NEWLY DEVELOPED TECHNOLOGIES FOR SOIL AND WATER CONSERVATION

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ABSTRACT
Recent discoveries and technological innovations in the field of soil and water conservation can be traced to the works of our predecessors. In this paper, conservation is defined broadly, to include the quality of water lower in watersheds, and is discussed according to contaminants. Within-field source prevention and reduction practices as well as off-site mitigation practices are described. Examples concerning point, field, and watershed scale assessments of the status and trends of conservation practices are given. In conservation as in production, researchers are increasingly aware of within-field spatial variation. The authors agree that soil and water conservation holds a place of high importance in research priority and potential to help improve the state of our world.

Key words: Soil conservation, erosion, sediment, water conservation, runoff, water quality, nutrients, pesticides, precision agriculture, precision conservation

INTRODUCTION
Any discussion of newly developed technologies for soil and water conservation requires definitions of what is “new,” what are “technologies,” and what is “conservation.” First, very little that is “new” springs forth unprecedented by other work that made it possible, so we will discuss many things in this paper that are a decade old or more if needed to illustrate the development. Second, “technologies” are often defined as being limited to devices of some sort, but here we have extended the term to include new knowledge that we think will provide the basis for future conservation tools. Finally, following Kitchen et al. (2005), we include the preservation of quality for both soil and water as paramount to their conservation.

In this paper, we will several times examine the trade-offs between profitability and environmental benefits such as conservation. Kitchen et al. (2005) asserted that in the field of precision agriculture, matching management inputs to specific needs is a compelling argument even for those outside agriculture. However, the producer’s goal is to improve profitability through improved crop performance (Kitchen et al. 2002), while the public sector’s goal is to improve the environment (Vanden Heuvel 1996). Berry et al. (2003) emphasized that these objectives need not be mutually exclusive.

Another common theme in this paper will be the interaction between conservation and precision agriculture. In many cases, displacement of topsoil created the spatial variability we are now facing, and variation in topsoil depth becomes the dominant factor for explaining soil and water quality impairments and management of water and nutrients (e.g., Lerch et al. 2005). Thus, a critical innovation in conservation comes from considering within-field issues rather than whole-field practices (Berry et al. 2005).
We have organized our discussions by modes of action first – on-site source reduction/prevention, and then off-site mitigation or transport-reduction practices. We then discuss methods of assessing and implementing practices at increasing scales – assessing soil quality at a point scale, followed by two approaches toward integrating multiple issues of concern into a complete system within a field scale, and finally a national effort to assess the effectiveness of conservation practices at very large scales.

**REDUCING USE OR LOSS**

**Water**

*Rainfed culture.* On-site approaches to conservation of water include retention of rainfall by decreasing runoff and increasing infiltration in rainfed culture, and reducing irrigation water applications under irrigated culture. Under humid conditions, with appreciable rainfall during the growing season, these may both be accomplished, or at least attempted, simultaneously.

One can affect the water balance of a soil surface by affecting any of the terms of the soil water balance. The main terms include the change in storage per unit time, which is equal to the rainfall (plus irrigation if applicable) less runoff, drainage, evaporation, and plant uptake (Sadler and Turner 1993). Often, the rainfall less runoff is termed infiltration, management for which effectively increases the capture of rainfall. The primary means of reducing runoff and thereby increasing infiltration is to increase either plant material or residue on the surface (e.g., Langdale et al. 1979). These means are not at all new – they have been known for a long time. However, as measurement and monitoring technology have improved, we have learned much more about why certain effects occur. In particular, we have learned how dynamic the soil moisture term in this equation can be, and how these dynamics interact with the other terms to provide sometimes surprising results.

The mechanisms whereby material on the soil surface increases instantaneous or seasonal infiltration include reducing soil crusting, increasing surface storage, and reducing evaporation. A natural consequence of all these effects is increased soil moisture content. However, depending on the sequence and intensity of rainfall events, soil under residue can have much higher moisture content, which means that subsequent rainfalls can exceed the now smaller unfilled storage capacity, and thus have the unexpected effect of increasing the runoff from later rainfalls (Ghidey and Alberts 1998). A second effect of live material is the accumulated effect of different trends of plant water uptake and transpiration among plant species. For instance, plant water use for cool-season C-3 and warm-season C-4 grasses peak during their respective active growing seasons. In one study, Lin et al. (2005) observed less runoff from warm-season grasses than from cool-season grasses during the summer and the reverse during the fall. One caveat to these considerations is that saving water by increasing plant water use presumes that the water is best used by the plants, and that there is no other use planned for it. Irrespective of whether increasing infiltration by increasing plant water use can be considered conservation of water, reduction of runoff has definite conservation benefits regarding reducing loss of soil, nutrients, and pesticides. Another conservation effect results from the link between the water balance and salt. Sadler and Turner (1993) described the reduced water use that replacing deep-rooted native trees with grasses in southern Australia had on the water balance. Higher water tables caused salinization. Fortunately, efforts to reforest the area (and increase plant water use) are proving successful in reversing the trend.

*Irrigated culture.* Historical approaches to conserving water in irrigation practice have included reducing losses during conveyance of water from the source to the irrigated area, including canal leakage and evaporation, and pipe leakage. Later, high-pressure overhead impact sprinklers were converted to lower-pressure sprinklers and other emitters that had larger droplet size to reduce evaporation. More recently, microirrigation systems have been used to further reduce undesired irrigation losses. Surface plastic mulch or burying the microirrigation systems can further reduce evaporation, leaving more soil water available for plant water use (Camp 1998). The former also reduces capture of rainfall; the latter usually leaves it reasonably unchanged.
Since Jensen et al. (1970), various forms of computer-based irrigation scheduling have been proposed. Despite the possible advantages, producers have been slow to adopt them. Consequently, more emphasis in the last decade has been on increasing the user-friendliness and decreasing the time required to use these tools (Henggeler 2002). Irrigating to a managed soil water deficit leaves some soil water storage in case of rain, but this is a management-intensive approach.

A recent innovation in US paddy rice culture is multiple-inlet irrigation (Vories et al. 2005). With the conventional flooded production utilized in the US, water is released from the well or riser to fill the highest paddy, from which it then flows over spillways into lower paddies. As it is often very difficult to predict the duration of water flow required to fill the lowest paddy exactly, there is often runoff from the lowest paddy. With multiple-inlet irrigation, the water source is connected to a pipe, and gates are placed in the pipe for each paddy. In this way, each paddy is watered concurrently. By adjusting the gates, the operator can fill all paddies simultaneously.

On-farm water use studies in Arkansas (USA) during the 1999 through 2002 growing seasons compared multiple-inlet to conventional water requirements for rice on a production scale. During the four-year study period, comparison data were collected from 14 pairs of fields ranging in size from 12.5 ha to 32.4 ha, with soils ranging from sandy loam to clay. The multiple-inlet method required 24% less irrigation water than conventional flooding and produced 3% more yield, resulting in a 36% higher irrigation water use efficiency than conventional flooding (Vories et al. 2005). These findings can lead to easing the groundwater and surface water shortages being experienced in rice-producing areas of the US and could be applied in other rice-producing regions.

**Precision irrigation.** A special case of irrigated culture involves aspects of precision agriculture. However, the term precision irrigation predates site-specific agriculture. In the irrigation industry, it has meant a precise amount of water applied uniformly across the field at the correct time (Evans et al. 2000). In parallel with precision agriculture, precision irrigation now includes a spatially variable capability. To do this, conventional irrigation machines need to add variable-rate sprinklers, position determination, variable-rate water supply, and possibly variable-rate nutrient injection or pesticide application. Potential for water conservation includes not irrigating non-cropped areas, reducing irrigation amounts to adapt to specific problems, or fully optimizing the economic value of the water applied through irrigation (Sadler et al. 2005). Results from their case studies suggest the potential for water conservation using precision irrigation ranging from marginal to nearly 50% in single years, and averaging from 8% to 20%, depending on the previous irrigation management strategy used. Critical research needs include improved decision support systems and monitoring and feedback to irrigation control in real time.

When one programs zero irrigation amounts in non-cropped areas, the degree of conservation depends on the scope of the non-cropped area, but that can often be substantial. Further, there may be policy incentives or regulatory penalties to prevent irrigation of non-cropped areas. For instance, irrigation overspray onto roads causes public relations problems, and increases possibilities of accidents. The benefits of precision irrigation are higher if one injects nutrients or pesticides into the irrigation water, or if one spreads animal waste with the irrigation machine. Precision irrigation can also adapt to spatial variation in infiltration rate and in soil water storage capacity. These soil properties can be lower in one place than in the bulk of the field, which will likely cause runoff from that place, despite the machine being optimally designed for the bulk of the field. Runoff collecting within the irrigated area can create a pond, with anoxic conditions damaging the crop. Runoff leaving the field represents wasted water and off-field movement of sediment, nutrients, and pesticides.

Exactly how water could be conserved using precision irrigation is a topic for continued research. There are some benefits beyond water conservation, such as increased harvestable area, decreased disease, and in some cases, reduced risk of leaching. Examples shown suggest that practical and important opportunities exist for conservation of water.
Soil Erosion

Reducing erosion is one of the most-studied conservation goals and various means to achieve it are widely practiced. Many of these conservation practices have been shown to consistently reduce soil erosion (e.g., Langdale et al. 1979; Ghidey and Alberts 1998). In the US, they are practiced on substantial areas, with some 40% of planted area in some form of conservation tillage retaining more than 30% of the residue, and another 20% retaining something less than 30% (http://www.ctic.purdue.edu/ctic/CRM2004/1990-2004data.pdf, accessed 4/28/2005). For many years, erosion control has achieved significant, but not complete success. Some technologies have recently provided improvements in either practices or assessments of erosion control. Two examples include means to reduce erosion caused by flowing irrigation water, and research to document how much erosion has occurred since cultivation started.

Irrigation-induced erosion has been studied fairly extensively for furrow irrigation and one management option to reduce it involves injection of polyacrylamide (PAM) in the irrigation water (Aase et al. 1998; Bjorneberg and Aase 2000). PAM has also been shown to improve infiltration rates for soils (Lentz et al. 1992; Lentz and Sojka 1994). Therefore, PAM injections to reduce soil loss can, by increasing infiltration, also reduce nutrient or other soluble chemical loss. PAM has also been applied to bare soil in construction projects to reduce off-site transport of soil (Flanagan et al. 2002).

Quantifying erosion that has occurred before awareness of its magnitude is an elusive, but still desirable, goal. One approach compared a field cultivated for 150-200 years to topographically similar landscape areas that have been preserved in native grasses (Lerch et al. 2005). In the latter, they examined soil horizons in landscape positions to estimate the antecedent (pre-cultivation) topsoil depth, then assessed the difference using geographic information system (GIS) tools to estimate the effect of agriculture. Averaged over the whole field, they estimated 13 cm of soil moved off the field, which would be about 11.3 Mg/ha\(^{-1}\) per year\(^{-1}\), assuming 150 years of intensive agricultural practices.

Nutrient Use

Given the direct relationship between fertility and crop yield, much of the emphasis on reducing use of fertilizer has been to precisely match the amount applied to the crop needs. Often, the nutrient being managed has been N. In conventional whole-field practice, this emphasis was on matching seasonal totals (e.g., Vanotti and Bundy 1994), matching timing of application to the timing of crop need (e.g., Karlen et al. 1987), assaying the soil with a late-spring or pre-sidedress nitrate test (Meisinger 1984), or assaying the crop with some indicator of chlorophyll and thus N content (Varvel et al. 1997; Shanahan et al. 2003). This last practice, when applied in precision agriculture, allows real-time detection of crop need and variable-rate application to match it (e.g., Stone et al. 1996). Many of these are reviewed by Kitchen and Goulding (2001).

Pesticide Use

Growing public awareness of the unintended, lasting effects of many agricultural pesticides has caused much effort to be directed toward reducing the amounts applied, seeking safer chemicals, and integrating biological and other control methods. Within precision agriculture, limiting the area treated to the area affected appears to have the most potential to realize significant reductions. For pests that stay in the same place from year to year, such as some weeds, pre-season applications of soil residual herbicides can be applied according to the map obtained the prior year. For other pests, including mobile insects and many diseases, this approach is not useful. For these, some near-real-time method to detect presence of a pest and apply a control measure appears to have potential for significant savings. This is an outgrowth of historical scouting methods, but automation allows for a much finer resolution in both the detection and control. Selective spraying systems activated by a weed detection device have been reported to save up to 80% of pesticide (Hummel and Stoller 2002).

Ghidey et al. (2005) showed that timing of rainfall after application of surface residual herbicides often dominates the magnitude of
pesticide lost, making decisions about long-term trends difficult unless truly representative weather is included during the trend. They also showed that the incorporation of herbicides cuts pesticide loss by about 50%, which poses a paradox for sites with both erosion and pesticide issues. Extensive research and monitoring in the northeast Missouri (USA) region demonstrated two findings. First, voluntary adoption appeared to have the desired effect in reducing atrazine in surface supplies of drinking water. On the other hand, even careful, label-compliant application can result in appreciable off-site transport of atrazine, with the worst-case scenario having rain immediately after application.

The widespread cultivation of genetically modified crops has allowed weed control to change from soil residual herbicides to broad-spectrum contact herbicides, such as glyphosate, for which resistance has been inserted into food crops. These herbicides typically have shorter lifetimes in the environment than do most soil residual types (ARS Pesticide Properties Database: www.ars.usda.gov/services/docs.htm?docid=6433, accessed 4/29/2005). The full environmental effect of this conversion between approaches is not yet clear, nor is how long the specific chemicals will remain effective before weeds develop widespread resistance to them.

REDUCING TRANSPORT AND MITIGATING OFF-SITE IMPACTS

Reducing transport of soil, nutrients, and pesticides off agricultural lands hinges upon the reduction of the runoff that carries them. Consequently, any of the measures discussed above that reduce runoff will lessen the need for off-site mitigation of sediment, nutrients, or pesticides. Given that runoff cannot be eliminated, many mitigation approaches have been proposed and implemented. Some examples of new methods and information follow.

Sediment Transport

Historically, areas in fields with naturally concentrated flow have been converted to grassed waterways to reduce erosion within that area and to some extent, filter out sediment that enter it. In many locations, grassed or forested areas have been preserved or implemented as riparian buffers. While these methods are not new, how they work and how well they work represent new knowledge. For instance, different grass species function quite differently in buffers. Grasses that entrain in flowing water, such as tall fescue, lose effectiveness at lower flow rates than do stiff-stemmed grasses (e.g., Blanco-Canqui et al. 2004). Grasses that use more water maintain a lower soil moisture content and thus higher capacity for infiltration (Lin et al. 2003). The effects caused by tree species in buffers differ from those by grass species in them (Lin et al. 2005).

Nutrient Transport

Leaving the field with runoff is one way dissolved nutrients can be lost and have off-site impacts. Mitigation measures include those used for reducing sediments mentioned above. Another route for loss of dissolved nutrients is leaching. As discussed above regarding spatially variable infiltration rates and topography, water can collect into a pond within a field, or to ponds outside the cropped area. This extends the duration of drainage through the profile under the pond, and it concentrates the drainage into an area much smaller than the area of the field that was the source of the runoff. The nutrients previously applied to the area that becomes ponded are clearly vulnerable to loss, but nutrients from the source area for the water will probably migrate with the runoff and make the problem worse (Sadler et al. 2005).

New information has been obtained in the last few years regarding action and efficacy of buffers and other conservation practices for removal of nutrients. For example, Lin et al. (2005) found that differences in timing of growth between cool-season and warm-season grasses significantly affect timing of their ability to mitigate contaminant transport. Tile-drained fields, which have usually been managed to leave the field relatively dry from harvest to planting, lose most of their nitrate during the winter. Simply raising the water table during the late fall and winter (remembering to drain again before planting) keeps the nitrogen in place because it remains
in reduced forms. A similar physical situation exists in subsurface drains from parallel terraces. These drains have been used to convey water from terrace basins to the bottom of the field in a successful effort to reduce gully erosion. However, once in those drains, there is no further mitigation of nutrients or other contaminants. The Missouri (USA) Natural Resources Conservation Service is working to retrofit terrace drains to outlet in grassed waterways, or other grassed areas, or to flow through or bubble up in a constructed wetland (Ball 2004, personal communication).

**Pesticide Transport**

New information about pesticide fate and transport includes which soils are more vulnerable to loss, how runoff and application timing interact, how surface residue helps control erosion but increases pesticide loss, how effective buffers are in scrubbing pesticides, and how much of a parent compound manifests as a metabolite. Lerch and Blanchard (2003) showed that vulnerability to pesticide transport depends in large part on the fraction of a watershed that has low permeability soils, which may be used to help target implementation of conservation measures. Lin et al. (2003, 2005) reported how forages and buffers affected degradation and transport of two herbicides and suggested that enhanced degradation of herbicides deposited in grass buffers might augment off-site mitigation practices.

**ASSESSMENT AND IMPLEMENTATION**

**Soil Quality**

Soil is an important component of natural and human-influenced ecosystems and often requires maintenance or improvement to sustainably perform a multitude of functions. Management of soils to ensure properly functioning biological, chemical, and physical processes led to the concept of soil quality (sometimes “soil health”) as a guide for optimizing agricultural and conservation practices to mitigate soil degradation. A simple working definition of soil quality is “the sustained capacity of a specific soil for plant and animal productivity, water and air quality, and human health and habitation” (Karlen et al. 2003).

Soil quality is described by measurement of specific soil properties, known as indicators. Assessment of individual indicators can reveal a measure of performance or changes in performance of certain soil functions. The nature of the function under consideration drives the selection of soil properties for evaluation. Soil properties that may serve as indicators are grouped under three broad categories: 1) physical (bulk density, aggregate stability, etc.); 2) chemical (organic matter content, pH, etc.); and 3) biological (soil enzyme activity, microbial biomass, etc.). Final selection of indicators depends on several factors including land use and sensitivity of the measurement to changes in soil management (Nortcliff 2002). Selection of indicators for soil quality evaluation in regard to a given function (e.g., soybean productivity under rainfed conditions on a Mollisol) will comprise several attributes selected from each of the three categories and constitute a “minimum data set” (Doran and Parkin 1994).

Appropriate indicators for assessment of soil quality for soil conservation and land management include those that are useful and understandable to farmers and land managers. For example, soil organic matter (SOM) influences multiple functions (nutrient cycling, soil aggregation, microbial activity, etc.) and is critical for identification of the extent of soil degradation. Further, the positive or negative effects of management practices on SOM-related properties make it possible for farmers to readily identify practices that will improve or degrade soil quality over time (Wander and Drinkwater 2000). Other properties related to SOM that link soil quality to management include water-stable soil aggregation, soil enzyme activity, and microbial biomass (Jordan et al. 1995; Kremer and Li 2003). Because mycorrhizal hyphae associated with perennial plant roots in ecosystems under long-term vegetation (grasslands, riparian buffer areas, and woodlands) extend into the soil and form stable soil aggregates, mycorrhizae may be excellent soil quality indicators for assessing soil conservation functions (Rillig 2004). Also, the fungal metabolite, glomalin, which is directly involved in stable soil aggregate formation and is readily measured, can serve as an effective soil quality indicator.
Evaluation of soil quality is important because of the widespread awareness of the need to protect and preserve the soil resource. A clear understanding of soil functions, whether natural or user-oriented, is necessary for proper measurement and interpretation of soil quality indicators (Nortcliff 2002). Critical assessment of soil quality can lead to development and implementation of management strategies for improved soil properties in soil conservation and land restoration.

**Precision Agriculture Approaches to Conservation**

Two efforts to develop comprehensive precision agriculture-based conservation systems have been reported. Berry et al. (2005) describe a quantitative approach to assessing needs for spatial conservation measures, and Kitchen et al. (2005) describe the result of a consensus-based approach that evaluated spatial profitability, water, and soil quality for a research field.

The term “precision conservation” was coined by Berry et al. (2003). This includes a set of spatial technologies and procedures linked to mapped variables so that conservation management practices can be adapted to spatial and temporal variability across natural and agricultural systems. This includes integrating the spatial technologies of global positioning systems (GPS), remote sensing (RS), and GIS with three spatial analysis tools: surface modeling, spatial data mining, and map analysis. Following this definition, Berry et al. (2005) described how these spatial technologies could be used to implement precision soil and water conservation in agricultural and natural ecosystems. They also discussed the status of precision conservation as it was shown by 26 precision conservation papers presented at the “Precision Conservation in North America” symposium during the 2004 Soil Science Society of America annual meeting.

Berry et al. (2005) described two approaches for precision conservation. The first was a spatial assessment of erosion vulnerability within a field. It combined the slope at a point with the upslope catchment area contributing to that point to rank the probability of erosion into nine classes. Their second approach used that ranking to adapt the width of riparian buffers specifically to the likelihood of erosion along two streams. This is in contrast to the conventional practice of having a constant-width buffer. In their example, the buffer width reached farther into the field where there was higher risk of erosion or contaminant transport, and was narrower where there was low risk.

In the other example, Kitchen et al. (2005) described a consensus-based approach to implementing a precision agriculture system on a field that had 11 years of pre-implementation site-specific data collection. They assembled a group of researchers, producers, and industry and agency representatives to discuss conservation and production concerns, rank them by priority, and then choose a course of action. Their goal was to use site-specific management practices to simultaneously improve farming profitability and conserve soil and water resources. Their approach used a four-step process: 1) analyze the existing long-term information database and assess the yield-limiting factors and water and soil quality impairment of the historical cropping system on the field; 2) prioritize the most important production and conservation issues identified in the first step; 3) develop the precision agriculture system plan, aimed at addressing these top priorities; and 4) implement and evaluate how the system performs.

In Kitchen et al. (2005) and a companion investigation (Lerch et al. 2005), long-term monitoring on that field showed that: 1) historical (150+ years) topsoil erosion had degraded the soil on shoulder and side slope positions for much of the field, negatively affecting crop production and soil and water quality; 2) corn-soybean rotations have rarely been profitable where the topsoil is shallow; 3) the same places where topsoil had been most eroded were where soil quality was lowest; 4) contaminants (sediment, nutrients, and herbicides) in surface runoff were major water quality concerns, but leaching to groundwater was minor for herbicides; and 5) nitrate leaching to groundwater was most affected by preferential flow through soil fractures and by climatic factors. They used profit maps to help define three management zones for the field. These were used to normalize yields of different crops and to communicate in units...
useful for financial decision making ($US). As the experiment has just recently entered the post-implementation phase, it will be some time before results can be seen.

**Conservation Effects Assessment Project (CEAP)**

In the last few years, increasing pressure has been placed on conservation agencies to account for the effectiveness of their conservation practices. Currently in the USA and Canada, similar projects are being implemented to assess the value of the results obtained. In particular, measures such as numbers of farms enrolled or area of riparian buffers installed are being replaced by performance measures of the environmental benefit obtained from the practice. The US Department of Agriculture (USDA)-Natural Resource Conservation Service (NRCS) and the USDA-Agricultural Research Service (ARS) are jointly examining this in two approaches. NRCS is leading a US-wide assessment corresponding to their National Resource Inventory structure, and ARS is leading a watershed assessment at 12 of their long-term research watersheds. The collective project is named Conservation Effects Assessment Project (CEAP) (Mausbach and Dedrick 2004). Major objectives are to develop a database of watershed measurements in a consistent format for ease of use and availability, to measure relevant information that will be the foundation of the assessment, to calibrate/validate watershed-scale models to assist in the assessment, and to regionalize models so that appropriate tools can be used in various regions. Some 50 plus scientists, engineers, and hydrologists are working on this five-year project. CEAP is likely to change the way conservation programs are implemented in the future.

**CONCLUSIONS**

This overview of new technologies for soil and water conservation necessarily depended on the experiences of the authors, but nonetheless illustrated a broad range of new tools and knowledge that can be used to preserve the world’s soil and water resources. While many of today’s “new” technologies have been available for perhaps decades, our understanding of how these technologies function is the subject of ongoing research that will lead to more effective implementation.

**REFERENCES**


