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LONG TERM PRODUCTIVITY BENEFITS OF SOIL CONSERVATION

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INTRODUCTION

Many studies have documented that erosion reduces crop yields (Langdale and Shrader, 1982; Follet and Stewart, 1985; Am. Soc. Ag. Engr., 1985). Few of those studies have incorporated the effect on yield of changes in technology (Young, 1984) and only one, to our knowledge, has considered the effect of yield-enhancing agricultural technical progress on erosion damage assessment (Walker and Young, 1986). Lost yield potential is the major on-site effect of erosion. Off-site effects in the form of sedimentation and impaired water quality are also important but are not discussed here. A conservation practice that reduces erosion and yield damage produces a benefit from conservation. This potential benefit, in the form of yield damage avoided, is the objective of soil conservation research and conservation adoption. Understanding the cost of erosion damage and the benefits from erosion control are essential for developing long range policies for conserving soil resources. The tri-state STEEP multidisciplinary research program is dedicated to finding solutions to the erosion problems in the Pacific Northwest. STEEP research results concerning the long term productivity impacts of erosion are the focus of this paper.

This paper describes the different types of erosion damage and presents concepts for correctly measuring that damage or the potential benefits from erosion control. STEEP research is presented to show the effect of erosion on the soil resource and on crop productivity. The potential for restoring productivity on eroded soils is discussed. The paper also describes how to separate the effects of technology and yield damage and presents empirical estimates of conservation benefits.

A first classification of erosion damage distinguishes between current damage and long-term damage. Current erosion damage is due primarily to seedbed erosion, reduced tillering, and plant suffocation by sediment, all of which reduce stand density. Current damage is yield loss this year due to erosion this year. These erosional effects do not carry over into subsequent years. Long-term erosion damage occurs when erosion this year reduces yield in future years. This yield loss is due to the loss of nutrient-rich topsoil, to degradation of soil structure and to reduction of plant-available water-

holding capacity of eroded soil. Long-term damage is of great concern because its effects are enduring, even irreversible in large part. Estimates of the long-term productivity benefits of soil conservation are formulated in terms of long-term erosion damage avoided by conservation.

CONCEPTS FOR MEASURING CONSERVATION BENEFITS

Four concepts are involved in assessing the benefits from avoiding erosion damage with conservation practices: (1) compare yields with conservation versus without conservation, (2) avoid confounding current yield penalty due to conservation practice with long term yield loss due to erosion damage, (3) distinguish between reparable and residual yield damage, and (4) separate the effects of technical change from those of erosion. The first three concepts are discussed assuming no technical advance in yields. The fourth concept then is discussed and explicitly includes the effect of technological change.

With Versus Without Comparison

Estimates of erosion damage should be based on the "with versus without" comparison that is common in economic analysis; yield with conservation versus yield without conservation. A curve with empirically confirmed properties is shown in Figure 1 to relate wheat yield to topsoil depth for a deep uniform soil in the Palouse (Walker and Young, 1986a). With initial topsoil depth of 45.7 cm (18 in), using a conservation practice for a number of years would reduce topsoil depth to 39 cm (15.4 in) and would produce a yield of 4488 kg/ha (68 bu/ac). This conservation scenario is the basis for comparison with the erosive alternative. If an erosive practice were used for the same number of years, topsoil would decline to 13.2 cm (5.2 in) and would produce a yield of only 3366 kg/ha (51 bu/ac). Erosion damage is 1122 kg/ha (17 bu/ac), the difference between yield with eroded soil and yield with conserved soil.

Avoid Confounding Conservation Yield Penalty with Damage

Since yields may differ between the conservation practice and the erosive practice for the same topsoil depth, the latter yield function is used in damage assessment on the premise that ultimately conservation will be required to protect the soil. Using the conservation yield-topsoil depth response function at the conserved soil depth and the erosive practice yield function at the eroded soil depth could underestimate erosion damage. Often, as evidenced in the Palouse, the conservation practice yields less than the erosive practice for the same topsoil depth, causing its response function to lie below the response function for the erosive practice as in Figure 2. If yield at the conserved topsoil depth (39 cm, 15.4 in) is measured with the conservation yield function (Y_c) but yield at the eroded soil depth (13.2 cm, 5.2 in) is measured with the erosive practice yield function (Y_e), erosion damage would be underestimated (660 kg/ha versus 1122, 10 bu/ac versus 17).

Reparable and Residual Yield Damage

It is useful to distinguish two types of long term erosion damage, reparable damage and residual damage. Reparable damage from erosion is associated primarily with loss of soil fertility due to erosion. This yield loss can be

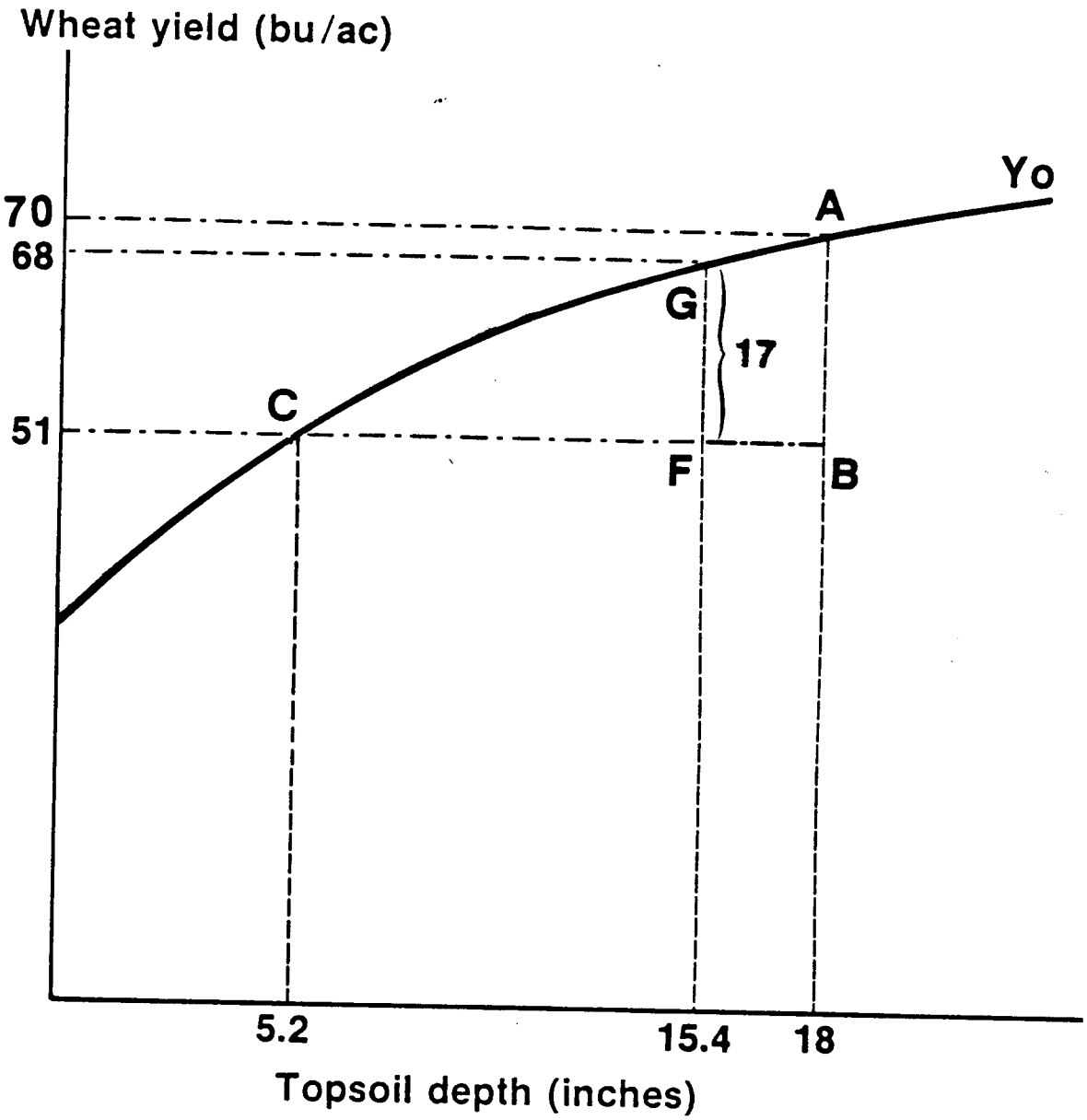

Fig. 1. Yield damage from erosion.

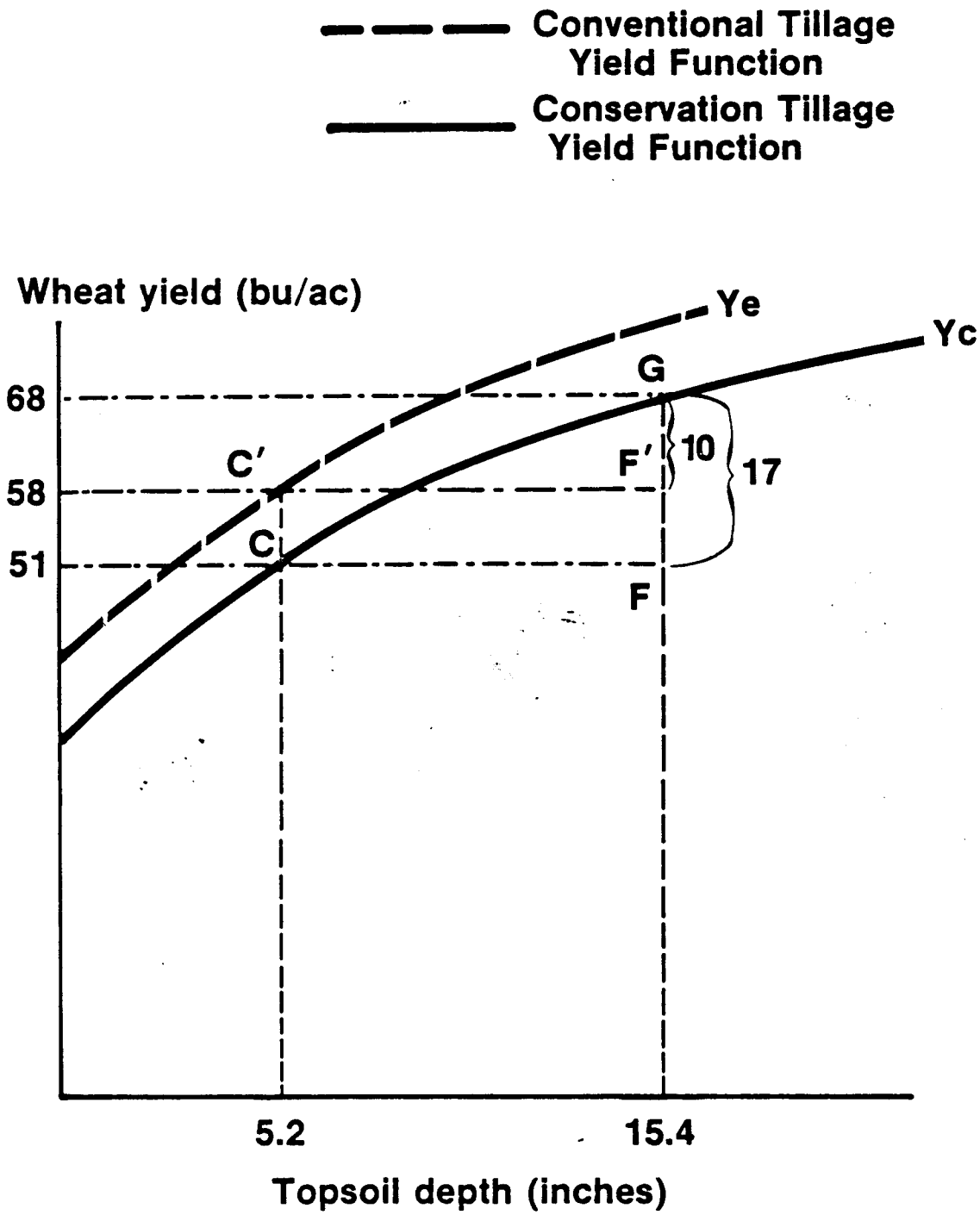

Fig. 2. Avoid confounding erosion damage with tillage penalty.

restored by increased inputs like fertilizer. The cost of reparable damage is the cost of the remedy, and it must be less than the value of the yield loss restored or the remedy would not be attempted. Residual damage is due primarily to deterioration in the soil environment from erosion. Loss of plant-available soil water-holding capacity, decreased depth of the rooting zone, and impaired soil structure cause damage to yields that cannot be remedied economically. These are therefore examples of residual damage.

The two components of long term yield damage are illustrated in Figure 3. With initial topsoil depth, A, using the conservation practice for a number of years would reduce topsoil to E and yield would be G. This conservation scenario is the basis for comparison with the erosive alternative. If the erosive practice were used for the same number of years, topsoil would be reduced from A to D. Without increasing other inputs, yield, compared with the conservation scenario, would decline with erosion along segment GB of the lower curve, called the constant-input yield curve. Total yield damage is given by GH.

Some of this yield damage may be restored depending on subsoil and climatic factors. Increasing fertilizer or other soil-substituting inputs, would boost yield from B to C on the restored-yield curve. This restored yield is the reparable component of erosion damage, BC in Figure 3. The restored-yield curve relates yield to topsoil depth after profit-maximizing input adjustments to erosion have been made. Input adjustments following erosion are limited by input costs and yield response to increased inputs on eroded soil. There are economic as well as technical limits on the extent to which yield on eroded soil can be restored. The net private cost of the remedy must always be less than the value of the yield damage restored.

Residual yield damage is measured along the restored-yield curve. Residual damage, FG in Figure 3, is the yield loss from erosion that cannot be restored. Residual damage is the difference between yield with conserved soil and yield with eroded soil and profit-maximizing input adjustments.

Do Not Confound Erosion Damage and Technology

Measuring erosion damage is greatly complicated by concurrent technical progress in crop yields. Yield observations over time reflect the joint influence of erosion that reduces yield and technology that increases yield. It is necessary to separate the projected effects of erosion and technology. Erosion damage should be measured with technology-augmented yield curves. Erosion damage is the difference between potential yield with conservation and the appropriate technology versus realized yield with erosion and the appropriate technology. This concept, which avoids confounding erosion damage and technology, is explained in more detail in a later section. Failure to project the effect of technology on yield could result in underestimates or overestimates of erosion damage depending on the interaction between technology and topsoil depth in influencing yield.

EROSION AND THE SOIL RESOURCE

The Palouse region in eastern Washington and northern Idaho is one of the

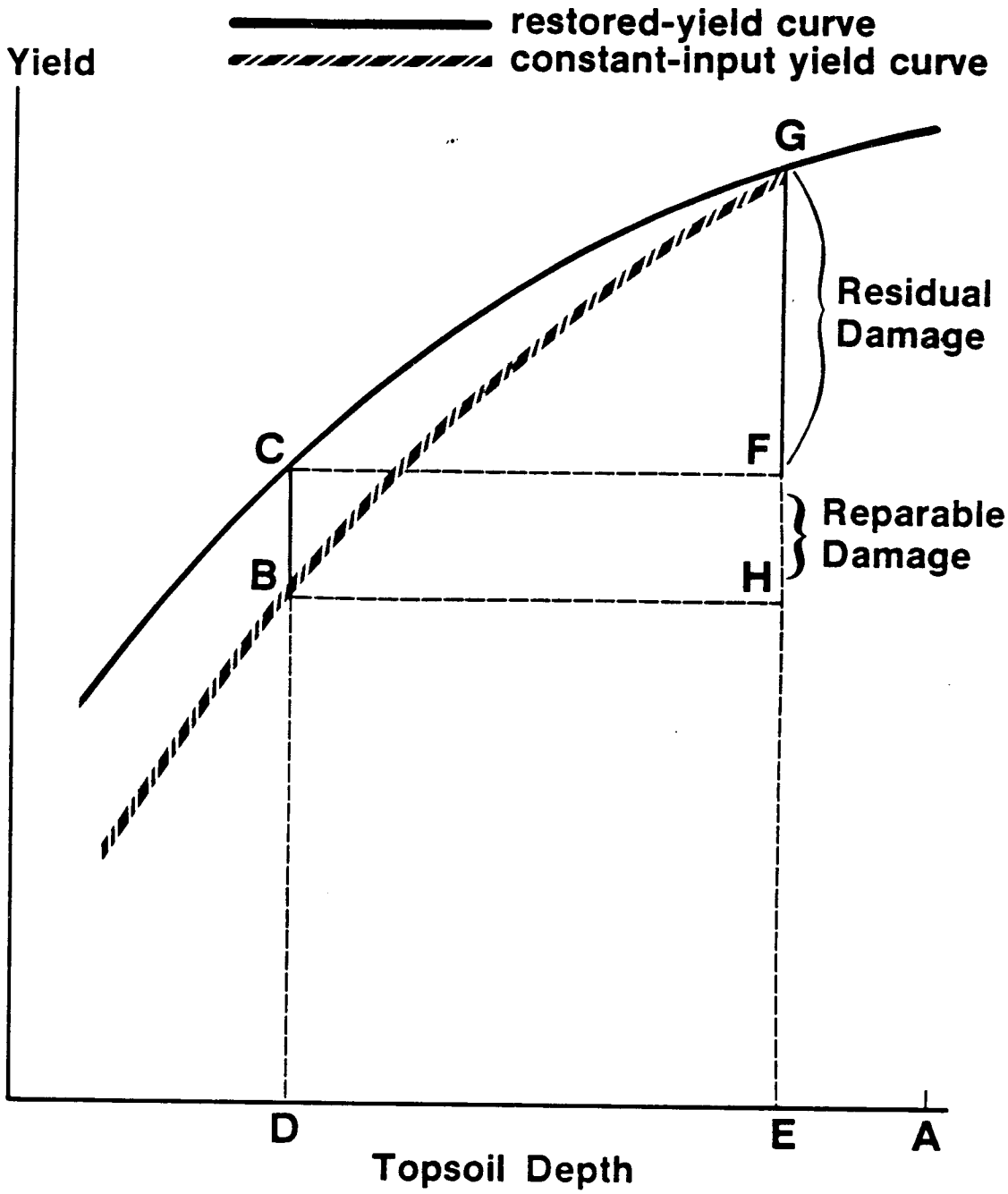

Fig. 3. Residual and reparable erosion damage.

most productive and one of the most rapidly eroding landscapes in the nation. Water erosion rates of up to 200 to 450 t/ha (90 to 200 t/a) in a single winter season have been measured on some steep slopes (USDA, 1978). This severe erosion is caused by a combination of factors: the majority of annual precipitation occurs in winter when there is little surface residue or crop cover to protect soil from runoff and erosion, rainfall or snowmelt on partially frozen soil that has little ability to infiltrate water, and steep slopes. Tillage erosion, caused by continued downhill plowing, also is moving large amounts of soil downhill.

Since the land was first cultivated about 100 years ago, all of the original topsoil has been lost by erosion from 10% of the cropland, and from one-fourth to three-fourths of the original topsoil has been lost from another 60% of the cultivated cropland (USDA, 1978).

Tillage and water erosion are changing the landscape and productivity of the Palouse, and the effect is more severe because of the unusual origin of the Palouse. The Palouse is made of loess, silty sediment carried as dust from the Columbia and Quincy Basins by prevailing southwesterly winds over the past 1 to 2 million years. The loess has accumulated in successive layers. During times when the landscape was stable and accumulation of silty sediment was slow, soils formed on the surface layer of loess. These soils were buried in turn during times when the accumulation of silty sediment was rapid. Today in some parts of the Palouse, there are ten or more of these buried soils, called paleosols (paleo:ancient, sol:soil), interlayered with sheets of loess in vertical succession (Fig. 4).

Some of the paleosols have strongly developed soil horizons and it is these more restrictive paleosol layers that cause the most severe problems in farming the soils. In the drier western Palouse, the stronger paleosols are calcium carbonate (lime) and silica cemented hardpans (duripans in Soil Taxonomy). In the eastern Palouse, lime and silica were leached during soil formation but clay-rich subsoil horizons (argillic horizons and fragipans in Soil Taxonomy) formed under higher precipitation. When layers such as these are exposed by erosion or are in the rooting zone, productivity can be markedly reduced.

The tremendous productivity of the Palouse lies mainly in the thin skin of fertile, organic-matter rich topsoil (A horizon) and weakly developed subsoil (B horizon) that formed under prairie vegetation in the most recent mantle of loess (Fig. 4). This sheet of loess has accumulated during the past 13,000 years or so, and was about 0.5 to 2 m (20 to 80 in) thick before farming began. Erosion of this mantle impairs soil productivity. Seen from this perspective, the soil resource in the Palouse may be much more vulnerable than thought in the past.

Exposure of Paleosols

The paleosols have a complex and poorly understood distribution under the thin covering of recent loess. We do know that restrictive paleosol horizons are within the rooting and tillage zones in parts of each hill in the Palouse. Generally, on hilltops, some south-facing slopes, and convex midslope knobs, the covering of recent loess with its fertile soil profile was origi-

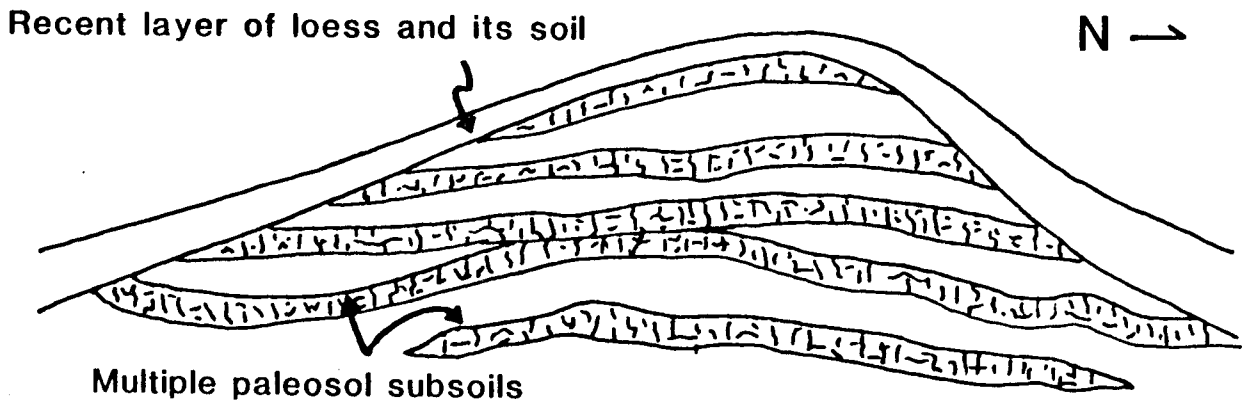

Fig. 4 One possible orientation of paleosols in a cross-section of a Palouse hill.

nally quite thin, often less than 1 m (40 in). On other parts of each hill, such as on north-facing slopes and in bottomlands, the covering of recent loess seems to have been thicker. Water erosion and particularly tillage erosion have exposed paleosols on many ridgetops throughout the Palouse. Exposed areas of subsoils can be recognized in the western Palouse as areas where chunks of lime-silica hardpan or white lime-enriched subsoil are mixing in the tillage zone, and in the eastern Palouse as brightly-colored, reddish, clay-rich patches. The subsoil materials stand in marked contrast to the dark organic-matter rich topsoil that they have replaced.

As significant as the areas of exposed subsoils are at present, it is important to determine what proportion of each hill in the Palouse has restrictive subsoils at shallow depth and at what rate, with current management, or with reduced tillage, the paleosols will be exposed in the future. Some idea of the extent of paleosols can be gained from examining the mapping units in a recent soil survey. Because some paleosols occur naturally at shallow depth and because others have been brought to the surface by accelerated erosion, superimposed profiles occur that have both recent and paleosol soil horizons within the normal 1.5 m (60 in) depth of soil description. Approximately one-half of the upland soil series mapped in Whitman County in the heart of the Palouse, representing about 30% of the upland area, have superimposed profiles (Busacca et al., 1985). Some recent data collected by Busacca and Frazier from transect studies in a field near Pullman, WA, are also useful for comparison. Restrictive paleosol subsoils, clayey argillic horizons in this case, lie within 0.5 m (20 in) of the surface on 29% of the sites, within 0.5 to 1 m (20 in to 40 in) on another 29%, and the remaining 42% were at greater than 1 m (40 in). As expected, the hill summits and convex knobs were the most strongly affected, averaging only about 40 cm (16 in) to paleosol subsoil materials. Data for similar transects in a field near Endicott, WA, in the drier zone reveal white lime-rich subsoils within about 1 m (40 in) of the surface on steep sideslopes, and a little deeper, about 1.3 m (51 in) , on the broad flat hilltops. Plates of hardpan up to 20 cm (8 in) across lie in the tillage zone in several parts of this field. While these examples are not definitive of the entire Palouse, they serve to verify the wide extent of shallow surface soil over paleosol materials.

Soil Properties Affected by Erosion

Reasons often cited for the decline in productivity of soils with progressive erosion are (1) loss of soil organic matter, (2) decreased volume of rooting with associated reduction of plant-available water and nutrient storage and supply, (3) reduced water infiltration, and (4) reductions in tilth (Langdale and Shrader, 1982; Schertz, 1983). These problems exist in the Palouse and are most severe on soils with impermeable and infertile paleosol subsoil horizons. The following data are taken from unpublished analyses of the National Cooperative Soil Survey and Washington State University and serve to illustrate some of the changes in soil properties resulting from erosion.

The organic matter in most Palouse-area soils is held primarily in the upper 75 cm (30 in) of the uneroded profile (see for example Kraszewski, 1952). Even on sites where erosion has been minimal, continuous tillage has reduced organic matter content. This means that in the drier western Palouse, surface soils have declined from about 2.0% to 1.0% organic matter, and in the wetter

eastern Palouse, surface soils have declined from about 4.5% to about 2.0% organic matter. For example, in two fields near Pullman, WA and Albion, WA, the average content of organic matter is 2.3% with a range from 1.2 to 3.9%. The organic matter content of argillic and hardpan subsoils is generally less than 0.5%. The decline in organic matter reduces native fertility and aggregate stability and increases surface crusting and rainfall runoff.

Some soils in the Palouse, such as the Palouse series (fine-silty, mixed, mesic Pachic Ultic Haploxerolls) in the geographic zone that receives 460-580 mm mean annual precipitation (MAP) and the Walla Walla series (coarse-silty, mixed, mesic Typic Haploxerolls) in the 300-380 mm MAP zone, have uniform soil profiles formed dominantly in young loess to 1.5 m (60 in) or more. Plant rooting volume or depth is not diminished significantly in these kinds of soils as erosion removes the upper layers. Other soils, such as the Risbeck (coarse-silty, mixed [calcareous], mesic Durorthidic Xeric Torriorthents) and Endicott (coarse-silty, mixed, mesic Haplic Durixerolls) in drier zones have hardpans or hardpan fragments from paleosols within 50 to 100 cm (20 to 40 in) of the soil surface. The Garfield (fine, mixed, mesic, Mollic Haploxeralfs), Naff (fine-silty, mixed, mesic, Ultic Argixerolls), and Thatuna series (fine-silty, mixed, mesic, Xeric Argialbolls) are examples of soils in moister areas that have strong paleosol argillic horizons in the rooting zone. The argillic horizons can have up to 48% clay and a bulk density of up to 1.75 g/cm^3, compared to about 24% clay and a bulk density of about 1.3 g/cm^3 for intact topsoil horizons in the young loess. When these kinds of horizons are near the soil surface they physically restrict rooting depth and thereby limit plant water and nutrient extraction. When they are at the soil surface they also create difficulties with tillage operations, seedbed preparation, severe crusting, and poor seedling emergence.

Infiltration rates for surface and subsoil horizons of soils such as the Palouse and Walla Walla are similar at 15-50 mm/h (0.6-2 in/hr). Progressive erosion on these soils does not change runoff/infiltration rates to the extent that they are changed when subsoils of the Endicott, Garfield, Naff and Thatuna series soils, with infiltration rates as low as 1.5 to 15 mm/h (0.06 to .6 in/h), are exposed. On these soils, water intake and storage may be greatly reduced as subsoil layers appear. Runoff and erosion hazard on lower slopes is increased as a result. Exceptionally high storage of plant-available water is arguably the most important factor in the success of dryland farming in the Palouse. Exposure of water-shedding subsoils reduces this natural advantage.

<u>Erosion Affects Soil Organic Matter and Bulk Density.</u> In an empirical study of soil properties and the yield-topsoil depth relationship, we hypothesized that (1) certain soil properties, such as organic matter (OM), bulk density (BD), soil reaction (pH), phosphorus (P) and micro nutrients will change as topsoil depth is reduced by soil loss from erosion and tillage; (2) because these properties influence yield, there will be a corresponding yield response; (3) the rate of organic matter change could be different for different parts of the profile, especially between plow layer and below; (4) P content and pH are affected by field and site differences that mask their relationship to topsoil depth.

How yield responds to changes in topsoil depth was explored with the rela-

tionship of yield to OM and BD (Brodahl-Bramble et al., 1985). These soil properties indicate the location in the profile of the transition from the surface horizon to subsoil horizons. Though they have overlapping information, OM is a more direct measure of soil properties related to the mollic epipedon (i.e. fertility), while BD reflects changes in textural and structural properties of the profile, which potentially influence plant-available water. We investigated how changes occur in these properties with topsoil loss and if they influence yield. This analysis was conducted on two soils of the Palouse region, Palouse series and Naff series. While OM content may be affected by cultural practices, study sites were selected from farms having a history of similar tillage and management practices.

We examined the top 30 cm (12 in) of soil for changes in OM content as topsoil depth varies. With regression analysis we found the same OM loss pattern for both soils as given in Table 1.

Table 1. Changes in organic matter with decreasing topsoil thickness for Palouse and Naff soils.

Topsoil Depth (in)	OM (%)
24 plus	2.84
12	2.26
0	1.67

The OM content decreased .05% per 2.5 cm (1 in) decrease in topsoil. Lower organic matter content is associated with lower soil fertility.

Bulk density (BD) in the top 30 cm (12 in) of surface soil also varies with the thickness of the topsoil layer. Naff and Palouse show slightly different relationships, as indicated in Table 2.

Table 2. Changes in bulk density with decreasing topsoil for Naff and Palouse soils.

Topsoil Depth (in)	Naff BD (gm/cm^3)	Palouse BD (gm/cm^3)
24	1.28	1.25
12	1.35	1.31
4	1.43	1.35
0	1.46	1.37

As topsoil is lost, BD inceases for both soils and BD is higher for Naff.

The data indicated that pH was higher in the 30 to 60 cm (12 to 24 in) layer of soil than in the 0 to 30 cm (0 to 12 in) layer. Consequently, as topsoil is lost, the pH in the 30 cm (12 in) mix should increase. Relationship of the 30 cm (12 in) mix pH to topsoil depth was variable, indicating that pH changes due to site differences can be more variable than the pH changes due to changes in topsoil depth. The same phenomenon was seen with phosphorus data. Phosphorus was lower in the 30 to 60 cm (12 to 30 in) mix than in the 0 to 30 cm (0 to 12 in) mix, suggesting that as surface soil is removed, phosphorus should decrease. Again, however, the relationship of phosphorus in the 30 cm (12 in) mix to topsoil depth was variable across sites.

Because of the systematic variation between topsoil depth and OM and BD, these two soil properties were considered for further analysis. Regressions of yield versus OM and BD were run for Palouse and Naff soils to calculate standardized coefficients for evaluating the effect of OM and BD on yield. Standardized coefficients indicate the change in the dependent variable in standard deviation units associated with a one standard deviation change in the independent variable. The estimated standardized coefficients suggested that the influence of OM on yield was similar for Naff and Palouse soils, .37 and .44 respectively. The standardized coefficients suggested a difference in the influence of BD on yield between the two soils. BD had a larger influence on the Naff soils (standardized coefficient = -.23) than on the Palouse sites (standardized coefficient = -.01). The R^2 for the Naff and Palouse regressions were .84 and .85, respectively.

The difference in yield response to topsoil depth between the two soils (presented in a later section) may be related to the soil factors changing with BD. The BD measure reflects changes in physical soil properties, such as structure and texture. The argillic horizon in Naff soils affects BD as topsoil depth changes. Palouse soils do not have a restrictive argillic horizon. Changing topsoil depth on Palouse soils appears to influence yield primarily through changes in soil properties reflected in the OM variable. Naff soils show yield response to changes in both OM and BD, reflecting the influence of the argillic horizon on yield.

Erosion Affects Plant-available Soil Water. Throughout the western dryland wheatlands, crop production is highly dependent upon plant-available soil water. It has been documented many times for virtually all crops that yields are highly correlated with the soil water that is present throughout the growing season, and particularly during the seed producing stages of growth (DeJong et al. 1984; Saxton and Bluhm, 1982). In low rainfall areas such as the Palouse (250 to 580mm, 10 to 23 in.) where 70% of the annual precipitation occurs during the months of October to March, there is inadequate precipitation during the growing season to produce a crop. Crop production requires storage of antecedent moisture in the soil. Under these conditions, reduced water infiltration and reduced water storage capacity of the soil due to erosion can be critical for crop yields.

The key to maximizing soil water is to minimize runoff, snow loss, and evaporation. Runoff results when the soil's infiltration capability is below the rate of rainfall or snowmelt. Almost always infiltration rates are determined by the large, open soil pores in the top few centimeters of the soil

profile. This porosity can be created naturally by space between the soil particles, but worm holes, cracks between clods, and tillage roughness are generally far more effective. Once created however, these macropores can readily become clogged by fine particles if the soil strength is insufficient to resist weathering, or if subsequent tillage can destroy them. Organic matter plays a key role in maintaining soil structure, and thus is important for keeping macropores open for infiltration. Soil water freezing often inhibits infiltration, especially where there are few large, air-filled pores that will not freeze closed.

Erosion almost always reduces infiltration and increases runoff. The organic matter-rich surface soil is the first to erode and subsoils, exposed by erosion, will much more readily disperse and seal surface pores. Deeper soil layers commonly have higher clay contents, thus less stability and permeability. The "clay-knobs" of eastern Washington and northern Idaho are prime examples of lost productivity through increased runoff.

Average annual runoff in the Palouse region of eastern Washington and northern Idaho varies from over 125 mm (5 in.) where annual precipitation is 630-760 mm (25-30 in.) to about 25 mm (1 in.) in the 250-300 mm (10-12 in.) precipitation zone. This 10-20% loss of water to the soil profile will directly affect wheat yields anywhere precipitation is less than that required for full production (generally about 500 mm (20 in.), depending upon the annual distribution). Using the generalized correlation that each 25 mm (1 in.) of available water above 100 mm (4 in.) results in approximately 470 Kg/ha (7 bu/a) wheat yield (Leggett, 1959), this lack of infiltration and "water-down-the-creek", can translate directly into yield losses of 335-1345 Kg/ha (5-20 bu/A).

Severe erosion can even reduce the depth of soil available for storing plant water. Generally this is less of an impact than the reduction of infiltration capacity unless the soil has shallow root-restricting layers. A 2 m (6ft) deep soil of silt loam has a maximum storage of approximately 360 mm (14.2 in.) of plant available water (Saxton, et al., 1986). Eroding 30 cm (1 ft.) would reduce this water storage to 306 mm (12.1 in.), or by 15%. For the shallow Beckley soil in the channeled scablands which has only about 0.5 m (20 in.) of silty loess topsoil over gravel, this amount of erosion would reduce the maximum plant available water from 81 mm (3.2 in.) to 27 mm (1.1 in.), or by 67%. Eroding at the severe rate of 112 t/ha/yr (50 t/A/yr) would require about 35 years to erode 30 cm (1 ft.). Such rates have occurred in the area and yields have decreased because of lost water storage capacity.

Tillage Erosion

Tillage erosion has not received the attention that water erosion has in the Palouse but appears to be responsible for the majority of soil lost from hilltops and ridges in steeply sloping areas. Repeated downhill plowing sets up a slow motion conveyor belt down slopes as each furrow slice is turned. The downcutting effect has been most apparent on hilltops, ridges, and convex knobs where soil removed is not replaced by soil moving from a higher landscape position. The importance of tillage erosion was recognized by Verle Kaiser, who documented a loss of 1.2 m (48 in) of soil from one hillcrest between 1911 and 1959 (Kaiser, 1961). Vertical walls at fencelines and at the

edges of roads flanking steep slopes are as high as 2.4 m (96 in) where the upslope operator has plowed toward the fence or road for many years, and the downslope farmer has plowed away from the fence.

Don McCool of the USDA, ARS in Pullman has calculated that a single downhill plowing to 18 cm depth on a 10% slope can result in a net soil loss of 29 t/ha (13.1 t/a) (Busacca et al., 1985). This single tillage operation is comparable to a high-normal annual soil loss by water erosion under conventional tillage. Given the shallow depth of paleosols on ridgetops and rates like those reported by McCool and Kaiser, it is fully predictable that areas of exposed subsoils should be expanding each year.

It has recently been recognized that clay-rich and hardpan subsoil materials that are moved downslope can actually cover intact fertile topsoil and create a layer that has some of the negative aspects for crop growth that are seen in complete paleosol horizons.

PRODUCTIVITY IMPACTS AND THE POTENTIAL FOR RESTORING REPARABLE YIELD DAMAGE

Productivity Decline in the Palouse Area

This section examines the impact of soil loss on winter wheat yields for two soils, Palouse and Naff, in the Idaho Palouse. Results are presented from data collected in 1983 and 1985 on these two Mollisols from the Genesee, Idaho, area (Brodahl-Bramble et al. 1985). The soils were sampled in ridge-shoulder and sideslope landscape positions on 10 to 25% south-facing slopes. The two soils differed in that Naff has an argillic subsoil, while Palouse has a subsoil which is texturally similar to the surface horizons and is not as strongly structured. The data were collected on fields where the 2 year crop rotation was Stephens winter wheat with dry peas or lentils.

The typical Naff with minimum erosion has an average topsoil (mollic epipedon) thickness of 40 cm (16 in). This overlies an argillic B horizon with an average clay content of 32% The typical Palouse with minimal erosion has an average mollic epipedon thickness of 63 cm (25 in). This overlies a cambic B horizon having an average clay content of 25%.

Yield-topsoil depth relationships were estimated with regression analysis. For Palouse soils, crop yield was related to the thickness of the mollic epipedon. For Naff soils, depth to the argillic B (DEPBT) is a better predictor of yields. For all regressions, the best fit was obtained with the following equation:

$$\text{Yield (kg/ha)} = B0 + B1(1 - \exp(-B2(\text{topsoil depth in cm})))$$

This nonlinear model exhibits an asymptotic upper limit on yield. The rate of decline in yield as topsoil depth decreases is not constant. The rate of yield loss is lowest for deep topsoils and then increases as topsoil depth decreases. B0 is the yield at 0 cm topsoil depth (yield with subsoil), B1 is the difference in yield between 0 cm topsoil depth and the maximum yield, and B2 defines the rate at which the maximum yield is approached as topsoil depth changes. Regressions for the two soils in 1983, a moist year, and 1985, a dry year, are presented in Fig. 5 and Fig. 6.

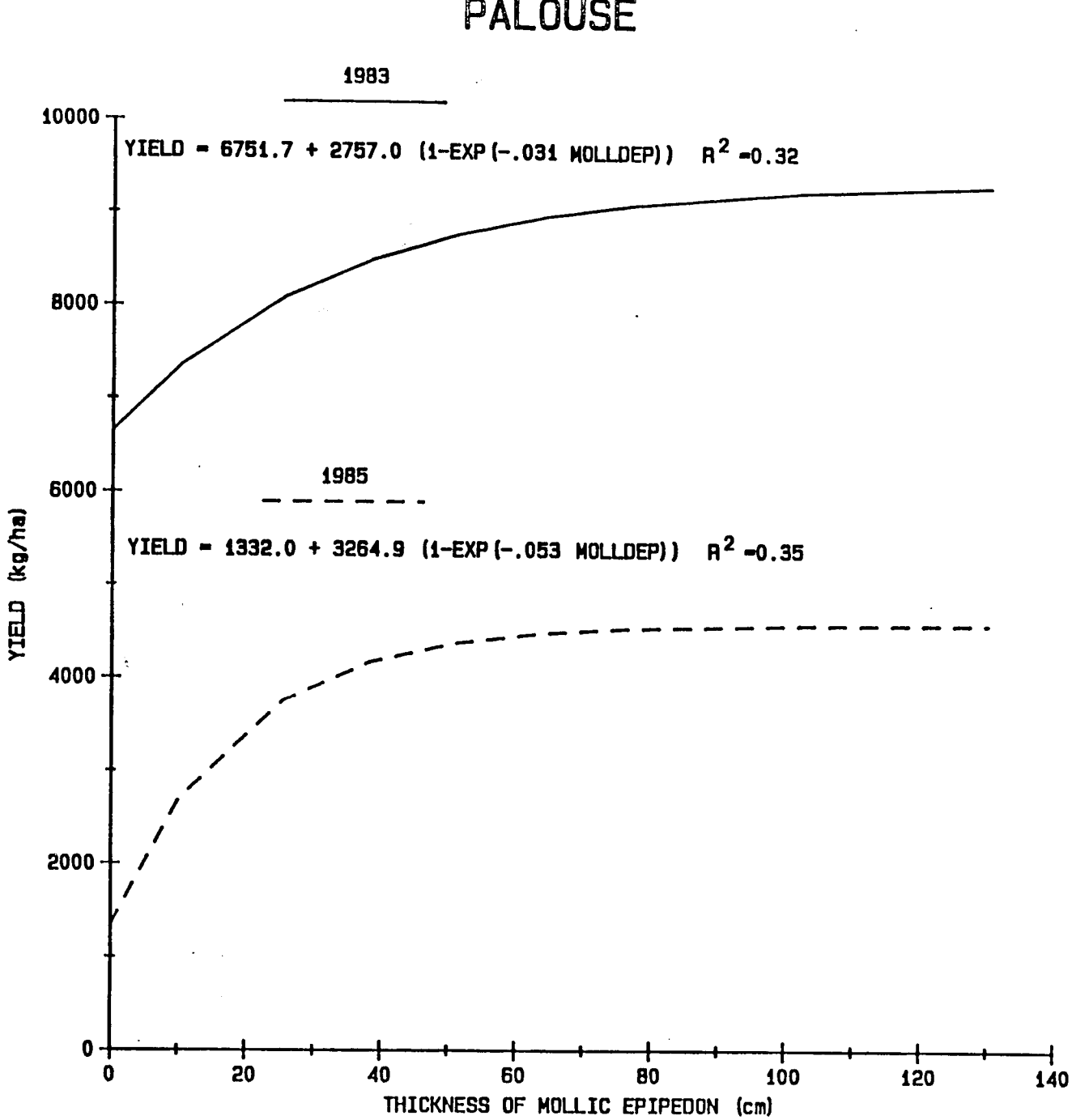

FIG 5. WHEAT YIELD - TOPSOIL RESPONSE FUNCTION ON PALOUSE SOIL.

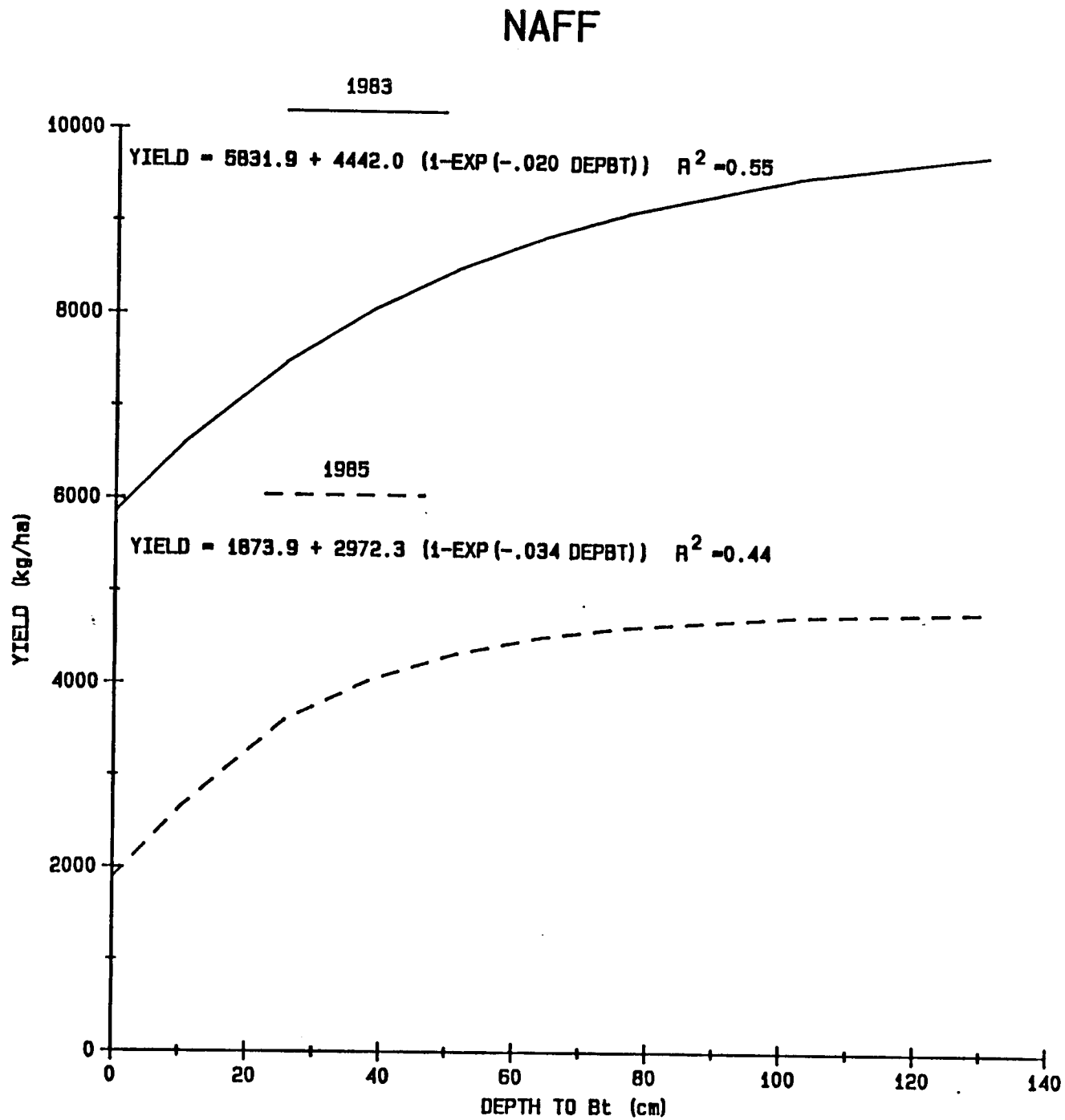

FIG 6. WHEAT YIELD - TOPSOIL RESPONSE FUNCTION ON NAFF SOIL.

Using these yield data and the distribution of soil loss presented earlier we estimated the yield loss from cumulative erosion in the Palouse River Basin. Overall in the river basin there has been a decrease in potential wheat yield of between 14 and 17% due to the erosion of soil since cultivation began. Stated differently, had there been no erosion, average wheat yield today in the Palouse River Basin would be 16 to 20% higher.

Productivity Declines on Furrow Irrigated Land

Furrow irrigation erosion has caused extensive topsoil redistribution on the silt loam soils of South Central Idaho (Carter, et al., 1985). The study area was first farmed and irrigated in 1905, and has therefore been irrigated for about 80 seasons. The topsoil depth averaged approximately 38 cm (15 in) when irrigation began. A predominant soil in the area is Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids). 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 has become whitish in contrast to the gray color of original topsoil. A survey of irrigated fields indicated that 75% of the fields now have whitish upper ends.

Individual field surveys were made to determine topsoil depth over the fields. Soil augers were used to bore holes and measure topsoil depth at points on a grid that would show depth patterns on each field. We found that some fields had lost 75 cm (30 in) of soil from near the head ditch, and most fields had lost more than 20 cm (8 in) in that area. Topsoil depths up to 152 cm (60 in) were found on the downslope portions of a few fields with depths of 60 cm (24 in) occurring frequently. Little yield gain occurred in deposition areas. The 75% of the fields with whitish upper ends exhibited the following average pattern: 33% of the field surface was whitish, an additional 10% or more of the field area had less than the original 38 cm (15 in) or more topsoil.

Crop yields for alfalfa, barley, wheat, dry beans, sweet corn, and sugarbeets were measured at known top soil depths ranging from 10 to 81 cm (4 to 32 in) for three growing seasons. To normalize yields across different varieties of a crop, the highest yielding plot or location on a field was rated 100% yield and yields at all other plots or positions on the farm were expressed as a percentage of that yield.

Data from both farmers' fields and research plots were combined and relationships between crop yields and topsoil depth were developed using regression analysis. The regression equation used was the curvilinear relationship (Mitscherlich-Spillman function), $y = a + b(1-e^{-cx})$, where y is yield, x is topsoil depth, and a, b, and c are constants. Figure 7 illustrates these relationships for the six crops, and the equation for each is shown. Applying these relationships to the fields in our study area, and using the average 33% of the fields as whitish and 10% with topsoil depth less than the original 38 cm (15 in), indicated an overall potential yield decrease of approximately 25% resulting from 80 seasons of furrow erosion on the entire study area. Therefore, average crop yields in the area today could be 33% higher had there been no erosion (Carter, et al., 1985).

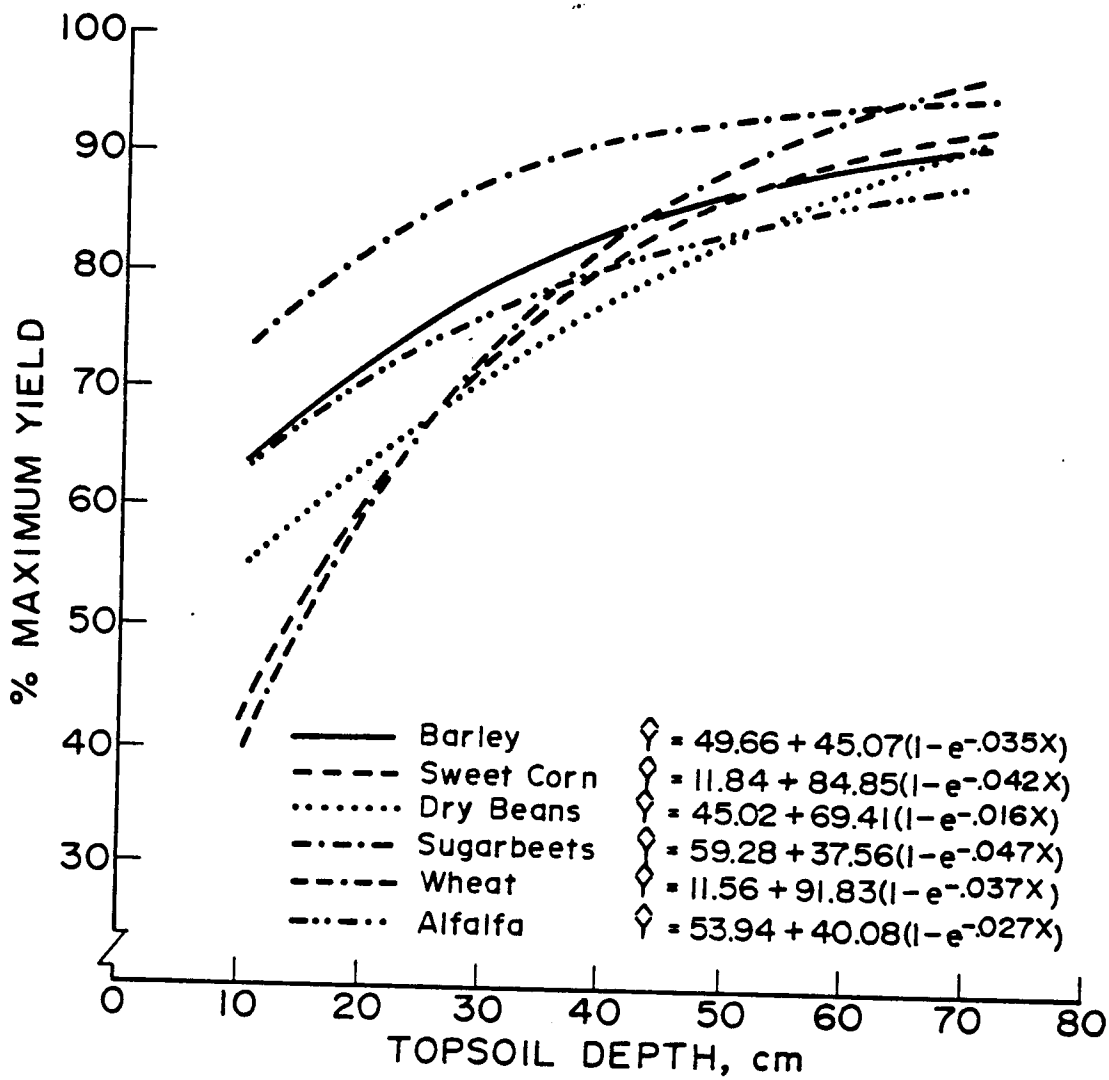

FIG 7. YIELD - TOPSOIL DEPTH RELATIONSHIPS FOR SIX IRRIGATED CROPS.

Increased Fertilization to Restore Productivity

With present technology there appears to be limited potential for restoring productivity on eroded lands in the Palouse of Idaho and Washington. A study by G. O. Baker, et al. 1965 applied both N and P on eroded hilltops in the Palouse. The yield response for phosphorous and nitrogen indicated that both were limiting factors for maximum wheat yield. However, this study did not include noneroded soils as a control. Soil tests show that noneroded Palouse soils also are limiting in nitrogen and phosphorus. Therefore, the use of N and P fertilizers in the study did not demonstrate successful restoration of soil productivity lost to erosion. The potential for restoring eroded yields in the Palouse could be limited by restrictive subsoil layers and by insufficient plant-available moisture in the soil profile.

Carter, et al. (1985) reported a study to restore soil productivity on furrow irrigated land. The irrigated fields and plots in that study in south central Idaho received sufficient water to insure that moisture levels were adequate to avoid water stress. Generally good cultural and weed control practices were followed. In some cases extremely eroded areas received double fertilization compared to the rest of the field; however, yields did not respond to the additional fertilizer. Carter, et al. concluded that present technology has little potential to restore crop productivity where topsoil depths have been decreased by erosion on soils with high-lime subsoils. There may be a toxicity factor in these subsoils that impedes yield restoration.

Restoring Yield Damage When Moisture is Limiting

Where plant-available soil water is limiting yields, the potential for restoring yields damaged by erosion is affected in two ways. First, increasing fertilization to replace fertility lost to erosion would not boost crop yields. Because of limited soil water the nutrients would not be available to the crop. Second, it is possible to increase infiltration rates and thus increase plant-available soil water and yields but only gradually. Conservation tillage can benefit and improve soil water storage through several mechanisms. The increase of soil organic matter and structure stability in the surface soil can begin to restore infiltration capacity. This is a rather long term process however, requiring as much as 5 to 10 years to show significant impact. Maintaining surface residues also protects the soil from degradation by weathering and encourages worm and microbial actions. Farming with reduced tillage results in less soil compaction and disturbance, thus promoting water availability to plant roots.

Increased surface residues associated with conservation tillage management increase plant water by improved snow catch, reduced evaporation, and reduced probability of soil freezing. Actual quantification of this available water has been difficult, but several studies have shown that increases of 25-75 mm (1-3 in.) are quite likely. A 20% reduction in the usual 100-150 mm (4-6 in.) of direct soil water evaporation could easily provide some 25 mm (1 in.) increase and in years of high snow blowing and snow evaporation, another 25 mm (1 in.) could readily be held and stored. Thus, residue management which conserves soil and prevents erosion damage, can also augment plant-available soil water and restore some yield damage from previous erosion. But the

potential for restoring yield damage by increasing soil water is limited and the process is often gradual.

DISAGGREGATE THE EFFECTS OF TECHNOLOGY AND EROSION

Expectations of technical progress must be considered in assessing erosion damage. To avoid confounding the opposite effects on yield of erosion damage and technology, separate projections of each need to be made. The effect of erosion can be represented by movement along a yield-topsoil response function while technical advance appears as a shift in that function. This section describes in conceptual terms the effect of technology on erosion damage assessment and presents a separate projection of technical progress in wheat yield for the Palouse region of North Idaho and Eastern Washington.

We consider first the effect of induced technology on damage assessment. Induced technology occurs when concern over soil erosion encourages research and development that results in yield-enhancing technical advance. Induced technology always acts to reduce erosion damage as illustrated in Figure 8. Curve Y_o is the yield-topsoil response function with current technology. In the absence of technical advance, yield damage would be GF, the difference between yield with conserved soil, G, and yield with eroded soil, C. Induced technology shifts the yield function from Y_o to Y_n, boosting yield from C to C' at the eroded topsoil depth. This offsets some erosion damage. In this case, erosion damage is GF', the difference between yield with conserved soil and unchanged technology, G, versus yield with eroded soil and induced technology, C'.

In contrast to induced technology, with exogenous technology, the rate of technical advance is independent of the rate of soil erosion. Because the rate of technical advance would be the same whether or not there was significant erosion, we measure erosion damage along a single technology-augmented yield curve. Technology shifts the yield function from Y_o to Y_n in Figure 9. Because technology is exogenous with respect to erosion, we measure erosion damage, G'F', as the difference between potential yield with conservation and improved technology, G', versus yield with erosion and the same improved technology, C'.

Notice that the technical advance represented here increased yield more on deeper soils than on shallower soils. We call this type of technical advance land-complementary technology. Such a shift could occur with improved crop cultivars which more nearly realize their genetic yield potential on deep topsoils where growing conditions are more ideal. Because land-complementary technology makes the yield curve steeper, yield damage increases. In this illustration yield damage increases from 1122 kg/ha (17 bu/ac) in the absence of technical advance along curve Y_o, to 2112 kg/ha (32 bu/ac) after technical advance along curve Y_n.

Some types of exogenous technology might increase yield more on shallower soils such as improvements that conserve soil moisture. Shallower soils would experience greater yield gain because moisture is more limiting in them than it is in deeper soils. With this case, called land-substituting technology, the yield curve becomes less steep. As illustrated in Figure 10, erosion dam-

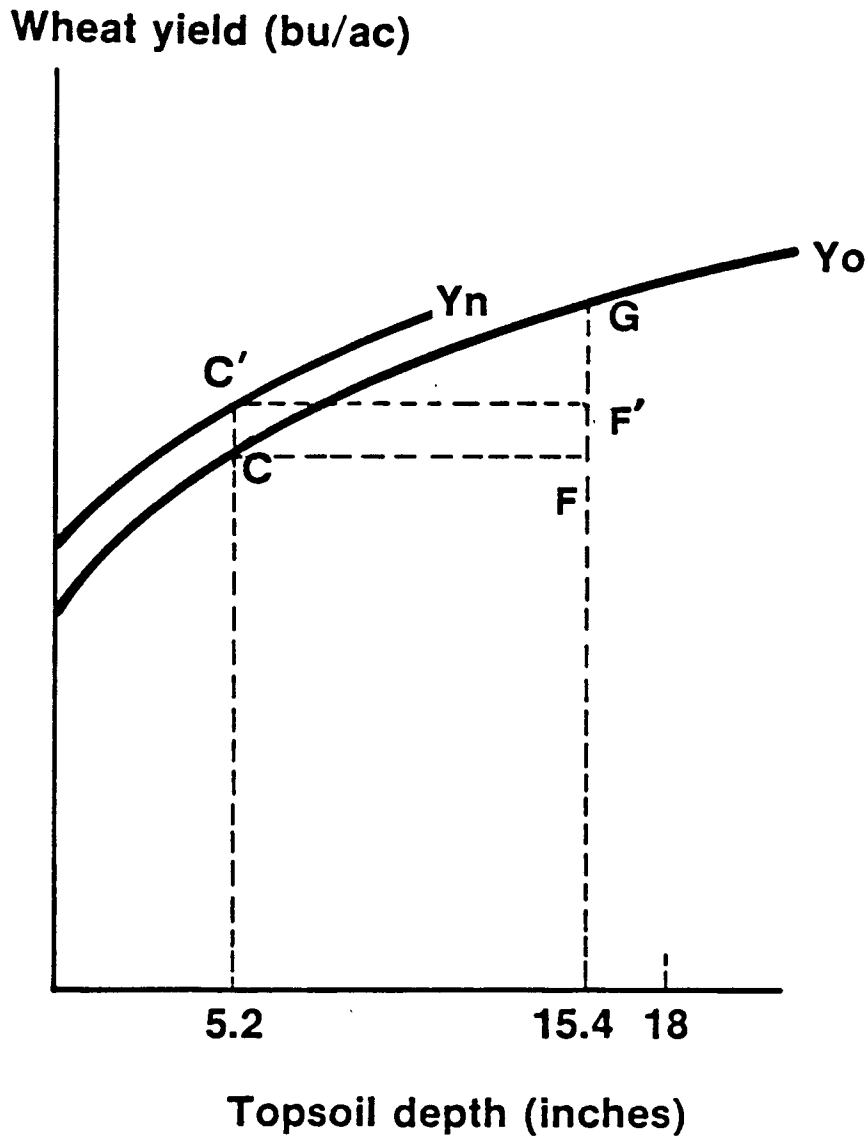

Fig. 8. Residual yield damage with induced technology.

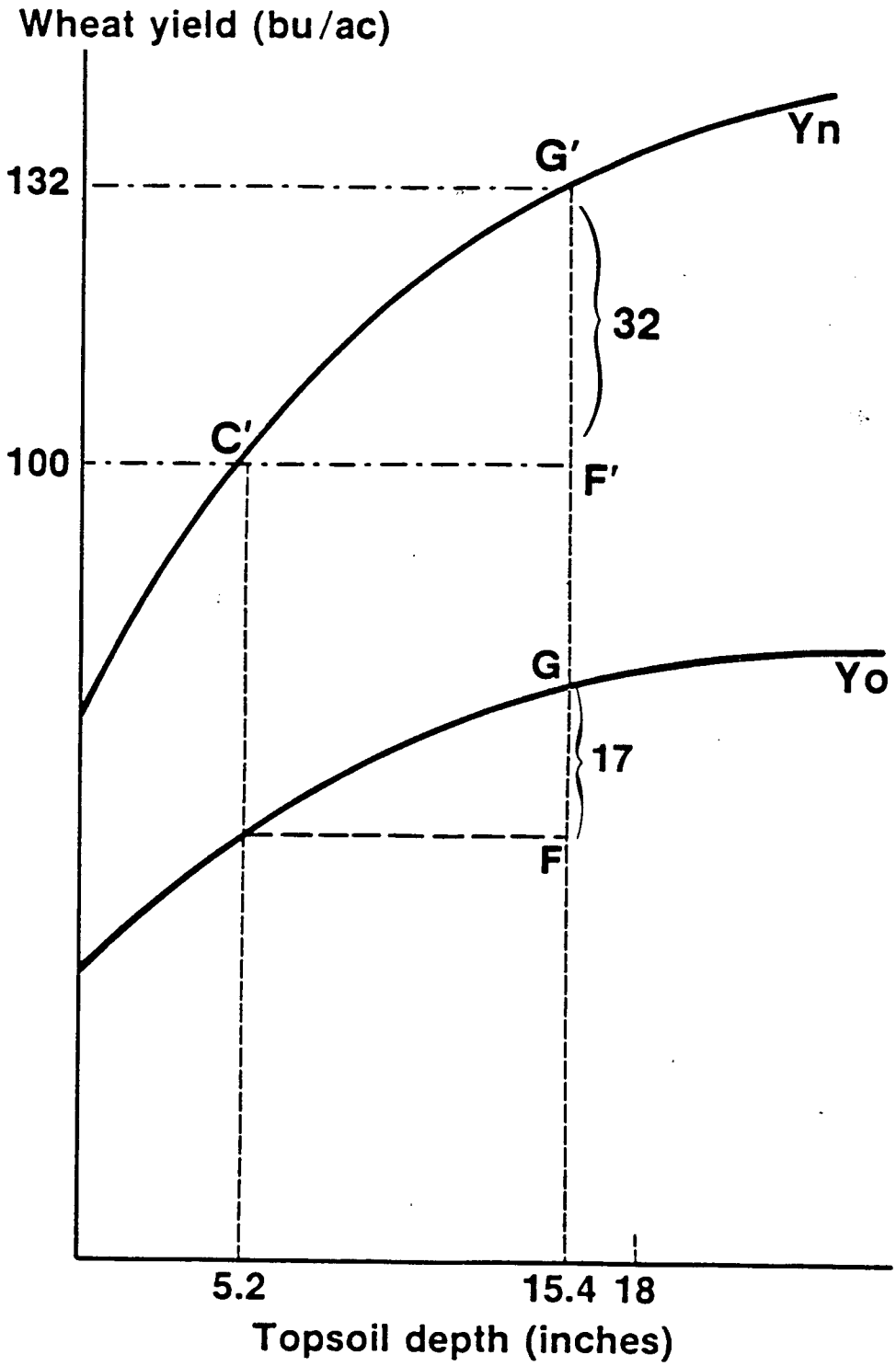

Fig. 9. Residual yield damage with land — complementary technical change.

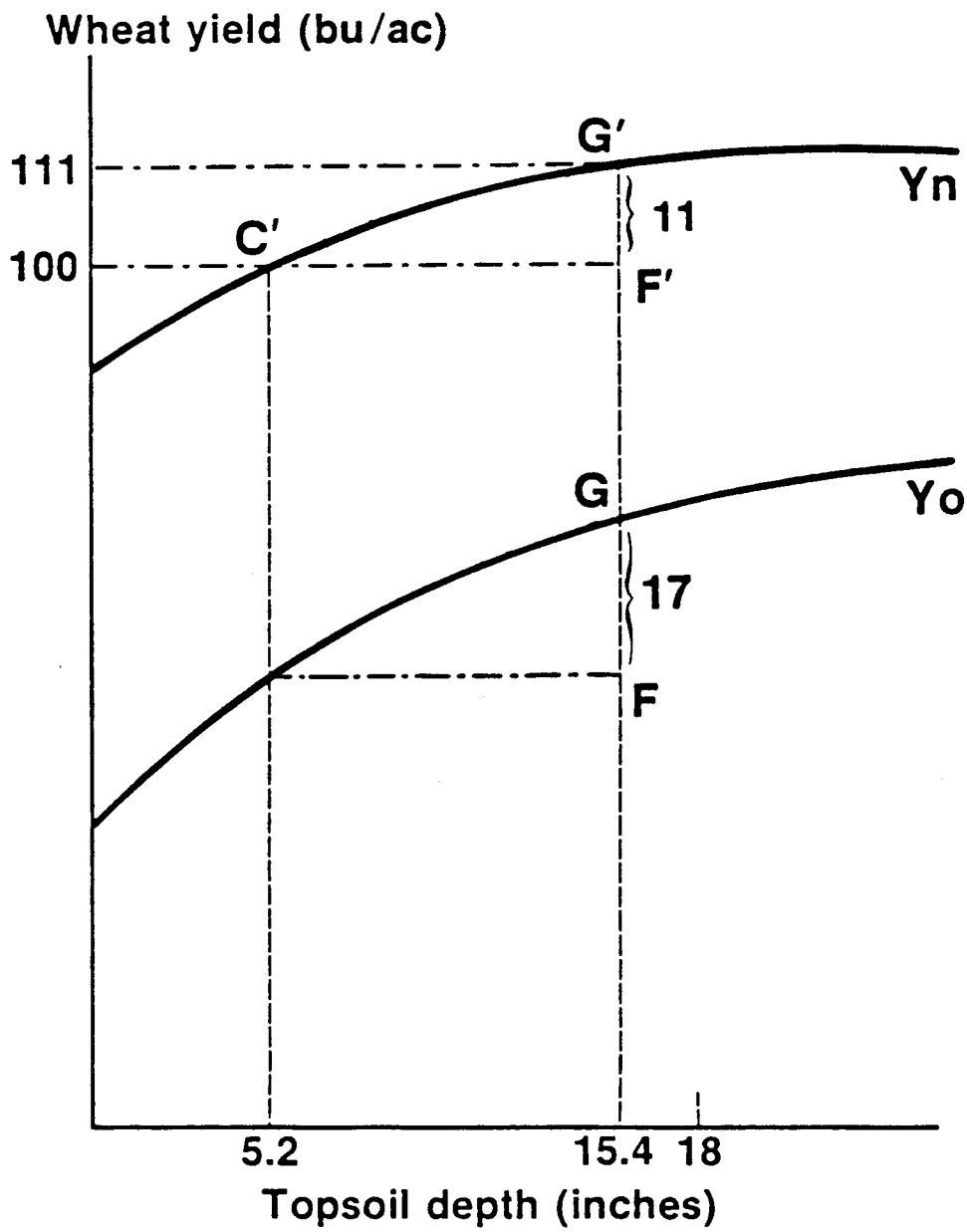

Fig. 10. Residual yield damage with land — substituting technical change.

age decreases to 726 kg/ha (11 bu/ac) in this example of land-substituting technology from 1122 kg/ha (17 bu/ac) in the absence of technical advance. A final type of exogenous technology might shift the yield curve in a parallel fashion. This type, called land-neutral technology, does not alter the slope of the yield function and erosion damage is unchanged.

Summarizing the consequences of technology for erosion damage, induced technology requires two yield functions for damage assessment and always reduces erosion damage. Exogenous technology may increase or decrease erosion damage and damage assesment involves a single yield function augmented with current technology. Ignoring technology leaves estimates of conservation benefits unbiased only in the case of land-neutral technology. Ignoring land-complementary technology will underestimate conservation benefits while ignoring land-substituting technology will overestimate benefits of conservation.

Evidence Favors Land-complementary Exogenous Technology

The impressive record of technical progress in United States agriculture, despite erosion, is proudly accepted as historical fact. For example, in Whitman County, Washington, improved crop varieties, fertilization advances, better pest control practices and other improvements in agricultural technology increased county-wide wheat yields from 1650 kg/ha (25 bu/ac) to more than 3960 (60) between the 1930's and the 1980's. Despite general acceptance of the importance of technical progress in sustaining crop yields, relatively little work has been done on the interactive effect on crop yield of technical progress and topsoil depletion. We showed above that technology will strengthen the benefits of soil conservation when it is exogenous and land-complementary. Probably more research has been directed to the technology-soil depletion question for winter wheat in the Palouse than in any other region in the nation. And the evidence for this crop and region, discussed below, clearly favors exogenous land-complementary technology.

The land-complementary nature of winter wheat technology in the Palouse, which boosts yields more on deeper top soils, was first reported by the late distinguished northwest soil conservationist, Verle Kaiser. He based his conclusions on unpublished data from the 1950's and 1960's. At first glance [the data] would seem to indicate that soil erosion is not an important factor in wheat yield in the Palouse, because yields have increased on eroded sites as well as on areas with little or no erosion. Closer inspection, however, shows the erosion is affecting wheat yields on the Palouse hill. While the overall field yields are increasing due to advancing technology, the increase comes primarily from uneroded portions of the hill. (underlining added) . . . as the area of eroded land increases in each field, loss of topsoil will become a more important factor in total field yields. (Kaiser, 1967, pages 89-90.)

More recently Young et al. (1985) have conducted a rigorous statistical test of the land-complementary hypothesis for the Palouse. This test made use of data collected by USDA-SCS researchers during the 1950's and 1970's. During this two decade interval, there were major advances in wheat production technology. These included use of commercial nitrogen fertilizer, introduction of the semi-dwarf higher yielding wheat varieties, effective chemical weed

control technology, and more efficient tillage practices. Figure 11 summarizes the statistical functions which describe eastern Palouse winter wheat yield response to topsoil depth in the early 1970's and early 1950's respectively. The 1950's function was derived from relationships estimated by Pawson et al. from over 800 observations collected from farmers' fields during 1952 and 1953. The 1970's function was estimated by Taylor from 89 observations, also from farmers' fields, collected by Wetter in the same region during 1970-1974. Readers are referred to Young et al. (1985) for detail on the estimation of these functions and the underlying data sets. Statistical comparison of the two functions confirmed at the 10% significance level that technology had increased yields more on deeper topsoils. On subsoil (zero cm topsoil), the predicted 1970's wheat yield exceeded the predicted 1950's yield by 950 kg/ha (14.4 bu/ac); on a deeper 76.2 cm (30 in) topsoil the yield advantage was 1511 kg/ha (22.9 bu/ac). Technical progress boosted yields about 60% more on the deeper topsoil.

A 1980 survey of Palouse farmers also revealed support for the land-complementary nature of technology in the Palouse. The 272 farmers surveyed expected, on average, wheat yield growth to be three times higher on typical hill slopes then on hilltops which are more eroded and have much shallower topsoils (STEEP Project, 1980).

Finally, it seems likely that most of the technology applied to Palouse wheat production has been exogenous as opposed to induced specifically by concern about erosion. For example, the breakthroughs in wheat varieties were primarily driven by desires for higher yield potential, reduction of lodging and better disease resistance. The wide-scale inexpensive production of inorganic nitrogen fertilizers and effective chemical herbicides grew out of pervasive exogenous breakthroughs in chemical technology during and after World War II. Because higher yielding semi-dwarf cereal varieties and commercial fertilizers increase yields relatively more on uneroded sites, it would be difficult to argue that these technologies were developed in response to concern about erosion specifically. It seems fair to conclude that much of the yield enhancing agricultural technology in the Palouse this century has been exogenous.

It would be inappropriate to automatically generalize the conclusions concerning land-complementary exogenous technology identified above for winter wheat in the Palouse region to all regions in the country. Differences in soils, topography, and the particular mix of technical progress characterizing different areas will influence these relationships. We encourage further empirical research based on historical yield trends for other locations. However, we believe that certain agronomic principles may favor a land-complementary relationship in many regions. Improved crop cultivars have among other properties greater genetic potential for converting chemical nutrients and moisture to harvestable grain. Consequently these responsive varieties will produce a relatively greater yield increase in the high moisture and nutrient absorbing and storing environment associated with topsoils. Eroded soils are more likely to be vulnerable to runoff, restrictive hardpans, or other restrictions that make nutrients, moisture, or the rooting zone limiting factors in plant growth. Furthermore, the greater genetic yield potential of improved varieties will be restricted at the outset if poor seedbed conditions on compact subsoils reduce stand establishment.

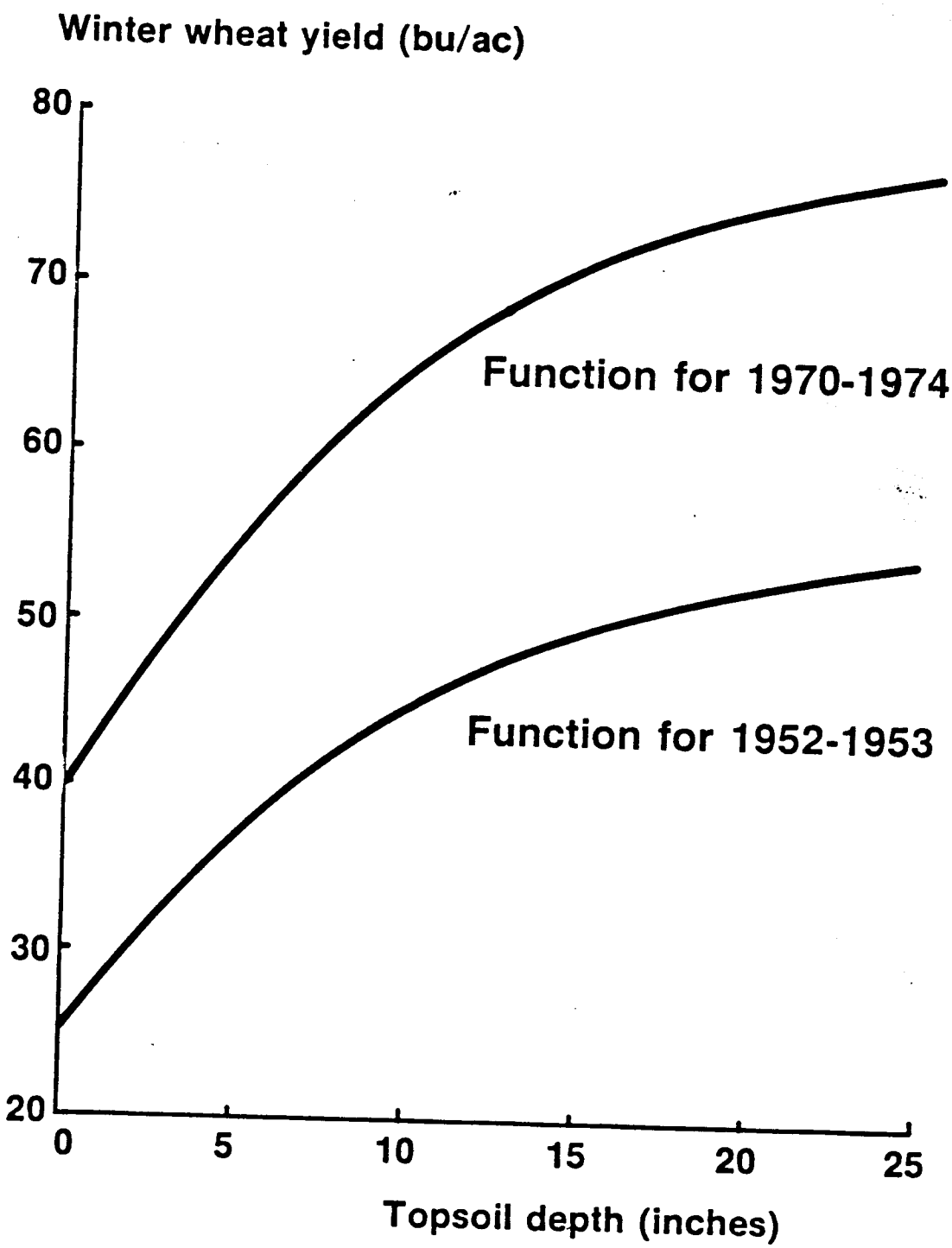

Fig. 11. Comparison of winter wheat yield — topsoil depth relationships from the 1950s and the 1970s, eastern Whitman County, Washington.

Source: Young, et al., 1985.

Adding nutrients, or other technical innovations, will be insufficient if erosion has created an environment where lack of moisture and rooting depth limit ultimate yield.

In contrast to this, one can imagine technical scenarios which would favor yield improvements relatively more on eroded sites. A nitrogen fixing cereal which rooted well on clay subsoils would be a (possibly extreme) example of such a technology. Economical tillage systems for breaking through hardpans exposed by erosion would be another example. These examples notwithstanding, it seems likely that most future technology will continue to favor uneroded soils.

In popular terminology, the farmer who fails to protect his topsoil in the near term exposes himself to a potential "double punch" in the future. First, future yields decline directly because shallower soils produce lower yields. Second, and equally important, future potential yield boosts from land-complementary technology are reduced, because these improvements have a lower payoff on shallower soils.

EMPIRICAL ESTIMATES OF CONSERVATION BENEFITS

The concepts outlined above for measuring erosion damage are now applied to estimate the benefit of conservation for a typical field in the Palouse. The benefit of adopting soil conserving practices is the cost of the erosion damage avoided. Erosion damage and hence conservation benefit is quite variable depending on soils, predominant crops, technology projections and discount rate. The effect of technology projections and discount rates on conservation benefit and conservation practice adoption are examined for the Palouse using a computerized model (Walker, 1982) which calculates the conservation benefit (erosion damage avoided) of adopting a conservation practice in the current year rather than postponing adoption. The first period of the simulation begins with current topsoil depth. The conservation benefit is the present value of the future income loss over a 75-year time horizon that is avoided by reducing erosion and maintaining soil productivity. The model predicts conservation adoption in the year when the benefit of conservation exceeds the cost of adoption.

The model evaluated the benefit of conservation tillage with a wheat-pea rotation (Walker and Young, 1986). Exogenous land-complementary technology, observed over the past 40 years in the Palouse, was assumed. Four rates of technical progress for wheat were explored: 1.71% per year, the rate observed over the past 40 years; .28% per year, the average rate that 272 surveyed farmers expected over the next 50 years (STEEP Project, 1980); 1% per year, an intermediate rate between the two; and 0% per year for comparison. For peas the rate of technical progress was assumed to be zero in all simulations based on a flat historical trend and surveyed farmers' expectations. Three discount rates were considered based on partitioning surveyed farmers into three equal groups by real discount rate. The lowest one-third had a mean real discount rate of 1.6%, the middle group had a mean rate of 5.4% and the highest group had a mean rate of 11.4%.

The benefit of immediate conservation adoption in present value terms ranged

from $1.89 per acre to $20.66 as displayed in Table 3. The cost of adoption is the current profit advantage with conventional tillage, $14.87, which is the difference in annual equivalent value of net income between the conventional practice and the conservation practice. This profit advantage with conventional tillage is lost by switching to conservation tillage. The benefit increased with the higher rates of land-complementary technology and with lower rates of discount. The highest conservation benefit occurred with technical progress of 1.71% and the low discount rate group (1.6%). Immediate conservation adoption was justified for only the low discount rate group (1.6%) when the rate of technical progress exceeded 1%. Only in these cases were conservation benefits high enough to outweigh the cost of conservation adoption at the outset.

Table 3. Conservation Benefits for Varying Real Discount Rates and Technical Progress Expectations

Real Discount Rate (%) p = % Tech. Progress	Future Benefit From Current Conservation ($/AC)	Adoption Year	Topsoil Depth in Adoption Year (in.)
High Discount Rate (11.4)			
p = 0	1.89	62	4.27
p = .28	1.94	61	4.44
p = 1.00	2.09	60	4.62
p = 1.71	2.26	58	4.97
Medium Discount Rate (5.4)			
p = 0	4.25	43	7.61
p = .28	4.48	42	7.79
p = 1.00	5.17	37	8.67
p = 1.71	6.08	30	9.90
Low Discount Rate (1.6)			
p = 0	11.51	12	13.06
p = .28	12.53	8	13.77
p = 1.00	15.90	1	15.00
p = 1.71	20.66	1	15.00

Source: Walker and Young, 1986.

In all other simulations, years elapsed before conservation benefits had increased sufficiently to justify adoption when compared to cost. Conserva-

tion benefits increased with time in these simulations for two reasons. Land-complementary technology increases the slope of the yield-topsoil response function and erosion over time results in movement along the response function to shallower topsoil depths where the slope of the function is steeper. Damage from further erosion and hence conservation benefit increases with steeper slope of the response function. In the worst case scenario, high discount rate group (11.4%) and no technical progress, adoption was delayed the longest, 62 years. Topsoil had declined from 38.1 cm (15 in) to a little over 10 cm (4 in) by the adoption year. This scenario illustrates that the segment of the farm population with high rates of discount may erode the soil for years seriously depleting topsoil unless economic incentives such as subsidies are provided.

It is important to reiterate that for each discount rate group, conservation benefit increases with the rate of technical advance because of exogenous, land-complementary technology. In this circumstance, technology should not be viewed as a substitute for soil conservation. This type of technology always increases the payoff from soil conservation. However, as Table 4 shows for high discount rates, technical progress does not increase conservation benefits very much. If high discount rates prevail, research on improving the current profitability of conservation practices would encourage conservaton adoption more than research on general yield-enhancing improvements.

CONCLUSION

Soil properties affected by erosion that influence crop yields were analyzed. Of two properties that varied systematically with topsoil depth, OM was more influential on yields although BD was also important for soils with restrictive layers. Yield-topsoil depth response functions were developed for the dryland Palouse and the irrigated Magic Valley in Southcentral Idaho. Though loessial soils in the Palouse are deep, because of restrictive subsoil layers in buried paleosols near the surface, the soils may be more vulnerable than previously thought and crop yields are affected by erosion. Since cultivation began, the loss of potential yield has been significant. Crop yield could be 16 to 20% higher in the Palouse and 33% higher in irrigated Southcentral Idaho had there been no erosion.

Quantifying the benefit of conservation is important for developing conservation policy. Concepts and a methodology for measuring conservation benefits were presented. The task of assessing conservation benefits is complicated by agricultural technical progress. Rather than mitigating the need for conservation, exogenous land-complementary technolgy can increase the benefits from conservation. In regions where this technological trend is expected, the greatest yield gain can be achieved by pursuing a vigorous conservation policy.

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