what it would have been without erosion. There are many areas in the western United States where furrow irrigation has been practiced for less time on erosive soils than the 80 years for our study area. We must direct our efforts toward controlling furrow erosion in these more recently irrigated areas before negative impacts become serious. For example, the productive Columbia Basin in Washington has been under irrigation about 40–50 years. No data are available on the effects of topsoil loss on crop production there, but several scientists have stated, based on observations, that furrow erosion is reducing crop yields. We need to be conscious of the potential that furrow erosion may cause serious reductions in soil productivity wherever furrow irrigation is practiced.

## CONTROLLING FURROW EROSION

Furrow erosion has been recognized as a serious problem since the 1940s (Gardner and Lauritzen 1946) but little attention was given to warnings of early researchers to control this problem. Water-quality legislation during the past two decades has focused attention on sediment in irrigation return flows as a pollutant (Carter 1976), and control technology has been developed to reduce sediment loss from furrow irrigated land (Berg and Carter 1980; Carter et al. 1985). Development of sediment control technology directed attention to the sediment source and the dynamic erosion and sedimentation process in irrigation furrows. We now know that this process has had disastrous effects upon crop production, and we must stop the progress of its further detrimental impacts.

Applying no-tillage and minimum tillage practices to furrow irrigated land offers the most promise for controlling furrow irrigation erosion and its detrimental effects on crop yield. Furrow irrigation farmers have been reluctant to consider these techniques because of fear that they could not effectively irrigate in the presence of surface residues. Recent research results have shown that no-tillage and minimum tillage can greatly reduce furrow erosion, and at the same time, significantly reduce production costs without reducing crop yields (Carter and Berg 1991).

Changing to sprinkler irrigation is another option to reduce erosion but costs of equipment and energy must be evaluated in relation to the crop production potential of the land. In some situations sprinkler irrigation is the best option.

Topsoil is a precious resource for us and future generations. We must act now to preserve it in place where it is most productive.

## SUMMARY AND CONCLUSIONS

Furrow irrigation erosion reduces topsoil depth on upslope portions of furrow irrigated fields and seriously reduces soil productivity. Crop yield decreases resulting from furrow irrigation erosion on irrigated areas are similar to those resulting from rainfall erosion in nonirrigated areas of the United States and in other countries. Crop yield potential was reduced 25% by furrow irrigation erosion in one large study area representing several million ha of irrigated land. Unfortunately, technology to restore this lost yield potential is not presently available except by hauling topsoil back to eroded areas. Implementing erosion and sediment loss control technology to limit further yield potential losses is imperative. The best control technology available is applying conservation tillage, including no-till, to furrow irrigated land.

## APPENDIX. REFERENCES

Berg, R. D., and Carter, D. L. (1980). "Furrow erosion and sediment losses on irrigated cropland." *J. Soil and Water Conservation*, 35(6), 267–270.

Burnett, E., Stewart, B. A., and Black, A. L. (1985). "Regional effect of soil erosion on crop productivity—Great Plains." *Soil erosion and crop productivity*, R. F. Follett and B. A. Stewart, eds., American Society of Agronomy, Madison, Wisc., 335–356.

Busacca, A. J., McCool, D. K., Papendick, R. I., and Young, D. L. (1985). "Dynamic impacts of erosion processes on productivity of soils in the Palouse." *Proc. Nat. Symp. on Erosion and Soil Productivity*, American Society of Agricultural Engineers, 152–169.

Carter, D. L. (1976). "Guidelines for sediment control in irrigation return flow." *J. Environ. Qual.*, 5(2), 119–124.

Carter, D. L. (1985). "Furrow irrigation erosion effects on crop production." *Proc. Nat. Symp. on Erosion and Soil Productivity*, American Society of Agricultural Engineers, 39–47.

Carter, D. L., and Berg, R. D. (1991). "Crop sequences and conservation tillage to

control irrigation furrow erosion and increase farmer income." *J. Soil and Water Conservation*, 46(2), 139–142.
Carter, D. L., and Berg, R. D. (1983). "A buried pipe system for controlling erosion and sediment loss on irrigated land." *Soil Sci. Soc. Am. J.*, 47, Jul./Aug., 749–752.
Carter, D. L., Berg, R. D., and Sanders, B. J. (1985). "The effect of furrow erosion on crop productivity." *Soil Sci. Soc. Am. J.*, 49(4), 207–211.
Christensen, L. A., and McElyea, D. E. (1985). "Economic implications of soil characteristics and productivity in the southern Piedmont, with comparisons to the Pacific Northwest." *Proc. Nat. Symp. on Erosion and Soil Productivity*, American Society of Agricultural Engineers, 233–242.
Eck, H. V. (1969). "Restoring productivity of Pullman silty clay loam subsoil under limited moisture." *Soil Sci. Soc. of Am. Proc.*, 33(4), 578–581.
Engelstad, O. P., and Shrader, W. D. (1961). "The effect of surface soil thickness on corn yields: II. As determined by an experiment using normal surface soil and artificially exposed subsoil." *Soil Sci. Soc. of Am. Proc.*, 25(6), 497–499.
Frye, W. W., Bennett, O. L., and Buntley, G. J. (1985). "Restoration of crop productivity on eroded or degraded soils." *Soil erosion and crop productivity*, R. F. Follett and B. A. Stewart, eds., American Society of Agronomy, Soil Science Society of America, and Crop Science Society of America, Madison, Wisc., 335–356.
Frye, W. W., Ebelhar, S. A., Murdock, L. W., and Blevins, R. L. (1982). "Soil erosion effects on properties and productivity of two Kentucky soils." *Soil Sci. Soc. of Am. J.*, 46(5), 1051–1055.
Gardner, W., and Lauritzen, C. W. (1946). "Erosion as a function of the size of the irrigation stream in the slope of the eroding surface." *Soil Sci. J.*, 62, Jul./Dec., 233–242.
Krauss, H. A., and Allmaras, R. R. (1982). "Technology masks the effects of soil erosion on wheat yields—a case study in Whitman County, Washington." *Determinants of soil loss tolerance*, B. L. Schmidt, R. R. Allmaras, J. V. Mannering, and R. I. Papendick, eds., Special Report 45, American Society of Agronomy, Madison, Wisc., 75–86.
McDaniel, T. A., and Hajek, B. F. (1985). "Soil erosion effects on crop productivity and soil properties in Alabama." *Proc. Nat. Symp. on Erosion and Soil Productivity*, American Society of Agricultural Engineers, 48–57.
Nawak, P. J., Timmons, J., Carlson, J., and Miles, R. (1985). "Economics and social perspectives on T-values relative to soil erosion and crop productivity." *Soil erosion and crop productivity*, R. F. Follett and B. A. Stewart, eds., American Society of Agronomy, Soil Science Society of America, Madison, Wisc., 119–132.
Papendick, R. I., Young, D. L., McCool, D. K., and Krauss, H. A. (1985). "Regional effects of soil erosion on crop productivity—the Palouse area of the Pacific Northwest." *Soil erosion and crop productivity*. R. F. Follett and B. A. Stewart, eds., American Society of Agronomy, Soil Science Society of America, and Crop Science Society of America, Madison, Wisc., 305–320.
Pierce, F. J., Larsen, W. E., Dowdy, R. H., and Graham, W. A. P. (1983). "Productivity of soils: Assessing long-term changes due to erosion." *J. Soil and Water Conservation*, 38(1), 39–44.
Schertz, D. L., Moldenhauer, W. C., Franzmeier, D. P., and Sinclair, H. R., Jr. (1985). "Field evaluation of the effect of soil erosion on crop productivity." *Proc. Nat. Symp. on Erosion and Soil Productivity*, American Society of Agricultural Engineers, 9–17.
White, A. W., Jr., Bruce, R. R., Thomas, A. W., Langdale, G. W., and Perkins, H. F. (1985). "Characterizing productivity of eroded soils in the southern Piedmont." *Proc. Nat. Symp. on Erosion and Soil Productivity*, American Society of Agricultural Engineers, 83–95.
Wolman, M. G. (1985). "Soil erosion and crop productivity: A worldwide perspective." *Soil erosion and crop productivity*, R. F. Follett and B. A. Stewart, eds., American Society of Agronomy, Soil Science Society of America, and Crop Science Society of America, Madison, Wisc., 9–21.