

STEEP: Impact of long-term conservation farming research and education in Pacific Northwest wheatlands

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Abstract: Erosion took a serious toll of prime topsoil from wheat fields in the Pacific Northwest United States since farming began in the 1870s. By the mid-1900s, it had become a serious environmental and economic threat to the region that produces world-record rain-fed grain yields and almost 13% of the US wheat crop. Of significance is that 80% of the nation's specialty soft white wheat is grown here for food grain, of which 90% is exported. To combat the severe erosion, wheat growers, the experiment stations, and the USDA in Idaho, Oregon, and Washington joined forces in 1975 to develop a multidisciplinary program named Solutions to Environmental and Economic Problems (STEEP). For more than 30 years, it has proved itself a national landmark in effective conservation farming research and education. The basic strategy was a systems approach that addressed all facets of farming from planting to harvesting in multi-year rotations. Its primary goal was to reduce soil erosion from the region's 3.3×10^6 ha (8.2×10^6 ac), consisting of highly productive but considerably steep cropland. Through the successful development and implementation of improved conservation technology and farming systems by the tri-state STEEP effort, regional soil loss rates averaging $45 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ($20 \text{ tn ac}^{-1} \text{ yr}^{-1}$) were reduced over the 30 years to a tolerable $11 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ($5 \text{ tn ac}^{-1} \text{ yr}^{-1}$) or less. In addition, financial returns to wheat growers using the conservation systems are equal or have increased, and long-term benefits to soil, water, and air quality have improved. A conservative estimate shows that the investment cost of saving soil and improving water quality was less than $\$0.50 \text{ ha}^{-1} \text{ yr}^{-1}$ ($\$0.20 \text{ ac}^{-1} \text{ yr}^{-1}$) over the life of STEEP. Though STEEP can boast success, much more is needed to preserve and protect the Northwest environment, natural resources, and productivity to ensure that agriculture is fully sustainable for the future. Ongoing solutions are needed to resolve emerging issues relating to greenhouse gas emissions, carbon storage, energy costs, and other farm inputs that can affect agricultural health. Its proven success provides strong assurance that STEEP can deal with future challenges relating to changes in farm policy, economics, technology, and sociological issues. This paper documents the extent that program goals were achieved and qualitative estimates of return from money invested.

Key words: conservation adoption—erosion—impact assessment—Pacific Northwest—special research grants

The US Pacific Northwest dryland farming region (locally referred to as the Inland Pacific Northwest) has long been the nation's leading grower of soft white wheat as a food grain for domestic use and export. Other classes are produced to a more limited extent, and barley and pulses are important with annual cropping. Unlike the wheat belt in the Northern, Central, and Southern Plains that are dominated by a summer rainfall climate, the Inland Northwest

climate is Mediterranean-like with cool, wet winters and warm, dry summers. Average annual precipitation ranges from 600 mm (23.5 in) on its eastern edge (Washington-Idaho Panhandle border) to less than 150 mm (5.9 in) on the west, bordering the Columbia Basin and southern parts. Some 70% of the precipitation occurs during November through March. Precipitation occurs as low intensity rainfall (<2 to 3 mm h^{-1} [0.08 to 0.12 in hr^{-1}]) and 20 to 30 mm [0.8 to 1.2

in] per event) with about one-sixth falling as snow. Soils seldom freeze more than 30 cm (11.8 in) deep, and thawing with rain and/or snowmelt may occur several times each winter. Soil depth ranges from less than 1 m (3.2 ft) to more than 7 m (23 ft) in the dry zones and up to 50 m (164 ft) where precipitation is higher. Soils are predominantly loess and are classified as Mollisols where the average annual precipitation exceeds 230 mm (9 in) and as Aridisols with some Entisols in the drier parts. Much of the topography is steep, with slopes of 30% being common and some up to 45% being farmed. The steepest slopes occur in the high and intermediate precipitation zones where annual cropping prevails and the landscape changes to gently rolling in the drier parts where summer fallow is practiced.

The Palouse croplands, noted for their world record wheat yields, have experienced some of the highest erosion rates in the United States since farming began there in the 1870s. Annual losses amounted to millions of Mg of soil annually. Historical annual erosion rates were estimated at 22 to 67 Mg $\text{ha}^{-1} \text{ yr}^{-1}$ (10 to 30 tn $\text{ac}^{-1} \text{ yr}^{-1}$) (approximately 3 mm [0.125 in] of topsoil) with conventional farming practices (USDA 1978). By some estimates, this is equivalent to 25 Mg of topsoil eroded for each Mg of wheat produced (0.75 tn of soil per bushel of wheat). Approximately a third of the eroded soil is washed into the region's bodies of water, creating an incalculable ongoing environmental cost.

Erosion is not just pollution; it is an accelerating process that has denuded untold hectares of topsoil and thus reduced the capacity of once-rich farmland to sustain economical production. The cause of erosion is a combination of (1) winter precipitation climate with high potential for frozen soil runoff, (2) steep and irregular topography (35% to 45% slopes) that does not lend itself to conventional structure or landscape modification to control erosion, and (3) a

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predominant winter wheat cropping system that, with conventional farming practices, leaves the soil bare during the winter rainy season. Traditionally, two thirds of erosion occurs from fall-seeded wheat fields that for the most part lack protection over winter.

By the 1970s, it was clear to stakeholders that wheat agriculture, the base of the farm economy in the region, was on a disaster course, and major changes in farming practices were urgently needed to reduce erosion and water pollution. There was a growing consensus that the three states must combine resources and generate a multidisciplinary, regional research effort to develop new strategies for erosion control. Solutions to Environmental and Economic Problems (STEEP), constructed as a special grant request guided by input from growers, researchers, extension specialists, and conservationists from the three states, was considered the best approach to solve these existing broad environmental and economic problems.

The program was launched in 1975 with a mandate to establish a cooperative effort between the state agricultural experiment stations of Idaho, Oregon, and Washington and the USDA Agricultural Research Service to develop new approaches to control erosion and water quality degradation. While focused mainly on the wettest zone (often referred to as the Palouse) averaging 450 to 600 mm (18 to 24 in) average annual precipitation, the studies encompassed an area of some 3.4×10^6 ha (8.3×10^6 ac) of prime wheatlands, including low (<300 mm [<12 in]) and intermediate (300 to 450 mm [12 to 18 in]) average annual precipitation zones in the three states. The objectives were to develop economically feasible conservation cropping systems based on principles of soil surface and crop residue management and to assist growers with adopting these new approaches to control erosion on their farms (Oldenstadt et al. 1982).

The core strategy was to shift away from the conventional moldboard plow-based tillage to reduced-tillage (conservation-tillage) and no-till methods. Historically, moldboard plowing was the primary operation to manage heavy residues from wheat crops, control weeds and prepare seedbeds. Plow-based tillage was acknowledged to be the root of the erosion problem because it buried most cover from the land that would otherwise be effective for slowing runoff and soil loss.

However, changing from the well-established moldboard plow and intensive tillage system to conservation systems involved stepping into a host of unknowns with risks that could cause financial disaster to the farmers if they increased costs and/or decreased crop yields. A change of this magnitude would require new approaches for crop residue management, crops and rotations, sowing methods, pest control, and fertility management. Economic viability and social impacts of the new farming systems had to be considered.

Since inception, the STEEP program received approximately $\$15 \times 10^6$ in US government grants to the state experiment stations and supplemental funding to USDA Agricultural Research units in the Northwest states. However, a unique feature of the special grant model was its power to attract and divert additional resources from the universities towards high priority research. As a result, the amount available for STEEP research and education was, by conservative estimate, at least double that allocated in direct federal support.

Completing thirty years of the STEEP program offers an opportunity to assess the accomplishments and effectiveness of a notable conservation research effort. If the program was indeed successful, there should be linkages of its accomplishments with reduced soil erosion, improved soil, water and air quality, enhanced farm profitability, and economic stability. The objective of this assessment was to document the major research results, applications, and impacts in achieving target goals.

Materials and Methods

Assessing the benefits of agricultural research and education is an indirect science, not easily accomplished by any specific procedure. The reasons are multiple: single research project results are not often directly related to broader cropping systems complexes; research accomplishments come about in small steps, often with negative findings; and the research benefits frequently accrue years after the result. The willingness to learn from failures as well as successes is a key component of effective agricultural research for development. Impact assessments and evaluations must recognize that “failure” may actually represent “work in progress” (Morris et al. 2003).

Most procedures to conduct a research assessment have been developed by economists and involve multiple methods of econometrics. However, these methods readily acknowledge the lack of economic values available for many agricultural impacts and in particular those with long-term effects on the natural resources where economics becomes general and intractable. In this case, other related parameters and data such as sustained production and reduced degradation of the soil become the indicators of choice to document changes and improvements.

Several surveys were conducted by STEEP projects that provided perspectives on grower attitudes and behavior regarding aspects of conservation farming (Carlson and Dillman 1999; Forté-Gardner et al. 2004). These also served as predictors of relative changes in the use of conservation practices. In addition, there was significant credible knowledge from regional farmers and conservationists to document changes in farming practices that occurred during the past 30 years to establish linkages with STEEP accomplishments.

The following sources of information were used to document the accomplishments and impacts of the STEEP program:

- Research and education accomplishments—Major documentation of the research accomplishments were readily available as published scientific papers, meeting proceedings, and extension reports.
- Interviews with wheat growers—Nine prominent regional growers were interviewed to provide detailed information on changes in practices on their farm and others in their locality over the 30-year period of the STEEP effort.
- Estimated erosion changes—The Revised Universal Soil Loss Equation Version 2 (RUSLE2) prediction model was applied to estimate erosion rates for representative farming systems at the beginning, middle, and later part of the STEEP 30-year evaluation period.
- Independent environmental assessments—Published information from regional stream monitoring studies, pre-1970 trends in erosion, climate, and water quality were compared with those of recent times.

Research and Education Accomplishments. The large volume of focused and related research accomplishments reported over the course of the STEEP evaluation period make it impossible to more than highlight those most prominent. Other reports and

two major reviews of the program have been published (Elliott et al. 1987; Michalson et al. 1999). The following accomplishments were selected as most significant in advancing resource conservation, environmental protection, and farm production:

Fertilizer Applications. Early research on application methods established yield advantages and improved use efficiency in conservation tillage and no-till systems with fertilizer banded near the seed row as opposed to surface broadcasting. This led to the design of drill openers that simultaneously sow and place fertilizer in close proximity to one side or below the seed row. New and improved no-till openers focused on minimal soil disturbance, residue clearance, reduced draft, uniform seeding depth, and a firm seedbed. Outcomes were a double furrow concept using a very narrow fertilizer opener positioned below a wider seed furrow to move dry soil aside; a low soil disturbance, parabolic shank opener to place liquid or dry fertilizer apart from the seed with low power requirements and good residue clearance; a twisted shank opener to provide uniform seeding depth, improved seed germination, low soil disturbance, and reduced draft requirements; and introduction of the Cross-Slot opener from New Zealand with capability to sow through heavy residue and sod without plugging while maintaining uniform seeding depth and band fertilizer placement. Variations of these designs are incorporated into most no-till drill openers now in use (Baker and Saxton 2007; Hyde et al. 1987; Koehler et al. 1987; Payton et al. 1985; Peterson 1999; Wilkins et al. 1983; Veseth 1985).

Seeding Systems. The development of the shank and seed concept by STEEP was the forerunner of the two-pass reduced-till seeding system for winter wheat widely used by Palouse growers since the 1990s. The first version, the Chisel-Planter, incorporated fertilizing and sowing in a single operation. The second version, the Chisel-plus-Drill two-pass system, consisted of a first pass with a chisel plow equipped with a fertilizer applicator, followed by a second pass with a grain drill with double disk openers. This met the need for a low-cost seeding system that could be easily duplicated by growers using their own equipment. Several modified adaptations to this system have been constructed by commercial firms and growers which follow the original concepts. In addition to

eliminating tillage costs, the two-pass system usually leaves the soil surface with 65% to 70% of the residue and moderate-sized clods that significantly reduce erosion (Peterson 1999).

Integrated Pest Management. An Integrated Pest Management (IPM) Project in collaboration with STEEP pioneered development of a conservation no-till grain production system that successfully controlled weeds, satisfied conservation compliance, and was more profitable and less risky than the conventional system. In the past, lack of weed control and residue management were major deterrents to adoption of conservation tillage, especially in the intermediate and high precipitation areas. These problems led to reduced crop yields compared with established intensive tillage methods. The success of the conservation production system is credited to its integration of a diverse crop rotation, limited tillage, and judicious use of herbicides for effective weed control. Profits increased, and risks decreased due to higher yields in dry years, equivalent yields in wet years, less damage to winter wheat in severe winters, and increased disease resistance to crops growing in high residue seedbeds. The USDA Natural Resources Conservation Service and Cooperative Extension relied on the outcomes of this research to develop farm plans for meeting conservation compliance provisions in the 1985 and 1990 farm bills. The results were also used by the US Environmental Protection Agency to establish pesticide use guidelines on agricultural lands. By 1995, half of the Palouse growers were using some aspects of the STEEP-IPM production system on their farms (F.L. Young et al. 1994, 1994, 1994, 1996; D.L. Young et al. 1994, 1999).

Rhizoctonia Disease Control. It was determined that volunteer cereal and weeds that establish growth in untilled soil between crops serve as a “green bridge” host for *Rhizoctonia* root rot, a serious fungal disease of spring wheat and barley. STEEP research showed that the severity of *Rhizoctonia* root rot was decreased and grain yield was increased by lengthening the time between glyphosate herbicide application and spring no-till seeding to allow for complete dying of the growing vegetation. Avoiding the “green bridge” markedly advanced progress with no-till seeding of spring wheat and barley (Smiley et al. 1992).

Wheat Disease Reduction. Risks with early fall planting to provide maximum vegetative ground cover over winter were reduced by development of soft white winter wheat varieties with increased resistance to stripe rust and some root diseases that have been major impediments to this proven erosion control practice (Allan and Peterson 1987).

Wheat Varieties. Early attempts with conservation tillage produced a range of wheat yields, almost all less than that achieved with conventional tillage systems. However, it was found that yields of wheat genotypes from no-till and conventional tilled systems were positively correlated. This showed that there was little or no difference in yield rankings of varietal performance and therefore no justification for conducting separate breeding programs for each tillage system (Allan and Peterson 1987).

Conservation Plans. The Revised Universal Soil Loss Equation (RUSLE) developed under STEEP with Northwest parameters served as a base tool for planning conservation practices region-wide and at the farm level. The model outputs from tillage and cropping practices were used by the USDA to establish guidelines to meet conservation compliance requirements in the 1985 and 1990 farm bills. They were also used to aid farm planners and growers to design practices that would reduce water erosion and be economically viable (McCool and Busacca 1999).

Residue Decomposition. A crop residue management model (RESMAN) was developed to estimate the rate of surface and buried residue mass loss, based on precipitation, air temperature, and residue composition. Residue decomposition is a key factor in maintaining residue cover for erosion control under different tillage and cropping systems. The theory and equations from RESMAN have been incorporated into the USDA's wind and water erosion models for national use (Stroo et al. 1989; Elliott et al. 1999).

Conservation Adoption. Research surveys conducted by STEEP in 1976, 1990, and 2002 showed that an increase in the adoption of erosion control practices was closely related to grower attitudes about conservation and erosion control and their income level. Absentee landlords were not an obstacle to acceptance and adoption of conservation practices on rented farmland; instead obstacles were mostly related to the risk, real and perceived, of the new technology itself

such as no-till seeding, Kinship farming and individual grower capability were important positive factors in the adoption of erosion control practices. Growers were more inclined to relate with peers or innovators to seek ideas to develop and adopt conservation technology than other communication processes. This suggests the importance to identify opinion leaders among growers and enhance their roles in the adoption process (Carlson and Dillman 1999; Forté-Gardner et al. 2004).

Extension and Education. The STEEP extension and education project played an extraordinary role to increase the awareness and adaptation of conservation technology through timely publications, conferences and workshops, on-farm testing, and field demonstrations and grower conservation organizations. STEEP used newsletters, popular articles, audiovisuals, and presentations at meetings and field activities to increase awareness. The STEEP Web site (<http://pnwsteepp.wsu.edu/>) is readily available to researchers and farmers and contains the *STEPP Pacific Northwest Conservation Tillage Handbook* series. On-farm testing and field demonstration programs brought growers and extension specialists/researchers together to evaluate the performance of new research findings or technologies on farm fields and thus aid and accelerate the adoption process. A major accomplishment of the education program was the organization of the Pacific Northwest Direct Seed Association (PNDSA), a grower-based organization of some 300 members dedicated to increasing economical conservation tillage and no-till farming systems (Veseth 1989–2007; STEEP 2008; Veseth and Wysocki 1999).

Spring Cereal Cropping. Cropping systems research in the low precipitation zone (<350 mm [<14 in]) prone to wind erosion showed that spring wheat–chemical fallow rotation and annual no-till spring cereal cropping were generally less profitable than minimum-till winter wheat–fallow. These systems would otherwise essentially eliminate wind erosion in the dry-farmed wheatlands. However, risks with precipitation variability make annual cropping less economical than the more erodible winter wheat–fallow cropping system. Minimum-till fallow was shown to reduce fine dust emissions that cause health risks by 54% compared with clean till fallow and equal its profitability, but in some years may not achieve the residue requirement for adequate wind erosion con-

trol (Janosky et al. 2002; Juergens et al. 2004; Lee 1998; Papendick 2004; Thorne et al. 2003; Young 2001).

Undercutter Method of Dryland Farming. A minimum till, broad-sweep implement was developed and evaluated in collaboration with scientists of the Columbia Plateau PM₁₀ Project as an economical and effective summer fallow practice. The machine (locally called an “undercutter”) is used for primary spring tillage plus nitrogen fertilizer injection that causes little surface soil disturbance and leaves significant standing residue for excellent wind erosion control throughout the 13-month fallow period. No agronomic advantages were lost when switching from conventional tillage fallow to the “undercutter” method. Due to recent higher energy and reduced herbicide costs, the undercutter method returns more profit to the grower than conventional fallow tillage methods, which are highly susceptible to wind erosion (Schillinger 2001; Zaikin et al. 2007).

Agricultural Policy. STEEP research had a significant impact on Agricultural policy and implementation for the Pacific Northwest. The 1985 farm bill played an important role in fostering soil conservation by linking eligibility for commodity payments with incentives for erosion and water quality control. STEEP research results available from pre-1985 provided fundamental concepts for conservation practices that growers could readily adopt to meet the compliance provisions of the farm bill. Aids for farm planning were field-tested conservation cropping systems, early fall planting, conservation-tillage or no-till seeding systems, and surface residue management methods (Michalson 1999; Painter and Young 1993; Walker and Young 1999).

Interviews with Wheat Growers. Nine regional growers were identified who had farmed throughout the life of STEEP, were innovative in their approaches to farming, and were also very observant of farming systems throughout their locales. Each farmer was interviewed carefully with a guideline of very general questions about the farming systems on his/her farm and neighbors farms during the study period.

Those interviewed included growers across average annual precipitation zones in Washington (four with >450 mm [17.7 in]), two with 400 to 450 mm [15.7 to 17.7 in]), Oregon (one with 400 mm [15.7 in]), one with 300 mm [11.8 in]) and Idaho (one with

560 mm [22 in]). All had personal farming experience that transcended the past 30 years in the STEEP impact area. The interviews lasted two to three hours each. By consolidating the management knowledge of their farms and others in their locality, it was possible to document the application trends of new technology, changes in practices, and expert opinion about soil erosion, water quality, and profitability. The growers identified changes in cropping systems, rotations, crop yields, tillage, use of farm equipment, and farm size. While the sampling was not rigorous, the trends that emerged were clear.

The major changes identified by the interviewees can be summarized into two general categories: those that were influenced by or were directly the result of STEEP research and education and those that were the result of outside influences. The following summary lists the most pertinent perceptions and changes in farming systems identified by the growers. All were judged to have a direct linkage with STEEP accomplishments except the last three, which were largely caused by outside influences.

Moldboard Plowing. Use of the moldboard plow has significantly declined. Prior to the 1980s, the plow was the primary tillage tool for residue management, weed control, and seedbed preparation. Its long-term detrimental effects damaged the natural structure of the soil and beneficial biological soil life, both of which made the soil more vulnerable to erosion and accelerated organic matter oxidation. These detrimental effects contribute to the decline of quality soil and productivity that are difficult and costly to restore. In recent years, the plow has been replaced by less aggressive equipment such as chisel plows, sweeps, and field cultivators that conserve surface residues. Moreover, most tillage following legume crops has been eliminated and reduced by 80% to 90% after spring cereals and 40% after winter wheat.

Residue Burning. Burning of winter wheat stubble, and the practice of summer fallow have been significantly reduced. In the 1970s, nearly 50% of the cropland in the high precipitation zone was planted to winter wheat (in a two-year rotation with spring pea), and of this cropland, about one-third of the stubble was burned after harvest and before fall plowing. Winter wheat occupied about 40% of the cropland area in 1990 and about a third in 2005. The standard rotation was winter wheat–spring cereal–spring legume.

Burning winter wheat stubble was reduced to 20% of the planted hectares in 1990 and to near zero by 2005. In the intermediate precipitation zone, some 50% of the cropland was planted to winter wheat in the 1970s, and 20% of the stubble was burned. By the 1990s, winter wheat was planted on 40% of the cropland in this zone, and of this, only about 10% of the stubble was burned. The amount of stubble that was burned dropped to near zero in 2005. Burning stubble never has been a practice in the low precipitation areas because of low residue amounts.

Fallow Reduction. Approximately 13% of the cropland in the high precipitation zone was fallowed in the 1970s; this practice dropped to about 6% in the 1990s and to near zero in 2005. In the intermediate precipitation zone, cropland in fallow was about 24% in the 1970s and 1990s, and about 20% in 2005 but shifted from a tillage fallow to an increase in chemical fallow over the past 20 years. Fallow hectares remained about 46% to 48% in the low precipitation zone over the past 30 years. However, there has been a significant increase in conservation-tillage fallow in the past 15 years. Widespread use of glyphosate herbicide for weed control has advanced conservation efforts by replacing tillage.

Conservation Tillage. Conservation tillage has become a standard practice on most farms. During the 1970s, winter wheat planted after a pulse crop or spring cereals required four to five tillage operations, and a spring crop after winter wheat needed eight or more tills through the sowing operation. Today, most growers have reduced tillage passes before seeding by eliminating and/or combining operations. A two-pass system was used by many growers in the mid 1980s and has become popular with winter wheat seeding following a legume. A cultivator with shanks to band fertilizer on untilled ground is followed by sowing with double-disk drills. By 2005, many farmers had adapted this operation into a one pass system. Spring cereals following winter wheat fields are now often fall-chiseled, spring fertilized, and then seeded with a double disk drill—three operations compared with five or six with conventional farming. With conservation tillage, legume crops (pea, lentil, garbanzo beans) following winter wheat usually require only four or five operations compared to eight or ten with conventional farming. An increasing number of growers are now able to use a no-till seed-

ing system as soil tilth improves after several years of conservation tillage. Herbicide applications are extra operations in both the one and two pass systems, but these do not disturb the soil or residues.

Longer Rotations. Most growers have shifted to longer crop rotations. Winter wheat-dry pea with intensive tillage was the dominant cropping system during the 1970s practiced on 90% of the farms in the Palouse. In the mid 1980s, many growers shifted to a conservation-tillage, three-year winter wheat-spring cereal-grain legume rotation (following results of the STEEP IPM study) or an even longer rotation, which reduces the frequency of winter wheat. Advantages of the longer rotation are improved and more economical pest control, which along with the rotational effect results in higher yields and more stable farm income in the long-term. Longer rotations spread the workload during planting and harvesting, provide for timely farm operations, and reduce machinery and labor requirements.

Increased No-till. The use of no-till is increasing, and the trend will likely continue. New knowledge developed by scientific effort and grower innovations, along with education and improved implements have removed many of the early concerns and limitations of no-till. For example, elimination of the “green bridge” by early herbicide application for weed control enhanced the success of no-till by reducing root diseases that killed crop seedlings. Longer crop rotations improved weed and disease control and required less use of herbicides with no-till. New and approved types of no-till drills have been developed, although adoption by growers is slow. The main factors limiting adoption of no-till by growers appear to be lower and more variable yields with high surface residue farming, lack of knowledge, and change-over costs in shifting to no-till from conventional farming. Education along with technological improvements, reduced costs of equipment, and reduced fuel use will help to resolve these barriers.

Reduced Erosion. Soil erosion in the Palouse and surrounding areas has decreased during the past 30 years, especially in the past 10 years, as adoption of conservation practices continues to increase. A significant observation was that county and state highway road ditches alongside farm fields do not trap as much sediment and require less frequent cleaning than in earlier times. More fields are

covered with residue or have rougher surfaces as a result of limited or no tillage with winter wheat planting compared with clean tilled seedbeds of the 1970s when erosion was severe. Fields that are not sown to winter wheat are left rough-tilled or untilled over winter and do not erode as severely. Rills and gullies are less evident on increasing numbers of fields as a result of conservation tillage. The lack of rills and gullies is indicative of reduced erosion rates.

Excess Straw. Large amounts of straw from high winter wheat yields (commonly >6.7 Mg ha⁻¹ [>100 bu ac⁻¹]) are an obstacle to the adoption of conservation practices. With current economics, most farm operations depend on high wheat yields to make an adequate profit. High yields result in high straw yields. With straw in excess of that necessary to protect the soil from erosion (usually 30% ground cover), practicing conservation becomes difficult, for many growers. Mechanical removal of excess straw is costly without any financial return; burning is not a conservation option and is environmentally unsound. No-till seeding in high residue situations is limited to growers with financial means to invest in new and innovative sowing equipment. Grower consensus is that residue management with high yielding wheat varieties is a continuing high priority research need.

Improved Soil Quality. Growers who have practiced continuous conservation tillage or no-till farming for several years consistently observed improvements in soil properties relating to tilth, cohesiveness, and organic matter accumulation: (1) topsoil was described as more mellow, which made placement of seed and fertilizer easier; (2) drainage was better and surfaces more firm, which allowed equipment on the field earlier in the spring; (3) more earthworms improved porosity and aeration; and (4) runoff and erosion after heavy rains and snowmelt were significantly less. As these soil properties became established, growers indicated that they were reluctant for any reason to change cultural methods back to intensive tillage. However, some have used tillage for severe weed problems.

Increased Yields. Plant breeding, improved genetics, and crop management have increased cereal yields but not of rotational crops such as grain legumes. Grower estimates indicate that winter wheat yields have increased an average of 40% compared with those 30 years

ago. The increase is attributed to improvements through plant breeding and genetics, availability of more effective and selective herbicides for weed control, improved seed placement and fertilizer banding technology, and improved water conservation with conservation tillage. Spring wheat yields have also increased to as high as 5.7 Mg ha⁻¹ (85 bu ac⁻¹) today compared with 4.0 Mg ha⁻¹ (60 bu ac⁻¹) 30 years ago, much for the same reasons as winter wheat. Yields of grain legumes have remained stable. Yields in three-year rotations are higher than yields in continuous wheat.

Government Incentives. Government farm programs with incentives that promote

conservation and environmental quality are attractive to growers, but because of under-funding, participation is too limited to have a significant regional impact to achieve soil and water quality objectives. Growers consider the programs to have well-planned objectives and incentives to achieve stewardship goals. However, funding may be restricted to only a few areas in the region. This limits its eligibility and causes dissension among growers who are interested in stewardship but who do not qualify for conservation program benefits. Other programs that pay for environmental services are often in the same situation. Growers find general

satisfaction with farm programs, such as EQIP, that reward them for implementing practices that provide environmental benefits, provided that these practices do not cause a loss of net income.

Increased Farm Size. Farm size has increased, with 50% fewer operators today than in the 1970s. Presently, most farms in the range of 200 ha (500 ac) that were profitable in the 1970s as full time operations have either gone out of business or increased in size. Farms in the range of 400 ha (1,000 ac) are now economically marginal, as their profit margins are small. To be sustainable, farmers must increase efficiency by reducing operations and input costs, maintain high

Table 1

Typical farming systems and crop yields in 1975, 1990, and 2005 for the high precipitation sites (500–560 mm).

Year	System*	Rotation†	Use (percent)‡	Yield (Mg ha ⁻¹)	Tillage system§
1975	H-1a	WW-P-WW-P-WW-F	60	WW: 2.4 SB: 6.7 P: 4.5	CT: plow WW residue (no burn). Surface tillages: six for P, four for WW. Includes deep chisel.
	H-1b	WW-P-WW-P-WW-F	20		CT: burn and plow WW residue. Surface tillages: six for P, four for WW. No deep chisel.
	H-1c	WW-SB-P	20		CT: burn and chisel WW residue, plow barley residue. Surface tillages: six for SB, six for P, four WW. Includes deep chisel.
1990	H-2a	WW-SB-P-WW-SB-P-WW-SB-F	50	WW: 2.7 SW: 1.7 SB: 3.4 P: 2.2	CT: Plow WW residue (no burn), plow SB residue. Surface tillages: six for SB, six for P, four for WW. Includes deep chisel.
	H-2b	WW-SB-P	35		RT: Chisel WW residue, chisel SB residue. Surface tillages: five for SB, six for P, four for WW.
	H-2c	WW-SB-WW-SW	15		RT: Burn and chisel WW residue. Surface tillages: five for SB/SW, four for WW.
2005	H-3a	WW-SB-P-WW-SW-P	40	WW: 3.4 SW: 2.4 SB: 4.5 P: 2.2	CT: Plow WW residue, chisel SB/SW residue. Surface tillages: four for SB/SW, five for P, four for WW.
	H-3b	WW-SB-P-WW-SW-P	50		RT: Chisel WW residue, chisel SB/SW residue. Surface tillages: four for SB, three for P, one for WW (two-pass).
	H-3c	WW-SB-P-WW-SW-P	10		NT: Direct seed all crops with intervening sprays, no surface tillage.

* Precipitation zone (H = high), period (1 = 1975, 2 = 1990, and 3 = 2005), and farming systems (a, b, and c).

† WW = winter wheat. P = pea. F = tilled fallow. SB = spring barley. SW = spring wheat.

‡ Percentage of area in rotation by regional farmers.

§ CT = conventional tillage. RT = reduced tillage. NT = no till.

yields and volumes of those crops with the best prices, and participate in government farm programs. Opportunities to maintain or increase yields depend heavily on flow of new and improved technologies of crops and farm operations. Farms grow in size through purchase or lease of additional land or consolidation of kinship holdings. Conservation technologies have reduced the number of field operations to grow

crops, thereby enabling an operator to farm more land. Most expect that farm size will continue to increase due to economic pressures and government programs that foster large operations.

Tractor Power. Horsepower has increased markedly on most farms since the 1970s. Tractor size has increased from the 37 to 112 kW (50 to 150 hp) common in the 1970s to 224 to 336 kW (300 to 450 hp) today.

Most machines are equipped with rubber tires or tracks, although some still have metal tracks. Increased tractor power has made wide equipment possible, increased speeds, and combined operations that result in fewer field passes. The result is less labor per hectare. Increased tractor power has also made possible more timely operations, which are especially important on larger farms. Increased tractor power has facilitated conservation because

Table 2

Typical farming systems and crop yields in 1975, 1990, and 2005 for the intermediate precipitation sites (400–460 mm).

Year	System*	Rotation†	Use (percent)‡	Yield (Mg ha ⁻¹)	Tillage system§
1975	I-1a	WW-P-WW-F	80	WW: 1.8 P: 1.6	CT: WW residue plowed (not burned). Surface tillages: four for P, four for WW, five for F.
	I-1b	WW-P	10		CT: WW residue burned and plowed. Surface tillages: four for P, four for WW.
	I-1c	WW-P-WW-F	10		CT: WW residue burned and plowed. Surface tillages: four for P, four for WW, five for F.
1990	I-2a	WW-P-WW-F	20	WW: 2.4 P: 1.8 SB: 3.9	CT: WW residue plowed (not burned). Surface tillages: four for P, four for WW, five for F.
	I-2b	WW-P-WW-F	10		CT: WW residue burned and plowed. Surface tillages: four for P, four WW, five for F.
	I-2c	WW-SB-F	50		RT: Chisel WW residue, chisel SB residue. Surface tillages: three for SB, six for F.
	I-2d	WW-SB-P	20		RT: Chisel WW residue, chisel SB residue. Surface tillages: three for SB, three for P, one for WW.
2005	I-3a	WW-SB-P	30	WW: 2.7 L: 1.2 P: 1.8 SB: 4.5	RT: Chisel WW residue, chisel SB residue. Surface tillages: three for SB, two for P/L, one for WW.
	I-3b	WW-SB-F	50		RT: Chisel WW residue, chisel SB residue. Surface tillages: three for SB, six for F.
	I-3c	WW-SB-CF	10		RT: Chisel WW residue. Surface tillages: three for SB, one for WW. Sprays: three for CF
	I-3d	WW-SB-L-WW-SB-P	10		NT: Direct seed. Sprays: one for WW residue, two for SB residue, no spray or till for P/L residue.

* Precipitation zone (I = intermediate), period (1 = 1975, 2 = 1990, and 3 = 2005), and farming systems (a, b, c, and d).

† WW = winter wheat. P = pea. F = tilled fallow. SB = spring barley. L = lentil. CF = chemical fallow (no-till).

‡ Percentage of area in rotation by regional farmers.

§ CT = conventional tillage. RT = reduced tillage. NT = no till.

Table 3
Typical farming systems and crop yields in 1975, 1990, and 2005 for the low precipitation sites (305–356 mm).

Year	System*	Rotation†	Use (percent)‡	Yield (Mg ha ⁻¹)	Tillage system§
1975	L-1a	WW-F	75	WW: 1.2	CT: Disk WW residue. Surface tillages: six for F.
	L-1b	WW-SB-F	25	WW: 1.3 SB: 2.2	CT: Disk WW residue, disk SB residue. Surface tillages: six for SB, six for F.
1990	L-2a	WW-F	75	WW: 1.7 SB: 2.2	CT: Disk WW residue. Surface tillages: six for F.
	L-2b	WW-SB-F	25		CT: Disk WW residue, disk SB residue. Surface tillages: six for SB, six for F.
2005	L-3a	WW-F	75	WW: 1.8 SB: 2.8	CT: Disk WW residue. Surface tillages: six for F.
	L-3b	WW-SB-CF	15		RT: Sweep WW residue, disk SB residue. Surface tillages: three for SB, one for F. Sprays: three for F.
	L-3c	WW-F	10		RT: Delayed tillage, sweep WW residue. Surface tillages: two for F. Sprays: two for WW residue.

*Precipitation zone (L = low), period (1 = 1975, 2 = 1990, and 3 = 2005), and farming systems (a, b, and c).

† WW = winter wheat. F = tilled fallow. SB = spring barley. CF = chemical fallow (no-till).

‡ Percentage of area in rotation by regional farmers

§ CT = conventional tillage. RT = reduced tillage.

of the higher power requirements necessary for one or two pass seeding systems to cover large farms.

Results and Discussion

Estimated Erosion Changes. The results of the STEEP program and farming system changes provide a basis to evaluate the environmental and economic impact of the research. The challenge is to integrate these facets of farming system changes to provide an estimate of expected environmental changes over the landscape. The most recent version (2007) of the Revised Universal Soil Loss Equation Version 2 (RUSLE2) was selected as a reliable method to evaluate STEEP impacts on water erosion prediction and soil quality indicators.

Dominant cropping and soil management practices were selected from the information obtained from the grower interviews and were then supplemented by information and experience of the regional USDA Natural Resources Conservation Service (NRCS) staff. Farming systems were identified that were representative of the three average annual precipitation zones (tables 1, 2, and 3) for each of three years within the study period: 1975, 1990, and 2005. Typical rotations and farming operations

are listed for each year and climatic zone. An estimate was made for the percentage of growers in the sample area which used each rotation (using farmer and NRCS personnel input) to provide a weighting factor to the conservation effect.

RUSLE2 was applied with soil and climatic parameters for the Pacific Northwest conditions and the crops and tillage associated with each rotation and management system. Estimates were made of long term annual sheet and rill erosion, the soil conditioning index (SCI), and the soil tillage intensity rating (STIR). The abbreviated management practices listed under “farming operations” were sequenced as a system for each rotation in the RUSLE2 input files. Estimates were made for each year and rotation, while the base conditions of climate, soils, and topography for each precipitation zone were held constant.

The SCI estimates the effects of management on the status of soil organic matter. It approximates the soil organic matter balance as influenced by crop production, decomposition, tillage, and erosion. A value of -1 represents highly degrading organic matter, 0 is neutral gain/loss, and +1 is very beneficial to organic matter gain.

The STIR evaluates the accumulative impact of soil disturbance by each tillage operation within the farming system. It is based on each tillage type, speed, depth, and area disturbed. This rating represents carbon loss, moisture depletion, and dust emission. A value of 200 indicates significant negative tillage impacts, 50 to 75 is significantly reduced tillage, and below 30 is a no-till production system.

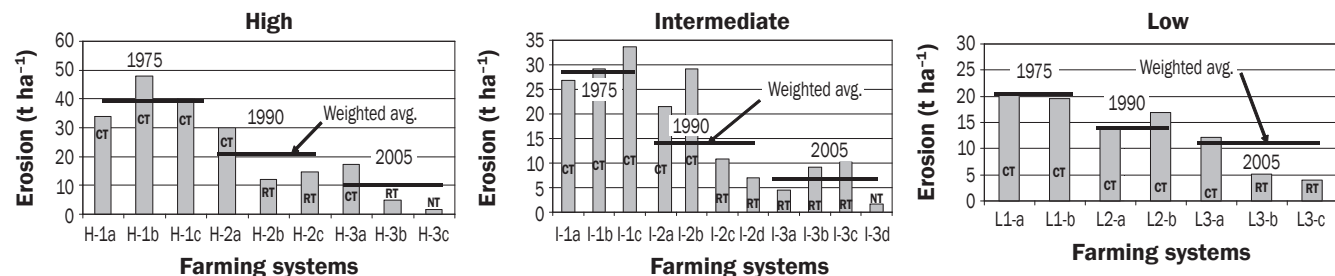
RUSLE2 estimates the management change effects for specific moisture zones (figure 1). These represent localized situations and should not be extrapolated or compared with results of watersheds or river basins where variables other than management affect average erosion rates and soil quality.

A dramatic reduction in estimated average annual erosion since 1975 is a result of decreased tillage, increased yields (providing more crop residue), and residue management (figure 1a). Erosion rates were reduced by one half in the high and intermediate precipitation zones by 1990, when conservation tillage was used on more than half of the land, compared with those in 1975 when conventional tillage dominated. The erosion rates were reduced by 75% when over half of the land on the high precipitation zone and

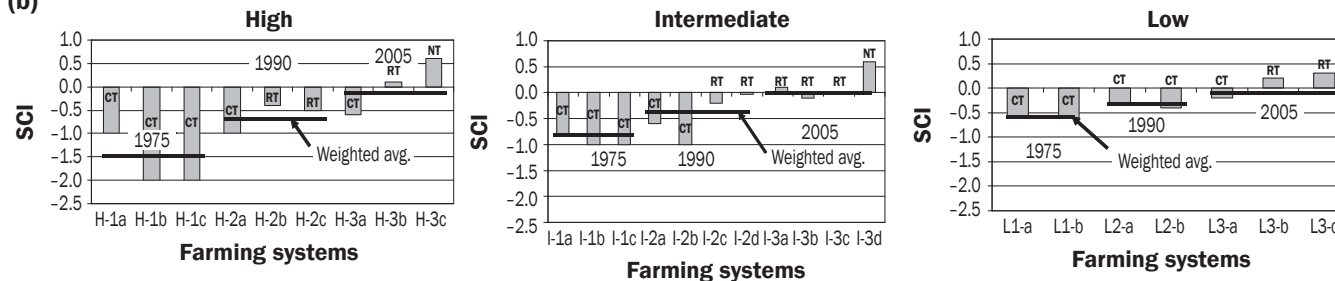
Figure 1

RUSLE2 estimates of (a) average annual soil erosion rates, (b) Soil Conditioning Index (SCI), and (c) Soil Tillage Intensity (STIR) and their weighted averages (horizontal bars) for typical farming systems during 1975, 1990, and 2005 in high, intermediate, and low precipitation zones. An erosion amount of $5 \text{ tn ac}^{-1} \text{ yr}^{-1}$ is considered tolerable for long-term sustainable farming. An SCI of -1 represents highly degrading organic matter, 0 is neutral gain/loss, and $+1$ is organic matter gain. A STIR index of 200 indicates significant negative tillage impacts, $50\text{--}75$ indicates significantly reduced tillage, and below 30 is a no-till production system. Refer to tables 1–3 for farming system (a, b, c) details.

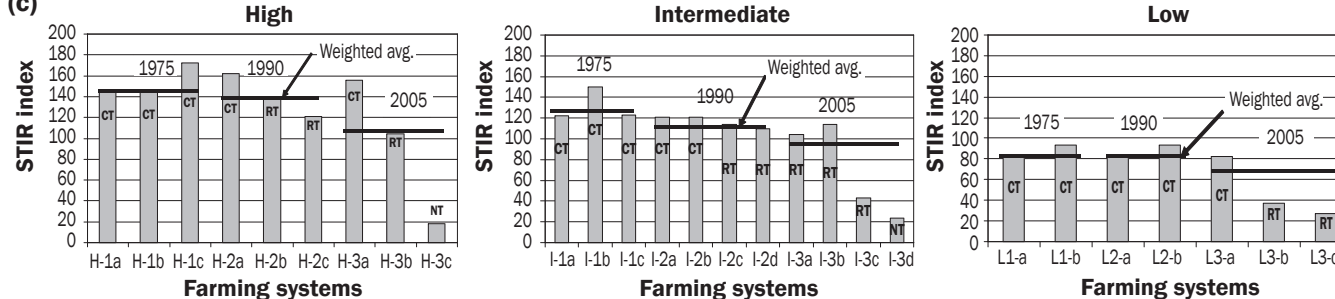
(a)



(b)



(c)



virtually all on the intermediate zone were in some form of conservation tillage. There was little change in the low precipitation zone between 1975 and 1990 in rotations and/or farming methods, but erosion rates were less by about 30% in 1990 and 50% in 2005 due to increased wheat yields (resulting in more crop residues) and increased use of conservation tillage.

Both the SCI and STIR indices show significant improvements as a result of management changes since 1975 (figures 1b and 1c). The SCI improved 40% to 60% by 1990 and 80% to 100% by 2005, when compared with 1975 values. These changes are an indicator of a turn-around in the decline of soil organic matter that has long been associated with conventional farming. The STIR values

changed very little in any of the precipitation zones between 1975 and 1990 but improved 20% to 50% by 2005, when compared with values in 1975. These indexes indicate credible improvements in soil quality brought about by decreased tillage and increased use of conservation practices.

Independent Environmental Assessments. Several independent sources were available to show environmental changes during the evaluation period. While these data and analyses were performed for other purposes, their trends provide supplemental support to our assessment of research impacts.

A study in 2005 sought to answer the question whether winter erosion in the higher precipitation areas had actually decreased since the early 1980s, and if so, whether the

causative factors were related to differences in climate or land management from previous times (McCool and Roe 2005). Findings were based on analyses of data sets of winter erosion obtained from monitoring sites within the Palouse River Basin during 1942 to 1982 and predictions with the Universal Soil Loss Equation (Ebbert and Roe 1998). Climatic record analyses of years 1940 to 1982 and 1983 to 2005 showed that freeze-thaw effects and precipitation during the latter period slightly favored reduced erosion hazard. However, USDA progress records for 1979 to 1994 indicate increased use of conservation practices in 1994 compared with 1979, with a large reduction in estimated erosion in the Palouse River Basin (McCool and Roe 2005).

In 1979, erosion control practices had been applied to <1% of the 8.1×10^5 ha (2×10^6 ac) of cropland in the Palouse River Basin. This increased to 21% by 1994 (Ebbert and Roe 1998). Using the USLE, these practices were estimated to decrease erosion by about 1.5 million Mg y^{-1} (1.6 million tn yr^{-1}), or by about 10% compared to the practices in the late 1970s. Conservation tillage, including no-till, was being applied on 31% of the cropland in 1994 and accounted for nearly 70% of the reduction in erosion. Strip-cropping and divided slopes accounted for about 54% of the hectares under erosion control practices but only contributed to about 14% of the reduction in erosion. The 14% of the cropland in the USDA's Conservation Reserve Program contributed 16% of the reduction in erosion (Ebbert and Roe 1998).

Erosion affects both soil productivity and water quality. It is estimated that about one third of the soil carried by runoff is discharged as sediment into streams and water bodies, where it becomes the primary pollutant. Figure 2 shows a 10-year relationship (1962–1971) between sediment concentrations in the Palouse River with estimated annual soil erosion within its watershed. Concentrations of suspended sediment are usually highest during storms that produce large discharges, conditions which were more prevalent in 1962–1971 compared with 1993–1996 (figure 3). These historical data compared with more recent measurements, show that the average sediment concentration (horizontal bar in figure 3) in the Palouse River during 1993–1996 was one-half the average for the years 1962–1971, which further confirms that recent erosion rates are lower than in earlier years (Ebbert and Roe 1998).

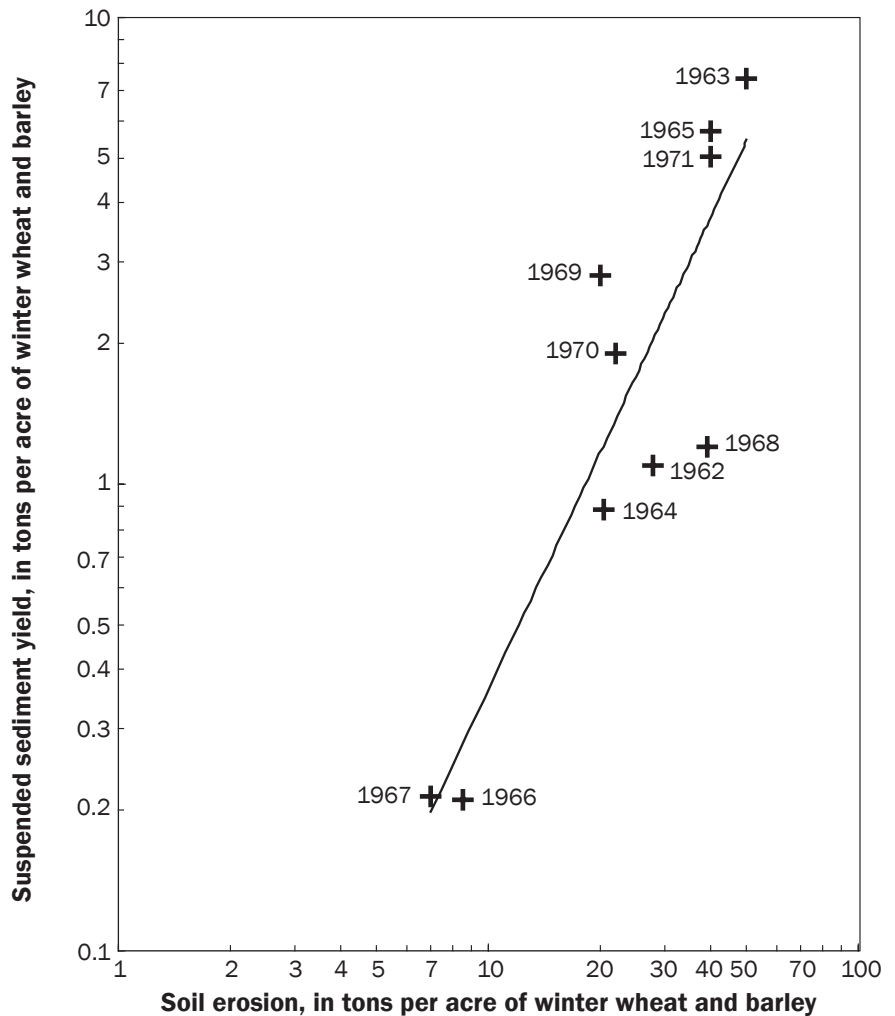
Summary and Conclusions

The widespread shift to conservation cropping systems and the estimated and observed reduction in soil erosion in Northwest wheatlands over the past three decades attest to the positive impact of STEEP accomplishments. These results were validated by the erosion/soil quality analysis, grower evaluations, and independent assessments of erosion and water quality. The USDA progress records for 1979 and 1994 substantiate a 37% increase in hectares utilizing erosion control measures over these years.

Development of low-cost minimum till planting tools by STEEP scientists was the

Figure 2

Soil erosion estimates from winter wheat and barley, correlated with suspended sediments yields from the Palouse River, 1962–1971 (ton per acre multiplied by 2.24 equals Megagram per hectare).



Note: Figure 2 is a facsimile from Ebbert and Roe 1998.

forerunner to the two-pass seeding system for winter wheat adopted by most growers today. This technology utilized in combination with a diversified crop rotation, along with judicious weed management, produced conservation cropping systems with superior agronomic, economic, and environmental results compared with the traditional intensive tillage systems. Today a three-year winter wheat–spring cereal–spring legume sequence, with no-till following the legume and conservation tillage following the cereal, has largely replaced the conventional, highly erodible winter wheat–spring pea rotation. Growers confirm that use of moldboard plows and stubble burning has declined significantly and that conservation tillage is standard on most farms.

Wheat yields have increased over the past 30 years due to improved varieties and water savings as a result of conservation farming. Growers note significant improvements in soil quality with no-till and conservation tillage in terms of tilth and organic matter accumulation. All of the interviewed growers claimed erosion had decreased significantly over the past 30 years but more so over the past decade as evidenced by lack of rills and gullies in fields and less sediment in road ditches and streams. Credit for reduction in erosion is given to STEEP, for making conservation technology available, and to government programs that favor implementation of conservation practices.

Calculations with the RUSLE2 water erosion prediction system for typical farm

practices showed that erosion rates decreased from an average of 45 Mg ha⁻¹ yr⁻¹ (20 tn ac⁻¹ yr⁻¹) in 1975 to 11 Mg ha⁻¹ yr⁻¹ (5 tn ac⁻¹ yr⁻¹) in 2005 on the high precipitation sites and from 27 Mg ha⁻¹ yr⁻¹ (12 tn ac⁻¹ yr⁻¹) in 1975 to 13 Mg ha⁻¹ yr⁻¹ (6 tn ac⁻¹ yr⁻¹) in 2005 on the intermediate precipitation sites. Erosion rates decreased from an average of 20 Mg ha⁻¹ yr⁻¹ (9 tn ac⁻¹ yr⁻¹) in 1975 to about 10 Mg ha⁻¹ yr⁻¹ (4.5 tn ac⁻¹ yr⁻¹) in 2005 on the low precipitation sites. Changes in soil quality indicators were positive and in line with the estimated decreases in erosion rates. A comparison of historical data with more recent measurements showed that the average sediment concentration in the Palouse River, which is the main drainage of the Palouse River Basin, during 1993–1996 was one-half the average for the years 1962–1971.

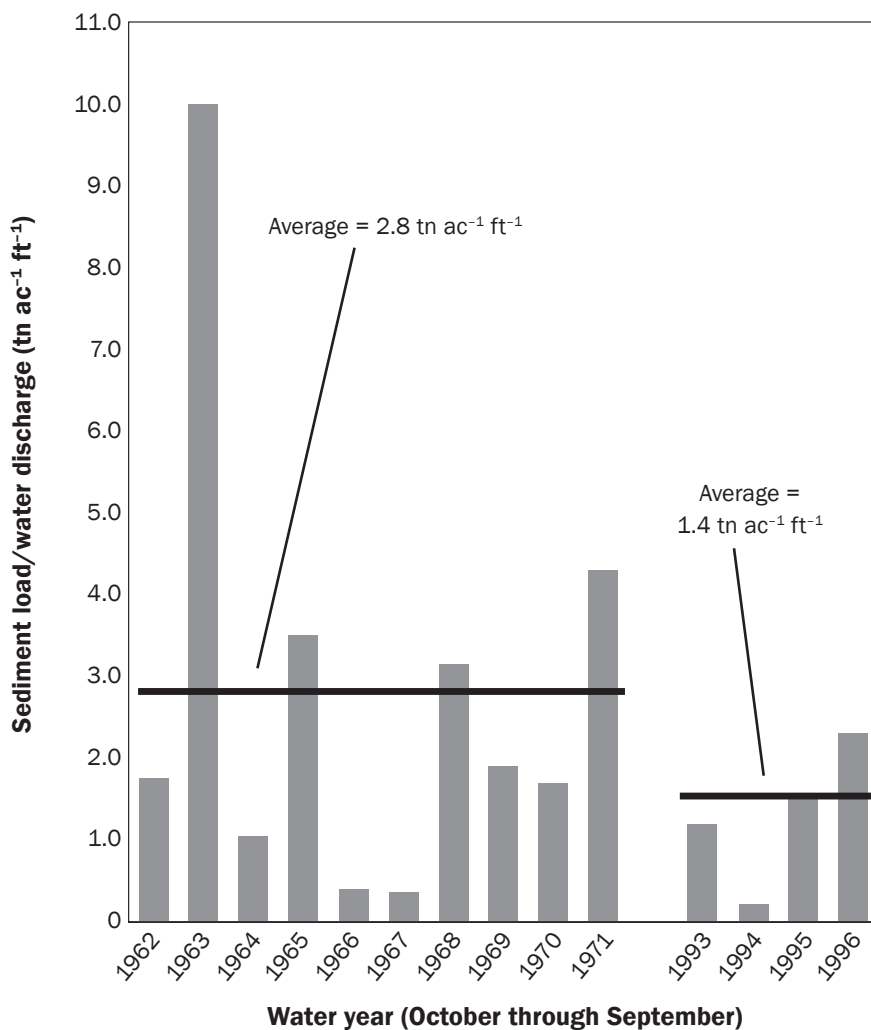
The conservation provisions of the 1985 farm bill and the modifications that followed were an asset to STEEP goals. STEEP research and education contributed to the design of practices that enabled growers to achieve compliance for erosion reductions without financial hardship. With the aid of STEEP extension and education, growers gave more attention to environmental and resource protection objectives, although government support funding has often been too limited to have the desired widespread impacts.

Although successful conservation farming systems have been developed and applied, both research and on-farm testing by growers will be needed to modify and adapt these to additional farming situations. For example, residues from high yielding wheat in the high precipitation zone poses limitations for conservation farming, especially with no-till. Yields of subsequent crops are generally lower with high surface residues mainly from difficulties with planting and weed control. Less tillage is needed in the dry zones to conserve soil moisture along with surface residues that reduce wind erosion and dust emissions.

The federal investment in STEEP averaged about $\$0.5 \times 10^6$ yr⁻¹ over the 30-year duration of the program. Significant additional funding was provided by the state's experiment stations and by USDA federal base funds. A rational judgment is that for the three Northwest states, STEEP operated on a total budget of approximately $\$1 \times 10^6$ annually, or $\$30 \times 10^6$ for 30 years. Using a conservative estimate that the benefits of

Figure 3

Comparison of historical record (1962–1971) to the years (1993–1996) from the Palouse River at Hooper, Washington, showing a decrease in the average annual concentration of suspended sediment (tn ac⁻¹ ft⁻¹ multiplied by 0.7353 equals kg m⁻³).



Note: Figure 3 is a Facsimile of Ebbert and Roe 1998.

STEPP extended to 2×10^6 ha (5×10^6 ac), the investment cost was $\$15$ ha⁻¹ ($\$6$ ac⁻¹) over 30 years, or $\$0.50$ ha⁻¹ yr⁻¹ ($\$0.20$ ac⁻¹ yr⁻¹). The investment is a trifle compared to the returns from saving and improving the quality of nonrenewable topsoil, soil water conservation, improving water quality, and safeguarding the well-being of the farm economy in the Pacific Northwest.

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