BEST MANAGEMENT PRACTICES FOR AGRICULTURAL NONPOINT SOURCE CONTROL

III. SEDIMENT

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In Cooperation With:

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STATE-OF-THE-ART REVIEW OF BEST MANAGEMENT PRACTICES FOR AGRICULTURAL NONPOINT SOURCE CONTROL

III. SEDIMENT

for the project

RURAL NONPOINT SOURCE CONTROL WATER QUALITY EVALUATION AND TECHNICAL ASSISTANCE

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EXECUTIVE SUMMARY

Sediment from soil erosion is the greatest single pollutant in U.S. surface waters; reducing stream and reservoir capacities, causing increased flooding, disrupting biological systems, degrading drinking water supplies and transporting nutrients, pesticides and bacteria to waterways (75). Farmland is recognized as the largest contributor of sediment to U.S. waters with over 6.4 billion tons of topsoil eroded each year. The purpose of this paper is to identify and discuss the state-of-the-art in Best Management Practices (BMPs) for reducing sediment inputs from farmland.

Presently, several Rural Clean Water Program (RCWP), Model Implementation Program (MIP) and Agricultural Conservation Program-Special Water Quality (ACP) projects across the United States are designed to demonstrate the effectiveness of various control mechanisms for abatement of agricultural nonpoint source water quality problems. In many cases, programs have been hindered in efforts to achieve water quality goals by a lack of information on the cause-effect relations between BMPs and water quality. Data from these research efforts may expand current assessments of the applicability of individual BMPs and BMP systems as water quality control mechanisms.

The literature establishes conservation tillage systems-systems which leave protective amounts of the previous year's crop stubble by minimizing the amount of tillage-to be the most efficient methods of dramatically reducing sediment loss while maintaining productivity. Research conducted in many areas of the country has consistently demonstrated the success of conservation tillage systems in reducing runoff volume as well as sediment and nutrient losses. Yields are generally increased relative to conventional tillage during dry growing seasons and decreased somewhat during excessively wet years. No-tillage systems, which reduce field operations to a single step of cutting a narrow slit and planting, consistently give sediment reductions of over 90% with comparable and often higher yields. The only potential limitation of conservation tillage as a nation-wide BMP pertains to the effects from increased use of pesticides which are not clearly understood.

Contour farming has also been proven to greatly reduce soil erosion on both cropland and rangeland. Contouring is most effective when crop rows are tilled up along the contour so that small ponds from along each row in heavy storms. Terraces are highly effective in reducing runoff and sediment loss. Several studies have shown terraces to be much more effective than countour farming in the western Corn Belt. The two major limitations of the practice are that terrace construction is relatively expensive and that nutrient leaching to groundwater may be increased. Diversions and grassed waterways are practices designed to facilitate the non-erosive dispersion of runoff. They reduce erosion more than runoff volume and thus are best used in conjunction with other runoff-reducing practices such as conservation tillage and contouring.

Rotating a sod crop with a row crop will result in large reductions in soil loss. On steep highly erodible marginal cropland it may sometimes be the only practical method of reducing erosion to a tolerable level.

Several studies have shown row crop yields to increase significantly following the sod rotation. In the short-term, however, this is not generally sufficient to offset total row crop production reductions over the rotation. Cover crops can greatly reduce soil losses during the non-growing season. The practice is limited only in northern areas where it may be difficult to establish a good cover before winter freeze or where the cover crop may hinder spring soil warming and drying, thus delaying timely planting. Filter strips have been shown to be effective in filtering and causing deposition of sediment from field runoff. Filter strips are best employed in conjunction with erosion reducing practices such as conservation tillage, contouring and sod-based rotations.

While there is evidence that various stream channel stabilization measures can effectively reduce streambank cutting and channel scouring, the practice is highly questionable as a BMP because this sediment source is generally a relatively smaller contributor in intensively cropped watersheds. The contribution of stream channels to sediment loads has not been adequately studied however, and this source may be significant in some topographic regions or where upland sediment control measures have reduced other sources. Present knowledge would indicate that efforts should generally be directed towards erosion and runoff control rather than channel stabilization.

Conclusions and recommendations regarding Best Management Practices for controlling sediment inputs from agricultural land include:

1. Erosion reductions on cropland are generally proportional to reductions in the amount of tillage performed. Conservation tillage systems can reduce soil losses from 60 to 99 percent compared to conventional moldboard plow techniques and are an effective alternative in areas where no-till is not well adopted. Surface runoff from conservation tillage averages about 25% less than conventional tilled fields.

2. No-till is extremely effective in reducing erosion losses with reductions of 70 to 99% but is not adapted to all regions and requires higher management than conventional tillage.

3. Reduced tillage systems also decrease absorbed pesticide and nutrient losses but not to the same extent soil losses are reduced. While overall nutrient losses are lower, dissolved fractions may increase.

4. Contour farming is an effective practice for reducing erosion and surface runoff by increasing rainfall infiltration. It is best adapted to permeable soils and moderate slopes.

5. Terraces are very effective in reducing erosion losses with reductions of 50 to 98% reported in the literature. Absorbed pesticides and nutrient losses are dramatically reduced and surface runoff decreased. However, terraces are relatively expensive to install, and nutrient leaching to groundwater may be increased when this practice is used.

6. The combination of diversions and grassed waterways is a widely accepted system reducing erosion and sediment transport but there are little quantitative data on loss reductions.

7. Cover crops can reduce erosion from 40 to 95%, increase soil organic matter and may reduce nitrate leaching. Legume cover crops provide available nitrogen for subsequent crops.

8. Rotations that include a sod crop can reduce erosion losses from 40 to 90%, increase organic matter and infiltration, and can improve yield of cash crops. The economic loss in years when a cash crop is not grown reduces the acceptability of this practice.

9. Sediment basins are effective in reducing sediment delivery from severe storms and in trapping small (1-50u) soil particles, but the cost-effectiveness of this practice relative to cropland protection has not been determined.

10. Although few data are available it appears that streambank stabilization is not a general BMP. One study estimated that only 5% of all watershed losses were due to streambank erosion, but a significant expenditure of funds was devoted to this practice.

11. Although pesticide costs increase, the total costs of production usually decline with use of conservation tillage systems, primarily because of savings in labor and fuel costs.

12. The overall profitability of conservation tillage depends primarily on the effects on yields on the conservation tillage system. When yields are affected not at all or only slightly, conservation tillage systems are generally more profitable and contribute to water quality improvement.

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PREFACE

There are currently many programs and projects across the country for reducing nonpoint source pollution from agricultural activities. Public and private monies are being spent to implement agricultural Best Management Practices (BMPs) for improving water quality. To assess these many efforts on a nationwide basis a joint USDA-EPA project, "Rural Nonpoint Source Control Water Quality and Technical Assistance," has been established. This undertaking commonly known as the National Water Quality Evaluation Project, will assess the water quality and socio-economic effects of BMP use in the rural sector.

This document identifies and discusses the State-of-the-art in Best Management Practices for controlling nonpoint source pollution from sediment. Any proposals for major changes in erosion and sediment control practices must be assimilated with economic realities, production concerns and institutional limitations. Conclusions and recommendations in this document are not intended to reflect production or institutional factors, and thus, inferences drawn from these statements should contain appropriate caveats in regards to these factors.

The scope of the literature reviewed for this document was restricted to published documents with supporting data. Two computer-based files, the Southern Water Resources Scientific Information Cetnter (SWSIC) and AGRICultural On Line Access system (AGRICOLA), were used for a large portion of the literature retrieval. Much additional information was obtained through citations follow-up, and interpretive insight was solicited from NCSU professionals.

SECTION 1

INTRODUCTION

Water pollution control efforts have historically emphasized abatement of industrial and municipal point sources. As a result of criteria and standards development, refinement of on-site control technologies and increased enforcement efforts mandated under PL 92-500, great reductions from these point sources have occurred during the 1970's. However, the overall quality of the nation's surface waters has not improved to an extent proportional with these point source reductions, and it is becoming well recognized that control of nonpoint sources may demand top priority in water pollution control efforts during the next decade.

In sharp contrast to reductions in point sources, pollution inputs from land activities, particularly agriculture, have increased greatly as land previously thought too fragile or infertile has been brought into production under the impetus of foreign grain sales (66). When such areas are brought into crop production to meet demands for increased food supply, the erosion problems are often much more serious than those on lands already being farmed (38). Yield-increasing production technologies which rely on increased use of chemical fertilizers and pesticides as well as more extensive soil preparation have also contributed to the increase in agricultural related water pollution. It has been estimated that agriculture related inputs are the major water pollution inputs in two-thirds of the watersheds in the United States.

Sediment from soil erosion has been considered the greatest single pollutant in U.S. surface waters (75). Soil is a water pollutant because 1) as sediment its mass volume often reduces stream and lake capacities; 2) it can upset stream and lake ecosystems by settling out of the water column destroying benthic habitats and can cause high turbidity which inhibits photosynthesis; and 3) other pollutants such as nutrients, pesticides and bacteria can be strongly adsorbed or attached and thus transported with sediment particles (85, 37). By weight the sediment load in U.S. waterways is 500 to 700 times greater than the total sewage load discharged to streams (33). Fortunately, however, by weight the pollution potential of sediment is much less than that of most other pollution materials (28). About 50% of the sediment in the nation's waterways is thought to come from cropland (78, 82), while it has been estimated that approximately 30% of the total probably represents the natural level of sedimentation (82). Other major sources include streambanks, road ditches, construction sites, urban areas, rangelands, mining projects and forests (85).

In spite of the low pollution potential by weight of sediment, excessive soil erosion and subsequent sediment deposition are being found to have severe negative impacts on both agricultural production capacity and water quality. It has been estimated (50) that in the Southern Piedmont grain yields could be expected to decrease by about 5.7 bu/hectare for each centimeter of soil eroded from Class II land. Soil is eroding at a record pace not only in rich farm states like Iowa but also in the East, the South and the Pacific Northwest. Much of the effect of cropland damage on yields has been masked by improved mechanical, fertilizer and pesticide developments; however, a recent USDA survey has warned that at present erosion rates, corn and soybean yields in the Cornbelt states may drop by as much as 30% in the next 50 years as the fertility of the soil declines (66). Erosion is the major crop production limitation on nearly half of U.S. cropland (43).

Suspended sediment can greatly limit use of water sources for drinking water supply. The maximum limit of one turbidity unit for finished drinking water is based on health considerations relating to effective chlorine disinfection (84). Suspended sediment provides areas where microorganisms may not come into contact with chlorine disinfectant (61). No standard has been set for suspended sediment concentrations in drinking water sources because the ability of usual water treatment process (i.e., coagulation, sedimentation, and filtration) to remove suspended matter depends on the composition of the suspended matter as well as its concentration (84). However, in general the greater the turbidity of the water, the greater the water treatment costs since additional coagulants and disinfectants are needed. These chemicals and filtration systems are one of the major expenses in the operation of many water treatment systems.

Reduction in channel and reservoir storage capacities may be the most serious and costly impact of excessive sedimentation. The median storage depletion rate for all U.S. reservoirs is 1.5% per year (53). The sedimentation rate is generally higher for small reservoirs than for large reservoirs (11). Many are filling at a rate of 5% of their capacity per year, while those with less than 123,000 m^3 are losing a mean of 2.7% or their capacity annually.

Replacement of sediment-filled reservoirs is often much more costly than the original construction because less optimal secondary sites must be used (85). It has been estimated (5) that $250,000,000 per year is spent on removing sediment from streams, harbors and reservoirs.

Sediment also increases flood damage by reducing stream capacities and clogging channels. While little quantitative research has been done, it has been estimated that flood water damages related to excessive sedimentation may amount to one billion dollars annually (53).

Excessive sediment, suspended and deposited, has very deleterious effects on fish and other aquatic life. These effects can be divided into those occurring in the water column and those occurring following sedimentation on the bottom of the water body (84). A review by the European Inland Fisheries Advisory Commission (24) identified four mechanisms by which sediment adversely affects fish:

1) by acting directly on the fish swimming in water in which sediment is suspended and either killing them or by reducing growth rate or resistance to disease
2) by preventing the successful development of fish eggs and larvae
3) by modifying natural movements and migration
4) by reducing the abundance of food supply

Fish kills generally occur as a result of silt clogging the gills of fish or from oxygen-depletion caused by oxygen-demanding sediment (70, 59). Deposited sediment which blankets the bottom of water bodies damage the invertebrate populations, block gravel spawning beds, and if organic, remove dissolved oxygen from overlying waters (21). It is thought that silt particles attached to fish eggs prevent sufficient exchange of oxygen and carbon dioxide between the egg and the overlying water resulting in low propogation success (24).

Suspended sediment reduces light penetration into lakes and rivers, reducing the depth of the photic zone, and thus reducing primary production (84). In addition the near surface water layer is heated more than the bottom resulting in a greater and more rapid stratification of the water body than would occur at lower suspended sediment concentrations. This prevents vertical mixing thus decreasing the dispersion of dissolved oxygen to the lower portion of the water body.

Nutrients, pesticides and bacteria may be adsorbed on the surface of sediment particles and then transported with sediment into waterways. Nutrients and pesticides occur in highest concentrations on the smaller sediment particles because of their larger surface area to volume ratio. Unfortunately, the smaller soil particles are those most easily eroded and transported to waterways with the overall effect that these adsorbed pollutants are preferentially removed from cropland. From a water quality standpoint, nutrients available for algal growth and eutrophication rather than total nutrients amounts are of interest. Phosphorus in particular has consistently been found to be almost totally sediment-bound rather than dissolved in agricultural runoff (64, 2, 48). It is unclear how much of this sediment-bound phosphorus is available for algal growth, but some recent studies have indicated that approximately 20% of the sediment-bound phosphorus is available depending on sediment composition (20, 39). In the case of pesticides, field loss is proportional to soil loss for strongly-bound types such as paraquat. More weakly-bound pesticides such as methyl parathion and atrazine are lost primarily in solution (74).

Sediment load estimates must be made for the specific watershed to be meaningful in terms of water quality. The largest annual sediment loads for a given stream are often as much as 20 times greater than the minimum sediment load. This can generally be correlated with those years of greatest runoff (28). Johnson et al. (41) observed a ten-fold difference in sediment yield between wet and dry years for an Idaho rangeland watershed. It was also found that five to ten percent of the annual runoff transported fifty to ninety percent of the annual sediment yield. A study in the Palouse region showed that sediment transport during a wet year could exceed the combined total of four or five other years indicating that sediment sampling programs of one or two years duration may give very misleading results for water quality trends (52). Large differences can occur in sediment yield from adjacent streams discharging at the same rate depending on land use and stream morphology. Even within the same stream, the concentrations of suspended solids can vary by a factor of ten for a given rate of discharge (78).

The lowest levels of sediment loss in the U.S. have been observed in the Rocky Mountains where sediment loss from undisturbed forests is generally less than 0.36 mt/ha (28). Mean sediment yields between 0.31 and 1.66 mt/ha were measured for a nine-year period from Idaho rangeland. Very low levels of sediment are also seen in small forested New Hampshire watersheds (78).

The areas with the highest erosion/sedimentation rates are generally those which combine intensive agriculture, hilly topography and erodible soil types. Of prominent concern among these are the Reelfoot Lake region of western Tennessee where mean soil losses are estimated at 70 to 90 mt/ha with losses up to 330 mt/ha and the Palouse basin of southeast Washington with mean soil losses of 38 mt/ha ranging up to 450 mt/ha. While soil loss rates are somewhat less in Iowa, they are of even more concern since this state produces fifteen and twenty percent of the nation's soybean and corn crop, respectively, and over half of the original topsoil has been lost (66).

SECTION 2

THE EROSION/SEDIMENTATION PROCESS

The sediment producing process involves soil detachment, transport and deposition. Erosion is generally defined as the detachment and transport of soil by water, wind, ice or gravity (81). Soil detachment can occur either from raindrop impact or from the shear forces of flowing water, but raindrop impact is usually the principal mechanism at the field surface (26). Primary clay particles are detached less easily than sand particles. Garriels et al. (30) and Ghadiri and Payne (32) found that rainfall kinetic energy was a major factor in the extent of soil detachment such that higher intensity storms have much higher detachment potential than light storms even if the total rainfall is equivalent. Calculations made by multiplying the number of soil particles detached by a single raindrop by the several million drops per square meter which occur during a rainstorm indicated that raindrop impact can easily detach more soil than overland flow on short slopes (27). Besides causing soil detachment, splashing raindrops also break down the soil aggregates into smaller aggregates and particles which are more readily transported. In addition the raindrop impact can lift larger particles into overland flow than would otherwise be detached and transported by the flow. These larger particles are then transported a short distance downslope before settling back to the soil surface (26).

Soil particles detached by raindrop impact are generally transported by shallow overland flow to rills. Once the sediment carrying capacity of the rill flow is exceeded, deposition will begin to occur (85). Frequently deposition, especially of large particles, will occur long before runoff enters streams or lakes (55). It has been suggested (58) that eventually nearly all sediment deposited in concentrated flow channels will be transported to waterways. The concept that deposition of sediment increases flow energy thus causing more detachment and transport has been studied by McDowell and Grissinger (53) who found that upland control measures that decrease soil loss more than runoff can actually cause downstream channel instability problems. Stream channels often become major sediment sinks for eroded upland soil. If soil erosion is reduced without corresponding reductions in runoff, this stored sediment will be remobilized during storm events producing high sediment yields which may continue for several years following upstream soil erosion abatement (80). It is presumed that the process would continue until the stream has re-established its original gradient and channel regime. For these reasons sediment control measures which reduce runoff volume are generally more effective overall in improving water quality. Also the time lag between source control implementation and observed water quality improvement must be considered in the evaluation of the effectiveness of soil erosion control measures.

SECTION 3

RELATIONSHIP BETWEEN EROSION AND SEDIMENTATION

A useful parameter for evaluating the relationship between erosion and sedimentation is the sediment delivery ratio (SDR) which is defined as the ratio of the amount of sediment delivered to a given stream station to the amount of gross soil erosion from the upstream watershed. The percentage of eroded soil in a watershed which becomes sediment in waterways will tend to be less in situations where the major erosion sources are either located distant from water courses or are separated from water courses by sediment holding areas such as woodlands, other vegetated areas or sediment basins. The SDR will also be minimized by larger drainage areas, course soil texture, gentle topography and a predominance of sheet and rill erosion as opposed to gulley erosion. Stewart et al. (75) have cited a range of 0.08 to 0.33 for SDRs. A major limitation in using the SDR to evaluate sediment related pollutant loading is that this parameter is an estimate of only the total sediment load. The percentage of finer soil particles, which carry the majority of adsorbed nutrients and pesticides, may be much higher than the overall SDR. From a water quality standpoint control of the smaller fraction of materials may be more important than reducing total sediment loads.

It is often assumed that if soil erosion is controlled, then sediment will also be controlled. While this is undoubtedly true, since soil erosion must occur to produce sediment, there are, as the previous discussion suggests, usually several possible alternatives to be considered either individually or in combination for controlling sediment in the most cost effective manner. Sediment can be controlled at any point between source and sink, while erosion can only be controlled at the field level. Sediment control strategies may be divided into 1) those which reduce the amount of field erosion and 2) those which reduce the sediment delivery ratio. The selection of appropriate combinations of control measures will depend on the relative importance of different objectives since erosion control has beneficial impacts on both agricultural productivity and water quality, while off-field sediment control practices will generally affect only water quality.

For these reasons it is very important to be able to correctly select the best control practices for specific production and water quality goals as well as the most critical sediment producing areas in order to implement the most effective sediment control. The following section is intended to describe the proposed Best Management Practices (BMPs) for sediment control and review research concerning their effectiveness in reducing the severe negative impacts of erosion/sedimentation described in previous sections. The objective is to summarize what is known about the effectiveness of the proposed BMPs (and other practices) and to highlight areas where the effectiveness of these proposed control measures is still not clearly known.

SECTION 4

PROPOSED BEST MANAGEMENT PRACTICES

Many sediment control measures have been applied under the leadership of the Soil Conservation Service over the past four decades. These have been directed at conservation of both soil and water resources and have been implemented nationwide to widely varying extents. The most prominent of these and a brief description of the manner in which they function to reduce erosion/sedimentation is given below.

1. Conservation Tillage Systems - which include no-tillage, sod planting, minimum tillage, chisel plowing and slot planting involve leaving protective amounts of crop stubble on the surface of the field. Such practices generally reduce the volume of surface runoff and prevent erosion by reducing both soil detachment and transport.

2. Contour farming - is farming gently (<8 percent) sloping land so that plowing, planting, and cultivation are done on the contour. Contouring is most effective when rows are ridged and furrowed which allows ponding of surface runoff resulting in greater infiltration and reduced runoff volume.

3. Cover crop - is a crop of close-growing grasses, legumes or small grains grown primarily for seasonal soil protection and for conservation tillage residue (81). Purpose is to reduce direct runoff as well as to reduce soil detachment from raindrop impact during the nongrowing season.

4. Diversions - are channels with a supporting ridge on the lower side constructed across the slope. Purpose is to help reduce soil transport capacity of runoff by reducing slope length and to prevent damage down-slope from the diversion.

5. Grassed Waterways - are natural or constructed vegetated depressions which carry surface runoff while preventing the formation of rills or gullies.

6. Grasses and Legumes in Rotation - is establishing grasses and legumes as part of a conservation cropping system. The

closely grown sod crop significantly reduces detachment from raindrop impact as well as the volume of surface runoff.

7. Sediment Basins - are structures designed to impound runoff and allow sediment to settle out. Their benefits are primarily off-site since only downstream water quality and not production capacity is affected. They can also significantly reduce downstream flow rates important for channel stability especially in small watersheds (26).

8. Streambank Protection and Stream Channel Stabilization - are measures both structural and nonstructural which reduce streambank erosion. They may also help to maintain channels to reduce sediment deposition and remobilization.

9. Terraces - are a combination ridge and channel constructed across the slope (81). They reduce erosion primarily by decreasing slope length. Secondarily they function to reduce sediment delivery by allowing eroded soil to be redeposited before reaching waterways although this redeposition may eventually render the terrace ineffective. Terraces also reduce runoff volume due to increased infiltration but generally not to the same extent that erosion is reduced.

10. Filter strips - are strips or areas of vegetation for removing sediment from runoff. While having no effect on soil erosion filter strips improve water quality by reducing sediment delivery.

EVALUATING THE EFFECTIVENESS OF PROPOSED BMPs

Studies in various areas of the United States which have attempted to determine the effect of the above practices on production and water quality are summarized below. These studies provide the basis for a national evaluation of the effectiveness of these proposed BMPs for controlling sediment. They also indicate where more information is needed before nationwide abatement strategies can be initiated with convidence.

The effectiveness of most BMPs in a given situation depends on variables such as topography, soil type, climate and type of crop. For this reason research on individual sediment-control BMPs is grouped by geographic regions for several practices. The geographic breakdown chosen is the SCS Land Resource Regions shown in Figure 1. A potential sediment control practice is shown as a BMP in a region

LEGEND

A	Northwestern Forest, Forage and Specialty Crop Region
B	Northwestern Wheat and Range Region
C	California Subtropical Fruit, Truck and Specialty Crop Region
D	Western Range and Irrigated Region
E	Rocky Mountain Range and Forest Region
F	Northern Great Plains Spring Wheat Region
G	Western Great Plains Range and Irrigated Region
H	Central Great Plains Winter Wheat and Range Region
I	Southwest Plateaus and Plains Range and Cotton Region
J	Southwestern Prairies Cotton and Forage Region
K	Northern Lake States Forest and Forage Region
L	Lake States Fruit, Truck and Dairy Region
M	Central Feed Grains and Livestock Region
N	East and Central Farming and Forest Region
O	Mississippi Delta Cotton and Feed Grains Region
P	South Atlantic and Gulf Slope Cash Crops, Forest and Livestock Region
R	Northeastern Forage and Forest Region
S	Northern Atlantic Slope Diversified Farming Region
T	Atlantic and Gulf Coast Lowland Forest and Crop Region
U	Florida Subtropical Fruit, Truck Crop and Range Region

Figure 1. Land resource regions.

if sufficient research has been done to confirm effectiveness. Practices are projected to be BMPs in some regions where little or no study has been done, based on topographic, soil, climatic and cropping similarities with documented regions. Regions which either have 1) no data relative to the effectiveness of a proposed BMP, 2) data which indicate the practice is not a BMP, or 3) no applicability of the practice due to lack of agricultural activities are also indicated in the figures.

CONSERVATION TILLAGE SYSTEMS

More research work has been done comparing various conservation tillage systems with conventional tillage systems than on any of the other BMPs in the past ten years. Conservation tillage seems to be one of the most effective BMPs for reducing erosion, particularly in rolling or hilly areas. While conservation tillage requires more herbicides to produce a good crop, yields from conservation tillage are roughly equal to yields from conventional tillage and are often better during dry years (81, 4, 56).

A recent review of work concerning conservation tillage systems in the western Corn Belt states of Iowa, Minnesota, Missouri and the eastern portions of Nebraska and South Dakota points out that the greater soil infiltration capacity made possible by various conservation tillage systems is extremely important in this region since evapotranspiration normally exceeds stored moisture and precipitation during much of the growing season. Burwell et al. (17) found that fall mulch-tilled fields (one pass with a chisel plow) previously cropped in oats provided nearly eight times greater infiltration capacity than conventional tilled fields before runoff began to occur in Minnesota. In a Nebraska study (16), soil losses from till-planted plots, were six times lower than from conventionally tilled plots. Increased infiltration and reduced runoff volume have also been noted by several other investigators (14, 22, 36).

One of the most comprehensive studies designed to evaluate the effectiveness of conservation tillage in reducing agricultural water pollution was done at the Watkinsville, Georgia, experimental site (49). In this study various tillage methods were compared over four years. In all cases the fields were tilled on the contour. The four tillage systems studied were 1) spring moldboard plow (conventional), 2) fall moldboard plow (conventional), 3) spring chisel plow, and 4) no-till. It was found that runoff was reduced by 47 percent between conventional tillage and double-cropped no-till. Soil loss, however, was reduced 86.9 mt/ha to 1.3 mt/ha or a 98 percent reduction. Moreover, actual edge of field flume measured sediment was reduced 99 percent between conventional and no-till systems.

Other studies have found considerable variability in the extent to which minimum and no-till systems reduce runoff volume. Laflen et al. (47) compared a wide range of plot watershed and simulated rainfall studies using various crop rotations and soils and noted that conservation tillage systems reduced the volume of runoff by an average of about 25%, but that in a few cases runoff volume was actually slightly greater from conservation than from conventional tillage systems. In nearly all cases no-till produced less erosion but somewhat greater runoff volume than minimum tillage chisel plowing. Simulated rainfall studies in the eastern Corn Belt (Indiana, Illinois) showed chisel, till-plant and no-till systems to reduce soil loss by 94, 69 and 85%, respectively, after an intense storm compared with conventional tillage (51). Oschwald and Siemens (62) observed disk chisel and no-till to reduce soil loss 89 and 91%, respectively, following corn and 71 and 85% after soybeans from high intensity storms. The difference is presumably due to the larger amount of residue left from corn crops. This difference is significant for the region since many eastern Corn Belt farmers alternate corn and soybeans (34).

In a comparison of no-till and conventional till systems for soybeans on small Mississippi plots of silty clay loam soil losses were seven times greater with conventional till under continuous soybeans (54). Runoff volumes and soil loss were lowest on plots of no-till soybeans double-cropped with wheat. In Illinois on a silt loam soil conventional till plots lost three and sixteen times as much soil as no-till plots on five percent and nine percent slope respectively from a single winter storm (29). Crop yields for the two tillage systems over nine years were approximately equal. A recent study in north-central Oregon (31) shows that reduced-tillage methods can be used successfully for wheat production. Erosion was reduced markedly when 1,120 kg/ha or more of wheat stubble was left on the fields, and yields were not affected.

Baker et al. (7) have suggested that the soil loss reductions from practices such as no-till and use of cover crops are a function of the percentage of soil covered by crop and crop residue. In a simulated rainfall study they found that the percentage of ground cover could explain 78 to 89% of the variation in soil loss between six different tillage systems. Similar results were obtained by Laflen et al. (45).

The erosion control provided by conservation tillage nearly always results in a reduction in total nutrient loss since the majority of nutrients are transported by sediment rather than in solution (8, 6). However, dissolved nutrient concentrations in the surface runoff are increased in most cases. There appear to be several contributing factors involved. The incomplete incorporation of fertilizers inherent in conservation tillage systems means that nutrients are more easily transported with surface runoff. Also, while sediment losses are substantially less under conservation tillage systems, the sediment which is lost is comprised of the most easily eroded fraction of the soil; i.e., the smaller particles with greater amounts of adsorbed nutrients and pesticides. Other studies (9, 79) indicate that increased nutrient concentrations may also be due to leaching of nutrients from plant residues on the soil surface.

The effect of conservation tillage systems on crop yields appears to vary greatly with weather conditions and geographic location. In an eleven-year northwest Iowa study (4), minimum tilled corn gave superior yields during six years with water deficits during the growing season while for years with adequate rainfall no yield differences were noted. Griffith et al. (34) compared no-till, chisel and till-plant systems with conventional tillage at four Indiana test sites. On well-drained sandy loam the conservation tillage systems equalled or exceeded conventional till corn yields; while on poorly-drained soils no-till yield was substantially less than conventional, and chisel and till-plant corn yields were slightly reduced. A West Virginia study (12) showed significant increases in corn yield for no-till versus conventional tillage following a sod cover crop. A comparison of studies on no-till in Ohio indicated that no-till gave approximately ten percent greater corn yields on well-drained soils, about equal yields on moderately well-drained and somewhat poorly-drained soils, and decreases averaging about ten percent on poorly-drained soils (25).

Climate has an important effect on the utility of conservation tillage methods. Tillage-incorporated mulch aerates the soil which facilitates more rapid spring warming. Lower soil temperatures delay germination, emergence and early plant growth. Research indicates that no-till systems are less successful in colder climates such as New York and New England for these reasons (77, 63). One way these temperature effects can be partially offset is by using a ridge-furrow system in which the crop is planted on the ridges. Considerable soil temperature differences can exist between the ridge and furrow depending on time of day and row direction (3). This system, used in till-planting, also reduces soil moisture and thus may provide an optimum tradeoff between sediment control and yields in poorly-drained soils. Another possiblity is the development and use of crop varieties compatible with cooler soil temperatures (3).

Pest control is another key factor in determining crop yields under conservation tillage systems. With little preplant tillage weed seeds accumulate near the soil surface, and many systems preclude the possibility of herbicides being incorporated prior to planting. For these reasons increased use of herbicides is almost always needed to ensure maximum production under systems of conservation tillage at the present time. In many cases both contact and systemic herbicides are necessary for optimal yields. Insects, nematodes and plant diseases would also be expected to cause greater problems under conservation tillage systems. Residues can serve as overwintering sites for insects and plant diseases. Nematode densities would be expected to increase in the unbroken root residue from no-till. The production, environmental and water quality consequences of large-scale adoption of reduced tillage systems in terms of increased pest risks and environmental contamination are at the present time not clearly understood.

In summary, sediment loss from cropland appears to be directly related to the amount of tillage performed; and thus, reductions can be impressive using minimum or no-till systems. Study results on soil loss and runoff reductions are summarized in Table 1. No-till systems, while exhibiting the greatest reductions in soil loss, appear to be best suited to warmer areas

TABLE 1. COMPARISONS OF SOIL LOSS AND CROP YIELDS BETWEEN CONSERVATION AND CONVENTIONAL TILLAGE SYSTEMS

Investigator	SCS Land Resource Region	Conservation Tillage Method	Crop	Soil Loss (m tons/ha)	Conventional Tillage Soil Loss (m tons/ha)	% Change Loss Reduction	% Change in Yield
Bulter (16)	M	till-plant	corn	-	-	83	-
Langdale et al. (49)	P	chisel plow	corn	12.1	64	81	-
Langdale et al. (49)	P	no-till	sorghum	2.86	71.2	98	-
McGregor et al. (54)	P	no-till	soybeans-wheat	1.8	17.5	90	-10
McGregor et al. (54)	P	no-till	soybeans	2.5	17.5	86	0
McGregor et al. (54)	F	no-till	corn	5.2	17.5	71	0
Mannering et al. (51)	M	chisel plow	corn	-	-	94	-
Mannering et al. (51)	M	till-plant	corn	-	-	60	-
Mannering et al. (51)	M	no-till	corn	-	-	85	-
Oschwald and Siemans (62)	M	disk chisel	corn	-	-	89	-
Oschwald and Siemans (62)	M	no-till	corn	-	-	91	-
Oschwald and Siemans (62)	M	disk chisel	soybeans	-	-	71	-
Oschwald and Siemans (62)	M	no-till	soybeans	-	-	85	-
Gard (29)	M	no-till	wheat	2.7	26.0	90	-14
Gard (29)	M	no-till	corn	0.09	4.9	98	+73
George (31)	B	mulch-tillage	wheat	58.0	13.4	77	-
Amemiya (3)	M	till-plant	corn	-	-	60-90	+3
Amemiya (3)	M	till-plant	soybeans	-	-	-	0
Forster (25)	M	no-till	corn	-	-	-	-10 to +10

with well-drained soils where, in general, higher yields can be obtained than under conventional tillage. Other conservation tillage systems can provide optimal tradeoffs between sedimentation and production under cooler climates and more poorly-drained soils. Figure 2 shows the SCS land resource regions where adequate research has been done to establish conservation tillage as a Best Management Practice for reducing sedimentation. Shown also are areas where research is lacking but climate, soil, cropping and erosion conditions would indicate that some form of conservation tillage is a BMP. Northern regions such as K and L are included in this category with the qualification that no-till systems may result in prohibitive yield reductions but that other reduced-tillage systems should provide a more optimal balance between production and water quality goals in these regions.

CONTOUR FARMING

Contouring works to reduce sediment losses by reducing the volume of runoff by slowing water movement and allowing increased infiltration. It is more effective in doing this on fields of moderate (<8%) slope which are free of depressions and gullies. Water is also held on the field by contouring when row crops are ridged and furrowed rather than "flat" planted (81). A study conducted in west-central Iowa (67) measured a 55% reduction in runoff volume from contoured plots. Since contouring reduces soil loss by increasing infiltration, it would be expected to be more successful on permeable soil rather than on soil of high clay content. Baver et al. (10) have shown that this is generally the case. Various other studies (40) report reductions in runoff volume in the range of 15 to 55% by contour farming depending on type of crop and soil (40). Few data exist concerning the relationship between soil loss reduction and nutrient or pesticide reductions from contour farming. Sediment reductions were found to be greater than nutrient reductions in one study using contoured continuous corn cropping in western Iowa (2). This was a result of 1) higher nutrient concentrations in the runoff relative to control fields between December and March presumably due to leaching from stubble, and 2) the selective erosion of finer soil fractions containing relatively more adsorbed nutrients from the contoured fields.

Wight et al. (86) used contour furrowing on semiarid Montana rangeland and found significant increases in forage production with corresponding decreases in rangeland erosion. A similar study (15) conducted in Colorado, Wyoming and Montana concluded that contour furrowing is the most effective treatment on medium and fine textured soils for conserving soil moisture and reducing erosion. The practice helps to impede overland flow and reduce flood peaks. Forage yields were increased by 118 and 136% in Montana and Wyoming, respectively. The practice has not been widely adapted, however, for economic reasons. The water storage capacity of the contoured furrows decreases rapidly for the first five years after construction, stabilizing after about nine years. In this time period, however, closer vegetative cover can become established providing long-term erosion control benefits.

Crop yields from contour farming would be expected to increase relative to non-contour farming under inadequate soil moisture conditions but be

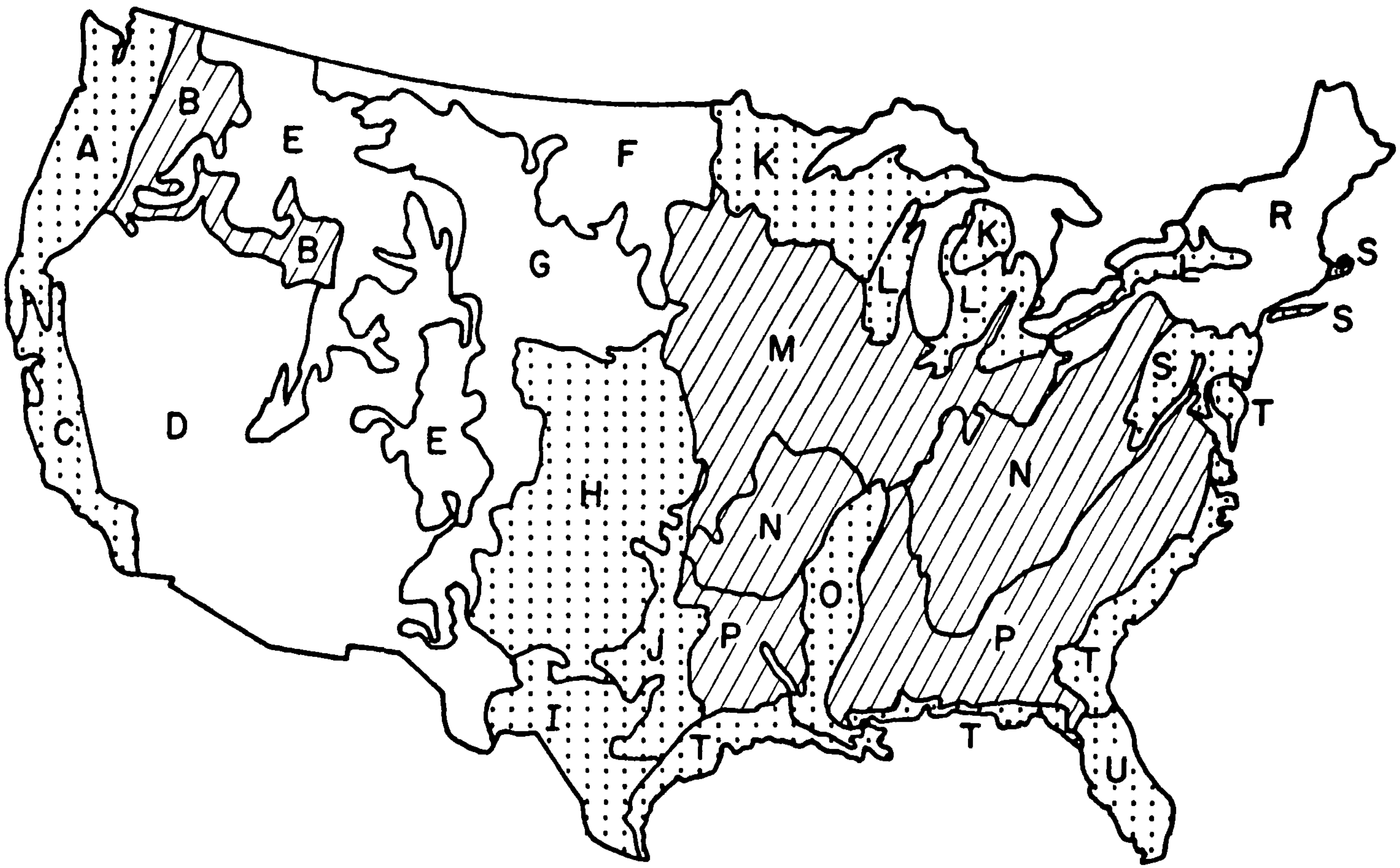

Figure 2. Land resource regions with literature references (///) and projections (:::) indicating conservation tillage as a BMP component.

reduced in areas with excess rainfall or poorly-drained soils. The USDA reported (73) from 30 different studies a 17% average crop yield increase from contouring. The practice is best used as part of a BMP system which would generally include diversions or terraces to reduce length of slope. Comparisons of soil loss, yields and surface runoff between contoured study systems and noncontoured or terraced are summarized in Table 2. Figure 3 indicates regions where research has shown contour farming to be a BMP, and areas where no conclusive data exist but where contouring would be expected to be a BMP. Region U is the only region where contouring would be expected to have no value as a BMP based on typically wet soils and lack of appreciable slopes.

COVER CROPS

The earlier discussion concerning the low sediment yields from forested watersheds and the correlation between soil loss and amount of residue in conservation tillage systems indicates that vegetative ground cover is an important factor influencing erosion. Cover crops are being widely adopted both as a sediment reducing and soil fertility building practice. In warmer areas of the U.S. where legume crops can be established over winter, nitrogen fertilizer requirements can be reduced significantly (57). There is also evidence that nonlegume cover crops may decrease nitrate leaching to ground water as a result of plant uptake (76). Large-scale studies on Black Creek, Indiana, watersheds (48) have clearly shown cover crops to reduce erosion. A recent Missouri study (44) found rye cover crops to reduce soil loss by over 95% versus conventional till continuous corn. Soil loss reductions from the cover crop were equal to those using no-till practices.

The effect of winter cover crops on the yield of succeeding row crops depends upon climate and soil moisture conditions (75). In warmer areas under excessively wet spring conditions, the cover crop can increase the soil drying rate through transpiration allowing more timely planting and hence increased yields. Counteracting the transpiration process, however, is the fact that the cover crop will delay warming of the soil in spring thus slowing soil drying by evaporation. This can be the overriding consideration in northern regions of the U.S. where planting must be done as early as possible to maximize yields. In addition the spring soil drying capability of the cover crop depends on its growth stage. In northern regions little fall cover crop growth will occur and thus the spring transpiration rate will be less than in southern regions. For these reasons as shown in Figure 4, cover crops are not recommended as a BMP in SCS regions F, K, L and R. While cover crops will undoubtedly reduce soil losses in these areas, production limitations suggest that other erosion-reducing practices such as some forms of reduced tillage probably provide a more optimal balance between production and water quality goals.

DIVERSIONS AND GRASSED WATERWAYS

Both of these structures are designed to facilitate the safe disposal

TABLE 2. COMPARISONS OF SOIL LOSS, YIELDS AND RUNOFF BETWEEN CONTOURED AND UNCONTOURED FARMING AND BETWEEN CONTOURING AND TERRACING

Investigator	SCS Land Resource Region	Practice	Soil Loss Contouring (m tons/ha)	Soil Loss Control (m tons/ha)	% Reduction in Soil Loss	% Change in Yield	% Reduction in Runoff Volume
Wight et al. (86)	G	rangeland contour furrowing	-	-	-	+165	-
Saxton and Spomer (67)	M	cropland contouring	-	-	-	-	55
Burwell et al. (18)	M	cropland contouring	23.2	1.1*	-95*	-	-
Branson et al. (15)	D	rangeland contouring furrow	-	-	-	+118	-
Alberts et al. (2)	M	cropland contouring	11.4	3.1*	-73*	-	-42
Spomer et al. (71)	M	cropland contouring	40.0	3.4*	-92*		-67
Johnson and Moore (40)	M	cropland contouring	-	-	-	-	15-55
Stallings (73)	-	cropland contouring	-	-	-	+17	-

*Control is level-terraced watersheds

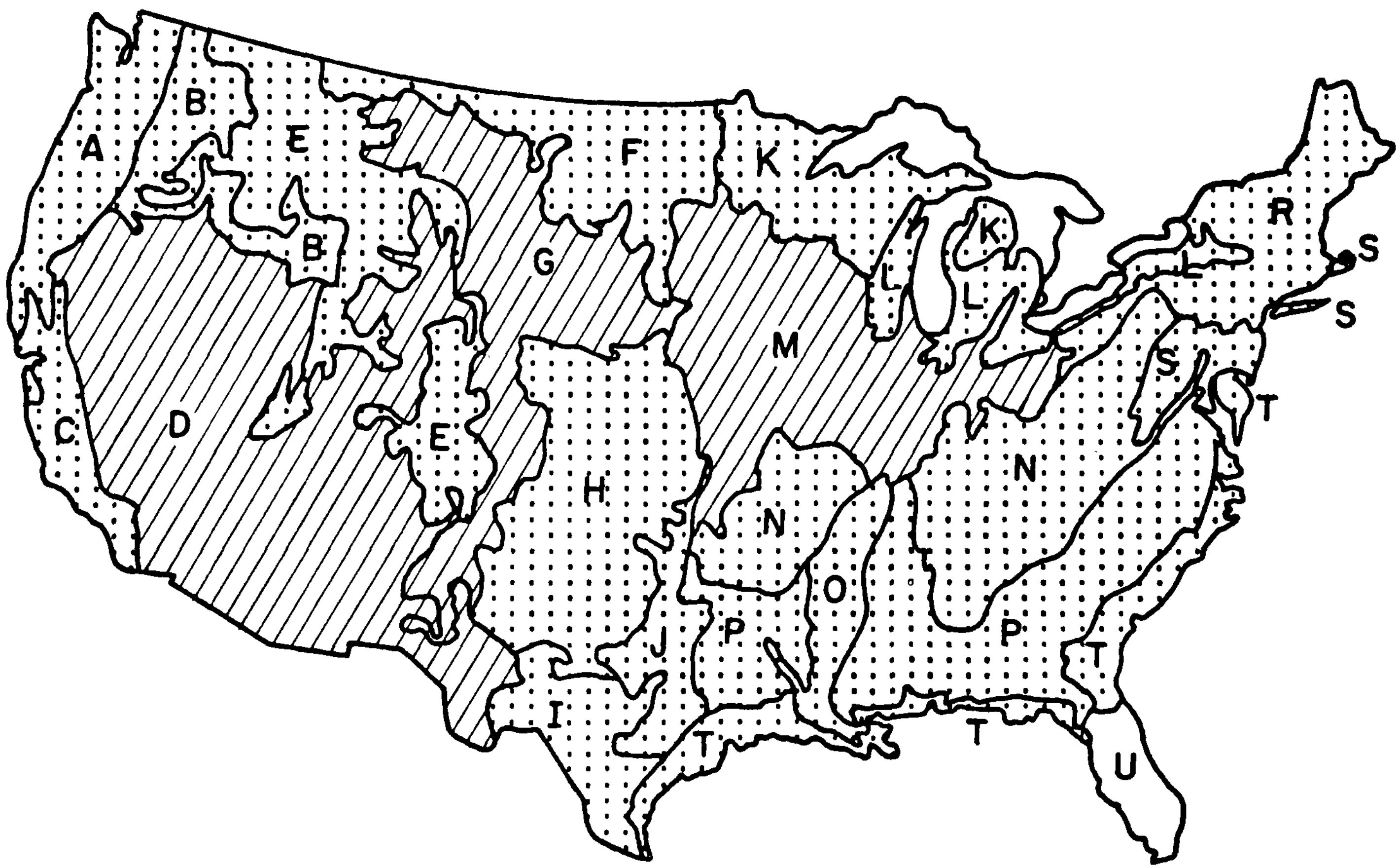

Figure 3. Land resource regions with literature references (///) and projections (:::) indicating contouring as a BMP component.

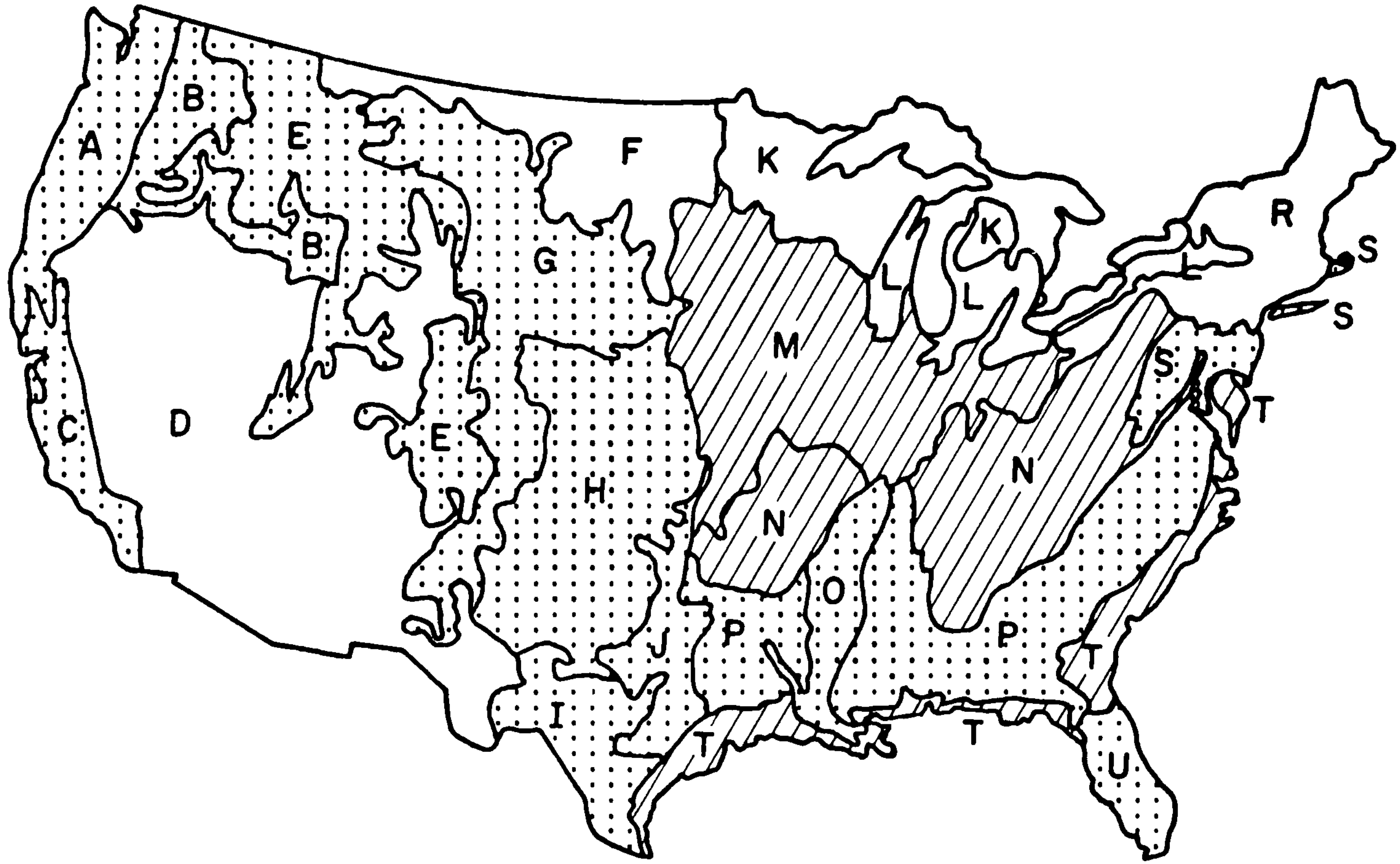

Figure 4. Land resource regions with literature references (///) and projections (:::) indicating cover crops as a BMP component.

of surface runoff. A search of the literature found no quantitative studies conducted to determine the amount of sediment reduction accomplished by these practices. Diversions generally serve to decrease slope length, and thus the reduction in soil erosion can be estimated from the Universal Soil Loss Equation.

Grassed waterways are constructed in natural field depressions or at field edges where runoff tends to concentrate. In this capacity they function to prevent rill and gully formation. A secondary erosion-reducing effect of grassed waterways is to filter sediment from runoff causing in-field deposition of eroded soil. The sediment deposition capacity can be easily exceeded, however, as noted in the Black Creek, Indiana, study (48), in which case they are quickly buried and rendered ineffective. The results of the Black Creek study indicate that grassed waterways should be considered a measure to reduce sedimentation in conjunction with other BMPs such as conservation tillage, diversions and terraces.

Diversions and grassed waterways should have little effect on crop yields. A small percentage of land is lost from production. Diversions, however, may help remove excess water from fields allowing more timely planting with resultant yield increases.

GRASSES AND LEGUMES IN ROTATION

Rotating row crops with sod crops inproves soil structure, organic matter content and infiltration relative to continuous row cropping. Adding a sod crop in a three-year rotation has been shown to reduce soil loss by as much as 80% relative to continuous corn (83). It is widely recognized that closely sown sod crops result in significantly less runoff than row crops. This effect is due primarily to an increase in soil porosity from the dense root system of the sod crop. On very erosive marginal cropland, sod-row crop rotations may be the only way to reduce erosion to tolerance limits. A study by Adams (1) on a clay soil in Texas showed sorghum forage yields to decrease 40% by the fourth year after clover (69). Cotton yields in the same soils were significantly higher in rotations with a legume. Laflen and Moldenhauer (46) determined soil losses and yields from various corn-soybean rotations in plot studies. No differences were observed in soil losses between corn-soybean, soybean-corn or corn-corn rotations; however, corn yields were considerably higher for the soybean-corn sequence.

Kramer and Burwell (44) compared continuous corn rotations with a four-year rotation of corn-wheat-pasture-pasture on a Missouri claypan soil. Corn in both rotations was grown under conventional tillage. Results showed that over 90% of the soil loss from the four-year rotation occurred during the year the plots were in corn. In addition, the soil loss from the rotation corn was only about 70% of that for the continuous corn even though both were grown under conventional tillage. This would indicate that the rotations of wheat and pasture have an erosion-reducing effect on soil structure.

Figure 5 shows regions where rotations which include grasses or legumes are a confirmed or projected BMP. While such rotations give proven reductions

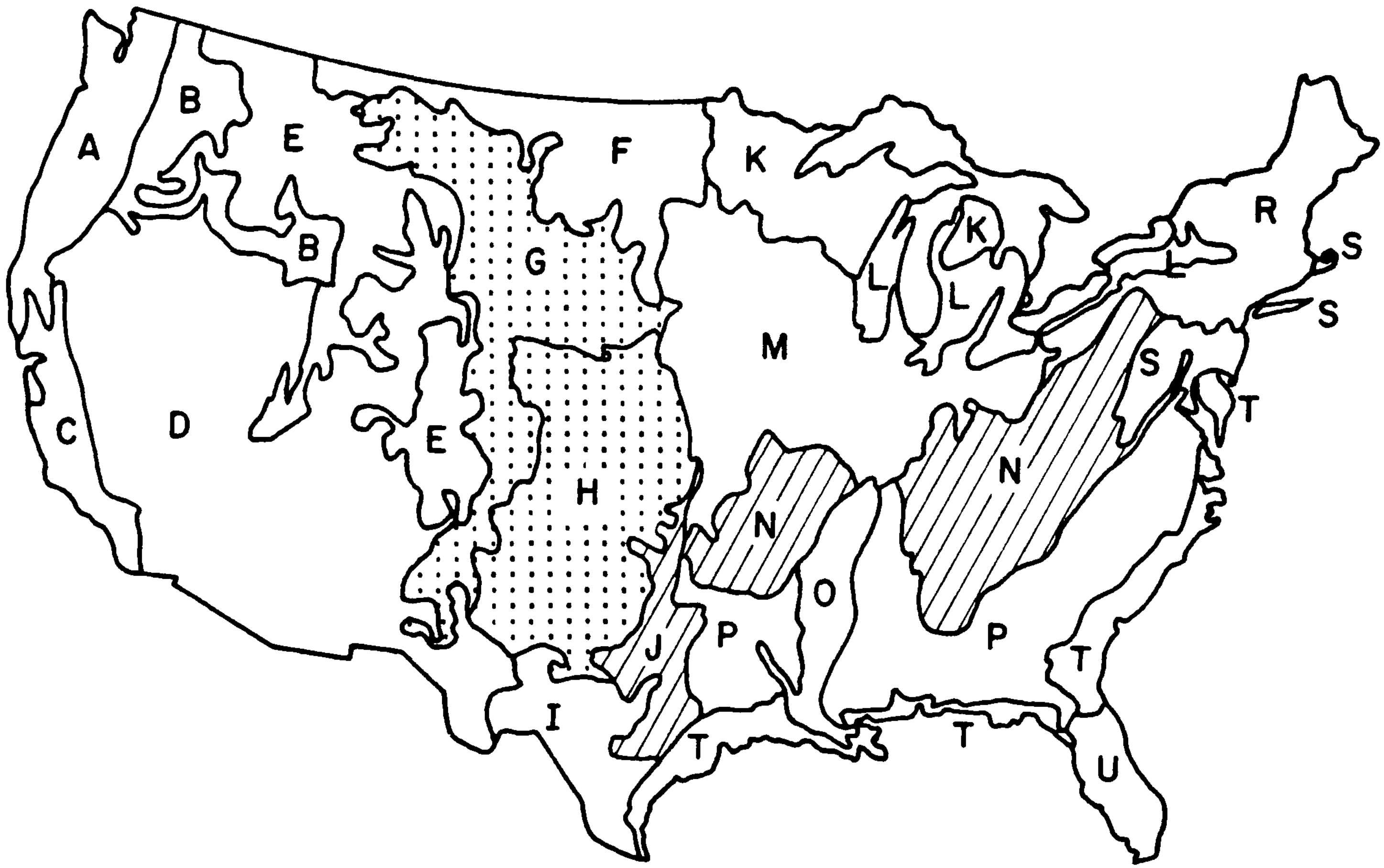

Figure 5. Land resource regions with literature references (///) and projections (:::) indicating rotations which include grasses or legumes as a BMP component.

in soil loss, production of the row crop is lost during grass rotations so that othererosion-reducing practices may provide a more optimal balance between production capacity and water quality.

SEDIMENT BASINS

Sediment basins are designed to retain sediment which has already been detached and transported from fields before it can enter streams or lakes. Hence the benefits are strictly off-site and have no effects on crop yields or farm operations. The most definitive work on the effectiveness of sediment basins in an agricultural watershed was done in the Black Creek, Indiana project (48). The most extensively monitored basin served a 209-ha drainage area. Sediment depositions were measured by fathometer and with probes. The basin was found to have a significant beneficial impact on water quality. In the first two years of its operation, the basin collected over 1000 mt of sediment or an average of 2.7 mt/ha/yr. for the entire watershed. Most of this occurred from one greater than 50-year recurrence storm, the effects of which overwhelmed many of the other BMP measures employed in the watershed. Most importantly about 95% of the sediment trapped was composed of particles less than 50 microns in diameter. This is a clear indication that sediment ponds can effectively retain small particles which are the most difficult to control by land treatment consistent with row crop agriculture (48).

Very little sediment was collected from low and moderate runoff events showing that sediment basins have their greatest utility as a back-up measure for severe storm events. If not used in conjunction with other BMPs, such basins will receive an excessive amount of sediment even from lesser intensity storm events. The larger the sediment load the sooner the basin will require difficult dredging in order to remain effective.

STREAM CHANNEL STABILIZATION

In the Black Creek study (48) it was determined that streambank erosion was responsible for less than five percent of the total sediment entering the waterways. In other areas, perhaps as a result of upstream erosion control practices, this percentage may often be larger; however, the Black Creek results make stream channel stabilization measures very questionable as a general BMP at the present time.

Erosion control measures which decrease soil loss to a greater extent than runoff volume can increase downstream channel erosion and instability (53). The reason for this is that the erosive capacity of water decreases as the sediment concentration increases. Thus as stream sediment levels are reduced by upland control measures, more erosion and undercutting of streambanks and channel bottoms tends to occur. Since it is highly unlikely that upstream sediment control measures will reduce sediment loads below the natural conditions under which stream channel regimes were formed, upland control measures will probably only remove channel-deposited sediment to the extent of returning the channels to natural gradients and cross-sections.

Myers and Ulmer (60) have presented design criteria for streambank stabilization measures in Mississippi. These include slotted board fencing, concrete jacks and loose stone riprap. The authors note that extensive deepening of channels and souring of streambanks are prevalent in this area from the enlargement and straightening of channels which allow higher flows to enter and move through channel systems at increased velocities.

Conditions which may occasionally require protective measures include:

1. Bare, nearly vertical, unprotected bank
2. Silt bar buildup on the inside or immediately downstream of a curve
3. Channel bank sloughing on straight sections and curves
4. Rapid loss of streambank on the outside of the channel curve (60)

Standard concrete jacks consist of three long concrete beams which are bolted together at their midpoints. They are used to preserve or establish a desired channel alignment. A row of jacks on each side of the channel can be used to confine meander and reestablish bank stability. These devices increase flow resistance and thus reduce flow velocities. Silt deposition then occurs partially covering the jacks allowing vegetation to be established and further protect the banks. Little information exists on the long-term effectiveness of this practice in use.

Slotted board fencing is designed to ensure reduced stream velocity against the banks. It is generally stronger than concrete jacks, and thus can be constructed on sharper curves and larger streams. Rock riprap is the oldest and most widely used streambank protection measure (60). The streambank is sloped to a 2:1 slope or less for maximum effectiveness.

Before any of these measures are employed however, a thorough knowledge of the original condition and regime of the stream channel must be available to indicate what actual changes have resulted from upstream agricultural activities.

Very little research has been done on the effects of streambank stabilization on water quality. In the Black Creek study (48), various bank mulch materials and slopes were compared for effectiveness in preventing streambank erosion. Stone, straw and wood chip bank mulches were all effective in controlling erosion and helping to establish vegetative cover. Of the three, stone mulch was concluded to be superior because it was much less easily washed away during high water flow. Vegetative cover establishment was most successful where bank slopes were 2:1 or flatter. Estimates of the contribution of streambank or channel erosion to the total stream sediment load should be made before these measures are employed. As suggested in the above discussion, present information indicates that stream bank and channel stabilization practices are not an appropriate starting point for controlling sediment in most cases. However the problem may need to be increasingly addressed in the future on watersheds where sediment loading is significantly reduced by the implementation of upland sediment control practices.

TERRACES

Terraces are designed to reduce erosion rather than runoff volume. They reduce erosion by decreasing slope length and steepness thereby reducing the transport of detached soil particles. Terraces are of two general types: graded terraces which divert water to a grassed waterway or similar drainage, and level terraces which hold water on the field increasing infiltration. In a study in the southern Mississippi Valley (19) soil loss reductions of fifty percent from terracing of highly erodible loamy soils were observed. Richardson (65) compared runoff volumes, soil loss and tillage efficiency between a graded-furrow and terrace cropping system on Texas clay soil of uniform two to three percent slope. Runoff was significantly less from the graded-furrow watershed, although runoff volumes for both systems were less than nongraded-furrow, nonterraced land. This was observed to be due to a more uniform distribution of excess water. Soil losses from both systems was approximately equal, but tillage efficiency was 21% better on the graded-furrow land though this may have been partially due to the atypically uniform slope of the study area.

Several studies in western Iowa, however, have found level terracing to be more effective than contour farming in reducing runoff volumes and soil loss. Two studies (2, 18) found soil losses to be over twenty times higher on contoured versus terraced corn cropland on these steeply sloping loess soils. Similar though less dramatic differences were observed by Spomer et al. (72). In all cases, however, contouring resulted in substantial reductions in erosion relative to uncontoured cropland.

A comparison of the effectiveness of conservation tillage systems, contour farming and terraces individually, and in various combinations for reducing erosion and sediment yield was recently conducted on the steeply sloping, silt loam wheat cropland of north-central Oregon (30). Terraces were found to be less effective than the conservation tillage system (chisel plowing) and contouring in reducing erosion, but were actually more effective in reducing sediment delivery to streams since most eroded soil was redeposited within the terraces. Sites which combined terraces with reduced tillage or contouring exhibited no measurable erosion indicating the complementary nature of these practices for reducing soil detachment and transport.

A 98% reduction of annual soil loss was observed by Saxton and Spomer (67) when terracing was applied to highly erodible loess soils in Iowa. By holding soil on the land, terraces should also reduce losses of strongly adsorbed nutrients and pesticides such as phosphorus and paraquat (68). Crop yields often decrease immediately following construction of terraces because the construction disturbs topsoil (69, 2). In dry areas, however, yields are usually higher eventually since terraces help make more efficient use of water. Also terraces are commonly used in drier areas with deep loess soils which minimizes the effects of topsoil disturbance (71). Early studies in such areas showed substantial crop yield increases relative to nonterraced land (73).

Research data on the effects of terracing on soil loss, crop yields and runoff volume are summarized in Table 3. As the research described above indicates, there is considerable variability in the relative effectiveness of terraces in maximizing yields and sediment reductions between geographic areas. Crop yields may be initially decreased in areas with less developed topsoils due to soil disturbance during construction. In deep loess soils this effect is less important. The research indicates that terraces are better adapted to drier areas such as the western Corn Belt and central Oregon and Washington where they facilitate more efficient water use by allowing increased percolation. In the more humid areas of the Northeast, Middle Atlantic, and Pacific Northwest they may, however, increase nutrient leaching to ground water, particularly in the absence of good fertilizer management systems.

These geographic considerations are summarized in Figure 6. In several of the regions where terracing is shown to be a proven or projected BMP, it must be remembered that terrace construction costs are high and comparable soil loss reductions can be achieved with alternative practices. In many instances terracing may be a less cost-effective BMP than other practices such as conservation tillage and contouring.

FILTER STRIPS

Filter strips are a relatively new practice for soil and water conservation and little field research work has been specifically conducted concerning their effectiveness. Karr and Schlosser (42) found that vegetative filters could effectively filter sediment from both sheet and shallow channel runoff flow. Variables which affect their utility include filter width, slope, type of vegetation, sediment size distribution, degree of filter submergence, runoff application rate and initial sediment concentration.

A study of logging impacts on stream biota in northern California (23) compared invertebrate diversities for streams with and without buffer strips. In logged areas with no streamside filter strips, significant changes and reduced diversity of invertebrate communities was observed; while for streams with thirty meter buffer strips, invertebrate communities and physical stream characteristics were unaffected.

Generally filter strips of four to five meters width are sufficient for cropland of less than five percent slope. Widths should be increased for steeper slopes (81). Filter strips are most effective in conjunction with erosion-reducing BMPs since their sediment-retaining capacity is limited and can be easily exceeded under high sediment inputs rendering them ineffective.

IRRIGATION

Sediment losses from irrigated farmland necessitate special types of sediment control practices. In most cases annual rainfall is small and soil

TABLE 3. COMPARISONS OF SOIL LOSS, YIELDS AND RUNOFF BETWEEN TERRACED AND UNTERRACED CROPPING

Investigator	SCS Region	Crop	Terraced Soil Loss (m tons/ha)	Unterraced Soil Loss (m tons/ha)	% Reduction in Soil Loss	% Change in Yield	% Reduction In Runoff Volume
George (31)	B	wheat	22.4	60.5	63	-	-
Carter et al. (19)	P	corn	-	-	50	-	-
Saxton and Spomer (67)	M	corn	-	-	98	-	-
Spomer et al. (71)	M	corn	2.2	56	95	-4	-
Spomer et al. (72)	M	corn	3.4	40.0	92	-	67
Alberts et al. (2)	M	corn	3.1	11.4	73	-	42
Burwell et al. (17)	M	corn	1.1	23.2	95	-	73

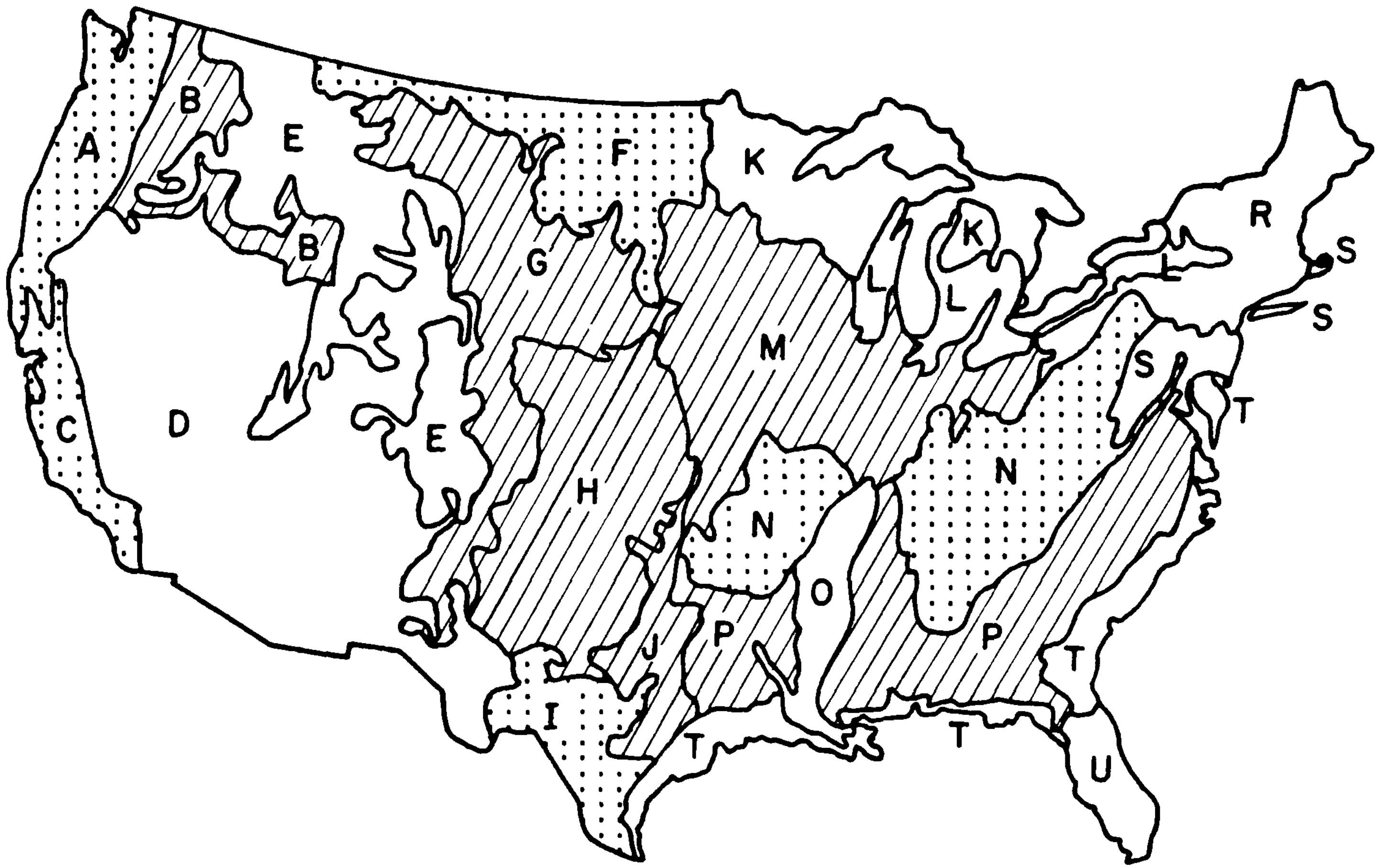

Figure 6. Land resource regions with literature references (///) and projections (:::) indicating terraces as a BMP component.

loss occurs primarily as a result of applied water. Irrigation systems can be divided into four general types: 1) sprinkler systems which include stationary, side roll and center pivot systems, 2) flood systems which are generally divided into open and border flooding types, 3) drop irrigation systems which are used primarily on orchards but are becoming increasingly popular for other crops because of their efficient use of water, and 4) furrow systems which require at least a small amount of slope. Among the variables affecting erosion on irrigated land are soil type, slope, crop, suspended solids content of irrigation waters, type of irrigation system and efficiency of water management in terms of irrigation rates and timing.

Studies on furrow-irrigated Idaho cropland (13) found that erosion occurred primarily because tailwater ditches were deeper than the furrow streams, thus causing small eroding waterfalls to move up the furrows from the sownhill edge of the field. After several years the irrigated fields assumed a convex shape. Soil loss also occurred when furrow streams were larger than necessary. The results indicated that soil loss from irrigated cropland could be reduced by 1) keeping the flow to the furrow only large enough to sustain to the end of the field, 2) decreasing the depth difference between furrows and tailwater ditches, and 3) planting vegetative filter strips on the lower end of the fields to filter out transported sediment before discharge to return flow. Present work at Rock Creek, Idaho, RCWP is investigating irrigation management practices further and should provide valuable information on the effectiveness of these practices on a larger scale. An ongoing MIP project in the South Yakima watershed, Washington, has similar goals.

SUMMARY

From the extensive research which has been done on the effectiveness of various sediment control practices, many conclusions can be made. In this section these are divided into "hard" and "soft" conclusions. "Hard" conclusions are those which are based on extensive nonconflicting data in a specific region. "Soft" conclusions carry less certainty and are based on less data or where there is some conflict between studies and also for regions where tentative conclusions can be projected based on research data in similar regions.

Hard Conclusions

1. Conservation tillage systems reduce soil erosion (60-99 percent) relative to conventional tillage regardless of geographic area, soil type, slope, climate or type of crop.
2. All other factors being equal, the extent of erosion reduction is a function of the amount of tillage performed. No-till systems will reduce erosion and sediment production more than reduced-tillage systems such as chisel plowing, which in turn will give reductions relative to moldboard plowing.
3. Conservation tillage systems will generally give higher

crop yields relative to conventional tillage systems on well-drained soils or in dry years, while this trend will be reversed for poorly-drained soils or in excessively wet years.

4. No-till systems are better adapted to warmer climates since in the cooler regions of the U.S. delayed soil warming and drying as a result of previous crop stubble may often interfere with timely planting causing yield reductions. Other reduced tillage systems will generally provide a better optimization of production and sediment reduction in these regions.

5. Contour farming will significantly (50-90 percent) reduce soil loss relative to noncontouring on sloping cropland. Runoff volume level is also decreased.

6. On deep loess soils in the western Corn Belt, level terraces are more effective than contouring in reducing soil loss and maximizing yields.

7. Cover crops can be considered a BMP for all topographies and soil types in warmer climates but have limited applicability in colder regions due to the difficulty of sufficient establishment before winter freeze.

8. Sod-row crop rotations can reduce erosion 80 percent in sod crop years and provide carryover effects when row crops are planted.

9. Terraces are effective in reducing erosion (50-99 percent reductions) but construction costs are high.

10. Initial crop yield reductions may occur with terraces due to disruption and compaction of topsoil during construction.

11. Because sediment control measures can act either by reducing on-field erosion or sediment delivery, combinations of the two types may provide the best control strategy.

12. Although pesticide costs increase, the total costs of production usually decline with use of conservation tillage systems, primarily because of savings in labor and fuel costs.

13. The overall profitability of conservation tillage depends primarily on the effects on yields on the conservation tillage system. When yields are affected not at all or only slightly, conservation tillage systems are generally more profitable and contribute to water quality improvement.

Soft Conclusions

1. Dissolved nutrient and pesticide concentrations from runoff reducing practices will generally be higher than from conventional tillage, but the total amount of nutrients and pesticides lost will generally be less due to the decreases in soil loss.

2. Sediment basins will retain sediment fines which are the most difficult to control by erosion control measures.

3. Stone mulches or riprap are more effective than other materials in preventing streambank erosion.

4. Some amount of trade-off between sedimentation and associated nutrient transport, and leaching of nutrients to ground water may be inherent in practices such as conservation tillage, contouring and terraces which reduce erosion but increase infiltration and percolation.

SECTION 5

ECONOMIC ASPECTS OF BMP'S FOR SEDIMENT CONTROL[1]

Economics of BMP's for sediment control can be viewed from three perspectives: (1) costs of installing and maintaining the BMP's, (2) effects on net farm income, and (3) cost-effectiveness. These three perspectives are briefly discussed here and some readily available information presented.

COSTS OF INSTALLING AND MAINTAINING BMP'S

Costs of installing and maintaining BMP's should be developed for each project area since these costs can vary considerably depending upon different local and site conditions. However, some BMP's in general are less costly than others. Costs developed by the Soil Conservation Service in North Carolina depict the differences among practices in installation costs, life spans, annual operating and maintenance (O&M) costs and total annual cost (Table 4). These data indicate such practices as crop residue, filter strips,

TABLE 4. COSTS OF CONSERVATION PRACTICES, NORTH CAROLINA, 1980

Practice	Cost Per 1/ Unit	Unit Per Acre	Cost Per Acre	Life Span	% Annual O&M Cost	Total Annual Cost 2/
Conservation Tillage	$ 10/Ac	1	$10.00	1	-	$11.00
Contour Farming	0/Ac	1	0	1		0
Cover Crop	15/Ac	1	15.00	1		16.00
Critical Area Pltg.	$ 900/Ac	-	-	25	3	111.00
Crop Residue	5/Ac	1	5.00	1		5.50
Debris Basin (Sediment Pond)	5,000/Ea	-	-	25	3	618.00
Diversion	.60/LF	200 Ft.	120.00	10	5	24.00
Filter Strips	.17/LF	175 Ft.	30.00	10	5	6.00
Grassed Waterway	1,200/Ac	.06 Ac	72.00	10	5	14.00
Grasses & Legumes in Rotation	5/Ac	-	175.00	3	-	68.00
Stripcropping	.20/LF	1	5.00	10	1	1.25
Terraces		400 LF	80.00	10	5	16.00

1/ Price Base 1980, Raleigh, N.C.
2/ Based on 8% Interest Rate
Adopted from: Soil Conservation Service, USDA, "Benefits/Costs of Soil and Water Conservation Practices for Erosion and Sediment Control," Raleigh, N.C., June 1980.

[1]This section was prepared by Dr. L.A. Christensen and Patricia E. Norris, Economic Research Service, U.S. Department of Agriculture (USDA), Athens, Georgia.

strip cropping and conservation tillage are less costly than sediment ponds, diversions, and terraces.

EFFECT ON NET FARM INCOME

The BMP could be a cost or benefit to the farmer depending upon the effect on net farm income. This effect depends on (1) the impact of the practice on farm production and hence sales, (2) the changes in production inputs and associated costs, and (3) the farmer's proportion of installation costs.

The impact on production would come mostly from changes in cropping pattern and short term yields, but with lower soil loss, long term improvements in soil productivity would also be expected. Also some practices such as terraces and grassed waterways may also remove a small surface area from production on the field.

Effects of a practice on short term yields depend heavily on soil and moisture conditions and pest control. These things considered, yield effects of some practices have been summarized as follows (5):

- Crop yields with conservation tillage are roughly equal to yields from conventional tillage, and were often better during dry years.

- Crop yields with contour farming may be higher under dry conditions, and lower under excess moisture or poorly drained soil conditions.

- Crop yields with grasses and legumes in rotation will likely be higher.

Production inputs and costs associated with various BMP's can differ substantially from those under conventional tillage (Table 5). Terraces require additional construction and maintenance costs. Rotations and strip cropping reduce the need for pesticides. Conservation tillage increases use of pesticides (herbacides), but will reduce labor and equipment costs (unless purchase of additional machinery is involved). Contour farming can increase equipment and labor costs, particularly if smaller equipment must be purchased and used.

Energy in the form of fuel is also an input which varies according to the type of BMP used. Fuel requirements for various rotations and tillage systems have been developed at Iowa State University (Table 6). These figures show a decrease of about 50 percent in the use of fuel between fall-moldboard and no-till systems for both continuous corn and a corn-beans rotation on a loam soil. The actual decreases are 3.8 gallons for the continuous corn and 2.75 gallons for the corn-beans rotation. Keep in mind that these figures will vary with the soil types in the fields where practices are applied.

Cost comparisons made by Crosson between conservation tillage and conventional tillage in 1979 for selected crops indicated total costs were lower for conservation tillage (1). Labor, machinery, and fuel costs were lower with conservation tillage, but pesticide costs were higher. For example, total costs for conservation tillage compared to conventional tillage ranged

TABLE 5. TYPICAL CHANGE IN VARIABLE COSTS ASSOCIATED WITH IMPLEMENTATION OF BMP'S AS COMPARED TO CONVENTIONALLY TILLED CONTINUOUS CORN GRAIN

BMP	N Fertilizer	Pesticides	Equipment	Labor	Construction Maintenance Other
			(Dollars/Acre)		
Conservation Tillage	0	+9.60	-4.00	-3.60	0
Rotation 1/	-10.40	-12.00	-6.00	40	-.80
Contouring	0	0	+2.40	+1.20	0
Diversion 2/	-.80	-1.20	+1.20	+.80	+6.00
Strip Cropping	-10.40	-12.00	-4.40	+.80	-.80
Terrace 3/	0	0	+2.40	+1.20	+40.40

1/ Six year rotation with 3 years corn, one year oats, two years hay. Values are average for the six years.

2/ One diversion ditch across center of 120 m slope, with contouring. Construction costs amortized over 45 years.

3/ Terrace system had a terrace at 30 m, 60 m, and 90 m, respectively, above lower edge of field with 120 m slope, with contouring. Construction costs are amortized over 45 years.

Source: (SCS-USDA, Raleigh, N.C.)

TABLE 6. FUEL REQUIREMENTS FOR VARIOUS ROTATIONS AND TILLAGE SYSTEMS

Rotation	Gallons per Acre		
	Light	Medium 1/	Heavy
Continuous corn, moldboard, fall	6.28	7.15	8.40
Corn-beans, moldboard, fall	4.57	5.54	5.95
Continuous corn, chisel, fall	5.96	6.95	7.10
Corn-beans, chisel, fall	5.89	5.69	5.98
Continuous corn, chisel, spring	5.96	6.95	7.10
Corn-beans, disk, spring	4.46	5.04	4.88
Corn-beans, double chisel, fall	4.61	5.44	6.06
Corn-meadow, moldboard, fall	2.70	3.11	3.65
Corn-meadow, chisel, fall	2.99	3.38	3.79
Corn-meadow, chisel, spring	2.99	3.38	3.79
Continuous corn, no-till	3.00	3.35	3.61
Corn-beans, no-till	2.44	2.79	3.05

1/ These figures are for a Central Iowa loam soil. The "light" and "heavy" column entries represent adjustments to these basic figures to reflect changes in fuel consumption. For contour tillage, these figures are inflated by 5 percent.

Source: U.S. Dept. of Agriculture, Cooperative Extension Service, Iowa State University, "Fuel Requirements for Field Operations," prepared by George E. Ayres, November. 1976.

from 86 percent for wheat to 95 percent for cotton. Labor was 50 percent lower for all crops studied. Annual machinery costs were assumed to be $5 an acre less with conservation tillage, fuel consumption two gallons per acre less, and pesticide costs were one-third more.

A Wisconsin study found a 3 percent increase in net returns when chisel plowing (a form of conservation tillage) replaces conventional tillage, assuming equal yields with each practice (3). However, a 10 percent decrease in yields was assumed when comparing no-till to conventional till, resulting in a 13 percent decrease in net returns. With equal yields, there was a 14 percent increase in net returns. A Tennessee study found a 13-14 percent reduction in corn and soybean production costs with no-till (2). Thus, if yields are assumed to be the same, higher net returns result for no-till farming.

A study in Missouri showed net returns from continuous corn were 13 percent greater with minimum tillage and 2.4 percent greater with zero tillage (4). For continuous soybeans, net returns were 22 percent greater with minimum tillage compared to conventional tillage.

COST-EFFECTIVENESS

Cost-effectiveness analysis of various practices requires matching up cost data with measures of the reduction in sediment delivery. What is included on the cost side depends mostly on the availability of information. Ideally for most analyses, the cost side would include both government (cost share, technical assistance, education and information, and administrative costs) and net private costs (net effects on farm income).

A system for estimating and displaying costs of soil conservation practices has been developed and applied to soils in Missouri (4). Some 50 practice combinations for corn production were ranked by the cost per ton of reduced erosion. For example, minimum tillage alone would reduce erosion from 40.4 to 15.5 tons per acre at a savings of $3.50 per acre compared to conventional practices.

A 1978 ACP Evaluation relating soil savings and costs for a variety of conservation practices in the Southern Coastal Plains found that the cost per ton of soil saved ranged from $0.10 with vegetative cover on critical areas to $4.21 per ton for cropland protective cover (5).

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SECTION 6

RESEARCH NEEDS

From the previous discussion it is obvious that a great deal is known about the effectiveness of various proposed BMPs for controlling sediment. There is no doubt that each of the individual BMPs discussed above can reduce sediment either on the field or prior to entering waterways under certain conditions. However, additional knowledge to most effectively address the sedimentation issue on a national scale is needed in three major areas:

1. While much definitive information has been gathered on the soil erosion effects of individual management practices, considerably less is quantitatively known about the effectiveness of combined systems of BMPs for controlling sediment.

2. Actual experimental information on sediment delivery ratios is very limited even within fields and on small watersheds. This means that we have limited knowledge of what level of treatment will have a given sediment reduction in larger watersheds and even more importantly, which areas should be treated and to what extent for the most cost-effective sediment control.

3. Most importantly, almost no information presently exists on the actual water quality effects of the various proposed BMPs. Studies have centered on determining erosion reductions attributable to BMPs rather than on the resultant downstream water quality changes. We have very little information about how water quality in a large scale, real world, agricultural watershed will change in response to implementation of a given set of sediment control measures or about the time-frame within which these expected improvements may occur.

SECTION 7

CURRENT RESEARCH

This section is intended to describe some of the more important on-going research on sediment control practices and to describe how this research will help to answer the above questions.

The most comprehensive study which has been completed to date is the Black Creek, Indiana Section 108a study (1972-1977). This pioneering effort demonstrated that an overall improvement in sediment-related water quality could be realized for a large scale system (5374 hectares) as a result of implementing sediment-control BMPs. Considerable quantitative water quality information relating to the use of specific practices such as conservation tillage, grassed waterways, diversions and sediment basins was obtained. Equally important was knowledge gained on how to best conduct such large-scale studies in terms of successfully securing an adequate level of farmer participation, selecting areas in most urgent need of treatment, and designing the research to minimize confounding variables so that clear cause-effect relationships between BMPs and water quality could be distinguished. Several lessons were learned that can be used to advantage in subsequent projects. Most significant of these was that little attention was given to critical area identification with the result that almost the entire watershed was treated without regard to the accessibility of the sources to waterways. This resulted in more extensive treatment at greater cost than needed for a given level of water quality improvement. Also nearly thirty percent of the monetary effort was directed to streambank stabilization measures while it was subsequently learned that this source contributed less than five percent of the sediment entering the creek. The water quality monitoring effort is continuing at Black Creek to determine the long-term effects of the BMP implementation and to evaluate their performance under infrequent, high-intensity storm conditions which have been shown to cause a major proportion of sediment production.

Present large-scale research efforts are being conducted under several programs including the Rural Clean Water Program (RCWP), the Model Implementation Program (MIP), and Agricultural Control Projects (ACP), as well as several special projects. The MIP projects were initiated in 1977 to continue through 1981. Among those that are concentrating on sediment control as a major priority are the Indiana Heartland MIP; Maple Creek, Nebraska MIP; Lake Herman, South Dakota MIP; and the Yakima Sulfur Creek, Washington MIP.

The Indiana Heartland MIP located near Indianapolis is a highly agricultural watershed in which over 99% of sediment loss is estimated to originate from cropland. Sediment control practices being implemented in the 65,260 hectare study area include permanent vegetative cover, terraces, conservation tillage systems, sediment basins, and grassed waterways.

In the Maple Creek, Nebraska watershed on the western edge of the Corn Belt, soil erosion loss has been very high concomitant with the introduction of intensive row cropping on steeply sloping land. Sediment control in this MIP project is being focused on terracing, contour farming and use of sediment basins. Presently soil loss in the study area averages over 49 mt/ha.

The Lake Herman, South Dakota MIP is studying whether the eutrophication process can be reversed and the time frame in which this can be accomplished following BMP implementation. BMP systems for sediment reduction include terraces, sediment basins and cover crops. Continued water quality monitoring in these projects will provide data to evaluate BMP effectiveness.

The projects under the Rural Clean Water Program (RCWP), initiated in 1979, are mostly in the operational phase and it is expected that BMP implementation and water quality monitoring will continue through the entire decade. These projects represent a major effort towards determining the most cost-effective means of achieving given agricultural water pollution control goals. These efforts should go far towards filling information gaps, particularly concerning water quality effects of BMPs in large, agriculture-intensive watersheds, and should point the direction for optimizing agricultural production and water quality goals into the next century. Among the RCWP projects with sediment control as a primary goal are: Lake Tholocco, Alabama; Prairie Rose Lake, Iowa; Double Pipe Creek, Maryland; Reelfoot Lake, Tennessee; Oakwood-Lake Poinsett, South Dakota; and Conestoga Headwaters, Pennsylvania.

The Lake Tholocco, Alabama RCWP is designed to control both sediment and animal waste sources. BMP systems being implemented for sediment control consist of combinations of terraces, grassed waterways, conservation tillage systems, filter strips and sediment basins. The Prairie Rose Lake, Iowa project is located in the hilly western Iowa Corn Belt and experiences an average soil loss of 67 mt/ha. One goal of the project is to reduce sediment loading to the lake by sixty percent emphasizing the use of terraces, waterway systems, conservation tillage systems, and sediment retention basins. In the Double Pipe Creek, Maryland project excessive suspended sediment concentrations following heavy storms have increasingly hindered drinking water treatment. Sediment control systems being implemented in the 49,000 hectare study area include strip cropping systems, diversions, grassed waterways, conservation tillage systems, sediment basins and streambank protection measures.

The Reelfoot Lake, Tennessee project represents an area with perhaps the greatest soil erosion problems in the U.S. Reversing this process and restoring the quality of Reelfoot Lake may be an impossible challenge, but the project should establish the effectiveness of BMP systems under extreme erosion conditions. Soil loss from cropland in the study area averages 114 mt/ha. Nearly all proposed sediment Best Management Practices are being tried in the project, but those being implemented most widely include diversions, filter strips, land-use conversion, pasture and hayland planting, contour farming and terraces. The goal is a significant reduction in sediment loading to the lake. The project will also determine to what extent nutrient loadings are reduced by controlling sediment.

The Oakwood-Lake Poinsett, South Dakota and Conestoga Headwaters, Pennsylvania RCWPs are both primarily aimed at controlling nutrient inputs to waterways by reducing sediment inputs. In the Conestoga Headwaters project it is suspected that the use of some sediment-reducing practices such as terraces and conservation tillage may increase groundwater contamination. The study should document the relationship between ground and surface water agricultural pollution.

Several other large-scale projects with sediment control as a major goal are underway nationwide. Among these are Saginaw Bay, Michigan ACP project (108,000 hectares); Little River, Connecticut ACP; Allen and Defiance County, Ohio EDA 108 project which is studying the effects of conservation tillage on soil loss and water quality; the Chowan River Agricultural 208 Project in eastern North Carolina; and the Washington County, Wisconsin EPA 108 project.

The results of these projects should each contribute to an understanding of how best to control sedimentation under varying conditions of climate, soil type, topography and cropping pattern. Taken together they should greatly enhance present knowledge about many aspects of sediment-related water pollution including:

1. The overall effects of practices which reduce runoff and increase infiltration to ground water systems, and how to maintain the optimal balance between ground and surface water quality in situations where both are a problem. Projects focusing on ground water such as the Conestoga Headwaters RCWP and Long Pine Creek, Nebraska, should be helpful in answering these questions.

2. Determining the most critical areas in a watershed, i.e., those areas making the largest sediment contribution to the waterways. The selection of these critical areas depends both upon the magnitude of these sources and their respective sediment delivery ratios. Increased understanding of critical areas is essential, since from the research already completed it is obvious that treatment of all sediment-producing sources is not economically or physically practical. Thus, allocating resources towards agricultural pollution in the most efficient and cost-effective manner will be contingent on clear understanding of the relative sediment contribution of various nonpoint sources.

3. The extent and time frame of actual water quality

3. (continued)
   improvements from erosion control and sediment reducing practices.

4. The water quality effects of combinations or systems of practices in large-scale, real world watersheds containing agricultural as well as nonagricultural sources.

A final point to be emphasized in relation to the present work is that while most of these studies (in particular the RCWP projects) may take several years or even a decade to complete, the magnitude, urgency and implementation lag time of the sediment related agricultural pollution problem require that the information gained from these studies be translated into agricultural management policy in an efficient and rapid manner. The magnitude of the sediment problem with its degrading effects on both the nation's land and productivity and water quality dictate that we cannot wait a decade for conclusive and final study results before confronting the problem with a comprehensive, national strategy based on our state-of-the-art knowledge while acknowledging that adjustments in this strategy may be needed based on increased information.

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