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REVIEW

Research, Extension, and Good Farming Practices Improve Water Quality and Productivity

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Abstract

Agriculture in southeastern Oregon and southwestern Idaho known collectively as the Treasure Valley has depended on furrow irrigation using heavy inputs of water and nitrogen (N) fertilizer. Crop rotations include onion, corn, wheat, sugar beet, potato, bean, and other crops. By 1986 groundwater had become contaminated with nitrate and residues of the herbicide chlorthal-dimethyl (DCPA); an official groundwater management area was established by the Oregon Department of Environmental Quality along with an action plan and well monitoring network. The action plan allowed for a trial period to see whether voluntary changes would improve trends. Researchers, producers, and agencies cooperated to develop production options that had the possibility of being both environmentally protective and cost effective. Options were tested to improve irrigation practices, increase N fertilizer use efficiency on several rotation crops, and find a cost effective replacement for DCPA. Research demonstrated the opportunity for increased productivity through both irrigation scheduling and the adoption of drip and sprinkler systems. Fertilizer research demonstrated that smaller, more frequent N applications were more efficient than a single large application. Effective, lower cost herbicides replaced DCPA. Research results were effectively delivered through many means and voluntarily adopted. Both groundwater nitrate and DCPA residues are declining. Productivity has increased.

Key words: DCPA, drip irrigation, groundwater nitrate, irrigation management, irrigation scheduling, nutrient management, voluntary cooperation

INTRODUCTION

Good agricultural farm management can not only conserve scarce water resources, but can minimize agricultural contributions to sediment loss and water pollution. This paper discusses the changes in agriculture in Malheur County, USA, since 1980 which contribute to both conservation of water and diminished environmental effects off-farm.

Prior to the development of irrigation projects, agriculture in Malheur County was impossible due to arid conditions during the growing season. Agriculture was initially restricted to narrow strips where irrigation was feasible along rivers. Along rivers water could be diverted with water wheels or in-stream diversion structures. Irrigated agriculture expanded in Malheur County with the construction of dams and the resulting reservoirs in the early 1900s (Stene 1996; BOR 1997, 2011). Malheur County agriculture, like the vast majority of agriculture in the in-land west, is dependent on irrigation.

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CROPS

The crops that have been grown in Malheur County have changed with changing economic opportunities over the years. By 1944, the greatest number of hectares produced wild hay, sugar beets (*Beta vulgaris*), and potatoes (*Solanum tuberosum*) (Gregg 1950). By 1961, surveying methods had changed to those used today; Malheur County Extension estimates not only the areas of major crops but also the crop values.

Forage and cereal crops

Over the last 45 yr, alfalfa (*Medicago sativa*), other hay, and wheat (*Triticum aestivum*) have been grown on the most acreage in Malheur County. 85% of the alfalfa hay produced in the county is either fed to animals by the producer or sold for local animal consumption. The best quality alfalfa hay is normally utilized by dairies and the remainder is utilized as feeder hay. Rye (*Secale cereale*) and grass hay are consumed locally. Barley (*Hordeum vulgare*) and corn (*Zea mays*) are raised primarily as feed grains and are utilized locally by feed lots and dairies. Corn grown for silage is all fed locally, either by the grower or nearby neighbors. It contributes heavily to the nutrient requirements for local dairy cattle and feedlots (Schneider 1990).

Wheat is the major cereal crop. Soft white wheat is exported to world markets for quality pasta and pastries. In addition to serving as a cash crop, wheat is produced as a rotation crop with row crops in order to maintain soil with lower amounts of weeds and diseases of other cash crops. Over 90% of the wheat is raised on irrigated soil (Schneider 1990).

Row crops

Onions (*Allium cepa*), sugar beets, and potatoes have produced the greatest income per acre and have had a very large impact on the county economy in terms of jobs created by processing and handling in addition to the field production. Onions are generally considered the most important cash crop in Malheur County. All the onions are produced for the open market which can be quite volatile; the value of onions is based on the national and worldwide supply of onions and consumer demand. A large majority of the onions produced are Yellow Sweet Spanish. Some acreage is also planted to red and white onions. Most of the onions are stored either in growers' storages or packing shed storages to be sold at a later date. Onions are processed or packed locally and shipped by truck or rail (Schneider 1990). Onions are processed into frozen chopped onions or onion rings at factories in Ontario, Oregon, Fruitland, Idaho, and Weiser, Idaho. The area planted to onions has increased over the years compared to the other row crops (Fig. 1). The volatility of the onion market contributes to fluctuations in the amount of acreage planted.

Most of the potatoes in the county have been produced for processing under contract with Heinz Frozen Food Co., Ontario, Oregon and J. R. Simplot Co. Caldwell, Idaho. Contracts have continually become more stringent on quality. Potatoes are the most difficult crop to produce because of their sensitivity to heat stress which makes it imperative that excellent irrigation techniques be practiced (Schneider 1990). Potato acreage in the county has been declining due primarily to subsidies to producers and processors elsewhere.

Sugar beets are a traditional row crop that has been produced in Malheur County since the 1940s. All sugar beets are grown under contract with the Amalgamated Sugar Company, a grower owned cooperative. The beet company regulates the contracted area and subsequent production. Sugar beets have been a relatively

Fig. 1 Increase in the cultivated area of onion production in the Treasure Valley over the last 50 yr. Approximately half of the area is in Malheur County and the other half is in the adjoining counties in Idaho.

stable crop in terms of price and yield but the effect of recent trade agreements is as yet unknown (Schneider 1990). Acreage planted to sugar beets in Malheur County has been declining.

IRRIGATION, FERTILIZATION, AND PESTICIDE MANAGEMENT

After the Owyhee dam construction and before 1980

Most of the land that farmers settled was sagebrush steppe that had to be modified before it could be brought into production. The surface soils in the alluvial basins were saline and sat atop a hard layer of caliche. The caliche developed by calcium carbonate leaching from the surface soil into subsoil over thousands of years. After irrigation water from the Owyhee dam became available it was used to leach salt from the surface soil by building a berm around a field and flooding the field. In the 1940s, the Malheur Experiment Station discovered that deep plowing would break up the nearly impermeable caliche and mix it with the topsoil and salt, promoting salt leaching (Lovell 1980; Anon 1983).

Prior to the advent of modern herbicides, growers used the same land year after year for the same crop. Fields for crops which required excellent weed control were kept fairly weed seed free by frequent hand weeding. The onion yields and size would decline considerably with repeated years of planting onions in the same field since root disease organisms proliferated. Onions are sensitive to water deficits and were once thought of as being a high user of nitrogen fertilizer. Supplying the needed water and nitrogen resulted in nitrogen leaching into the vadose zone (the zone between the roots and above the ground water level) and eventually into the shallow aquifers.

After World War II, chemical fertilizer was readily available and inexpensive. More row crops were planted due to the increase in consumer demand and higher commodity prices of the strong economy following the war. Due to high demand and commodity prices, more farmers switched from cereal crops to row crops. Row crops were fertilized at higher nitrogen rates and these crops were more sensitive to water deficits.

Situation about 1980

Irrigation In 1980, irrigation in meadows and pastures was still dominated by surface flood irrigation from dirt ditches. Irrigation of crops was primarily by surface furrow irrigation from dirt and concrete ditches. Siphon tubes were used to deliver the water from the ditch to the irrigation furrows. Fields had been leveled, but not with laser leveling. Irrigation scheduling was based on the calendar and grower intuition and experience.

Soil preparation and DCPA use Soil was prepared in the fall after harvest and in the spring. Spring soil preparation tended to compact and dry the soil. Since efficient weed control through the adoption of herbicides was becoming established in the 1970s, these practices were already leading to fall bedding of the soil (conserving winter soil moisture and protecting the soil from physical damage when the soil was worked wet in the spring) and the adoption of environmentally sound crop rotations. Herbicides reduced weed competition, allowing crop rotations that included onions, sugar beets, wheat, corn, dry beans, potatoes, alfalfa forage, alfalfa seed, spearmint, peppermint, and other crops. Growers used a variety of crop rotations.

The herbicide DCPA (chlorthal-dimethyl; chemical name dimethyl-2,3,5,6-tetrachlorobenzene-1,4-dicarboxylic acid) was widely used in Malheur County by onion and alfalfa seed growers to control a wide spectrum of weeds. Several chemicals such as DCPA were applied at the full broadcast rate, 13 kg ha^{-1} broadcast to prepare the ground for planting. Ample labor was usually available to help conduct supplemental hand weeding.

By the mid 1980s, groundwater in northeastern Malheur County had become contaminated with the breakdown products of DCPA and with nitrate from the heavy use of nitrogen fertilizers (Bruch 1986).

Fertilization Prior to the 1980s, fertilization management decisions were based on perceived need of crops, not analytical chemical assessments of what nutrients were lacking. Farmers formulated their own special mixes of fertilizer. Soil analyses or follow-up testing of plant tissue samples from roots or petioles (the leaf stem that supports the blade of a leaf) were rare. Each grower had his own special blends of fertilizer for onion, potatoes, and sugar beets. Up through the early 1980s, it was common practice for farms to have their secret crop mix made up of 1 100-1 700 kg ha^{-1} of 16-16-16 for fall fertilizer. Fall fertilizer mixes containing 170-225 kg ha^{-1} of nitrogen were followed up in the spring with another 170-335 kg ha^{-1} of nitrogen sidedressed. Due to relatively high commodity prices and relatively low fertilizer prices, excess nitrogen was applied in the attempt to achieve maximum yields.

Fertilizer rates were determined by the growers' financial condition and yield aspirations, not based on carefully identified crop needs. Even the published fertilizer guides appeared to be based on assured yield maximization, with little thought as to the fate of excess nutrients, not yet a part of the public environmental mindset (Feibert *et al*. 1998; Shock *et al*. 1996, 2004).

Pesticides Prior to their being banned, growers used DDT, Aldrin, Endrin, and other similar products. These products have very long half lives, hence they decay slowly. Traces of the legacy pesticides can be found in runoff water and sediment.

Crop residues Crop residues from growing wheat and sweet corn and growing and processing sugar beets were largely recycled. Beet pulp was recycled into cattle feed. Manure from dairies was recycled onto farm lands as a fertilizer.

Alfalfa seed screenings, the by-product of processing alfalfa seed, were hauled to the landfills for burial due to environmental regulations against their traditional use as an animal feed supplement. Alfalfa seed screenings constituted 16% of local land fill volume in the 1980s. Potato processing waste was fed to cattle, but the residual sludge from processing was trucked to holding ponds where it was stored and accumulated. Cull onions were buried in shallow pits.

Challenges in 1980

By the end of the 1970s, environmental concerns for Malheur County indicated a need for irrigated agriculture to 1) reduce soil loss and nutrient loss from crop land, 2) improve irrigation efficiency, 3) reduce nutrients added to groundwater, 4) preserve soil structure, and 5) transform agricultural chemical use so that very low rates of agricultural chemicals would be required. Where chemical products were required, they needed to degrade quickly without effects off the farm. Irrigation-induced losses of phosphorus (P) and sediment were problems documented by a local citizen's committee (Malheur County Court 1981). In 1989, an official groundwater management area was established in northern Malheur County by the Oregon Department of Environmental Quality (ODEQ) culminating in an action plan (ODEQ 1991).

What types of changes might be needed to solve the environmental challenges of the 1980s. The reduction of soil and nutrient losses from crop land could be managed with additional field leveling, better irrigation management, and the adoption of more efficient irrigation systems. Increases in irrigation efficiency could facilitate reductions in irrigation-induced erosion and excessive nitrate leaching. Irrigation management should include better timing of water application to plant needs. Reexamination of fertilization practices was needed to redirect fertilization toward only satisfying plant nutrient needs and economical crop responses. Keeping sediment on the crop fields and water in the root zone of the crops would reduce the contaminate load leaving the field in both runoff and in losses to the ground water. Reduced and timely tillage could reduce the physical damage to the soil that was resulting from cultivation. Innovations in the development of integrated pest management and the use of short half-life agricultural chemicals could reduce the pesticide load carried off of farms.

Nitrogen management and irrigation management are closely linked, and trying to manage one without the other becomes self-defeating. In a semiarid environment with rare large precipitation events, nitrate usually only leaches when excess water is applied and conversely excess water can only leach large amounts of nitrate if substantial amounts of nitrate are available to be leached from the soil profile. The goal is to have just enough nitrogen available to maximize crop growth and just enough water in the soil profile to keep crop growth adequate without excess water carrying nutrients to greater depth. Both goals required irrigation innovation since reducing the application of excess nitrogen is hard with furrow irrigation systems. It is difficult to use furrow irrigation systems without substantial downward water movement and nitrate leaching. Nutrients are also washed off the field when large amounts of water move across the field with substantial force and remove soil from the field.

Changes since 1980

Major changes in agricultural practices have occurred over the last two and a half decades in Malheur County. Progress has been made in reducing groundwater contamination, reducing soil loss and nutrient loss in runoff, and improving water use efficiency. Research, education, and implementation funding was obtained to pursue long term environmental goals while respecting economic constraints faced by producers. These changes have been made through a cooperative process, led by the Malheur County Soil and Water Conservation District (SWCD). Agencies contributing to this cooperative endeavor included the Natural Resource Conservation Service (NRCS), the Farm Services Agency (FSA), the Oregon Watershed Enhancement Board (OWEB), Oregon Department of Agriculture (ODA), ODEQ, and the US Bureau of Reclamation (BOR). The Malheur Watershed Council, the Lower Willow Creek Working Group, and the Owyhee Watershed Council along with growers' associations, growers, and ranchers were instrumental in implementing the changes. The Malheur Agricultural Experiment Station (MES) and the Malheur Cooperative Extension Service of Oregon State University (OSU), and the Agricultural Department of Treasure Valley Community College provided research and dissemination of the results of the research.

A wide range of research, demonstration, and implementation efforts were planned and conducted to improve production efficiency and ameliorate environmental problems associated with conventional farming practices. With each initiative the potential benefits and extent to which a new practice would be adopted were unknown, as was how it would eventually modify crop production, product quality, or the ease of farming and ultimately economics.

Incentives to implement changes include both attitudes of stewardship and farming practices which result in decreased costs, improved productivity, improved crop quality, and the eligibility for cost share programs. Disincentives for change are practices which increase costs, reduce productivity, increase risk or uncertainty, require large capital outlays, or involve substantial red tape.

Furrow irrigation Wide arrays of practices were investigated to improve the efficiency of furrow irrigation and reduce irrigation-induced erosion.

Laser leveling Prior to the 1980s, fields had been leveled by conventional means. Fields were surveyed, staked, and soil was moved about within a field by farm tractor powered equipment. Fields with slopes of 0.6-0.7% or more required too much water to irrigate due to excessive runoff and resulted in too much soil erosion. Fields with slightly irregular slopes or flat spots would have parts which required long duration furrow irrigation resulting in other parts of the same field experiencing excessive water infiltration and the associated excessive deep leaching. Crop plants growing on steeper, drier spots were subject to yield and quality losses from water stress. Plants growing on flatter spots were subject to losses from ponded water and decomposition.

Dressing fields with laser leveling to a slope of 0.3-0.4% slope provided immediate benefits for surface irrigation. Herb Futter of the Soil Conservation Service (SCS, later to be the NRCS) was able to show less soil was lost from the field and the field irrigated much more uniformly. The uniformity of irrigation allowed for the conservation of water, less leaching in the wetter parts of the field, and improved crop performance. During the early 1980s, the Agricultural Stabilization Conservation Service (ASCS) would not fund laser leveling, but starting in the latter half of the 1980s, laser leveling was included in cost share practices based on Herb Futter's results.

From 1985 through 1999, approximately 1 820 ha of cropland in Malheur County were laser leveled through cost share programs, improving irrigation efficiencies. Efficiency increases of 15-20% have been obtained from leveling alone. The practice became widely accepted and adopted by growers to the point that the practice now seldom receives cost share incentives.

Straw mulch In the early 1980s, Malheur County growers Vernon Nakada and Joe Hobson were applying wheat straw mulch by hand to reduce irrigation-induced erosion. The process of using straw mulch in irrigation furrows is not a new concept. In fact, the hand mulching of onions and other various crops has been used for many years. Spreading the mulch by hand can be extremely expensive, so there was a need for another cost effective way to spread mulch.

Mechanical straw mulching is one method of reducing soil movement within the field and loss of sediment and nutrients off the field (Shock *et al.* 1997). Joe Hobson's mechanical mulcher made the spreading of mulch economically feasible for farmers. Several variations of his original idea are used in the Treasure Valley. Early mechanical mulching trials, starting in 1985, demonstrated its effectiveness in reducing erosion (Shock *et al*. 1988a) and improving sugar beet yields (Shock *et al*. 1988b). Mechanical straw mulching improved onion yield and market grade (Shock *et al*. 1999b) and provided a financial incentive to growers to adopt this practice (Shock *et al*. 1993a).

From 1985 to 1999, growers applied straw mulch to approximately 1 600 ha using cost share funds.

Gated pipe Gated pipe was introduced to allow more uniform irrigation of many surface irrigated fields. With gated pipe, the water flow in each furrow can be less than with siphon tubes. Gated pipe allows for surface irrigation with conservation of water, reduced irrigation induced erosion, and lower leaching potential.

Gated pipe was first used in a substantial way in Malheur County in 1977, a year of severe drought. The project was promoted by the SCS and was cost shared by the ASCS. The fiber glass pipe proved to have poor durability outdoors in the sunlight. More durable plastic gated pipe was introduced and supported by cost share programs. From 1985 to 1999 growers, converted the water delivery systems from siphons off open ditches to gated pipe on approximately 25 000 ha of cropland. Gated pipe decreased water use by 35-40%.

Weed screens With trash flowing in the water, gates in gated pipe have to be set to wider openings or larger siphon tubes have to be used to ensure that trash does not clog the gate or tube. With trashy water, more water has to be set on a field than is really necessary, hence more water is present than is required to irrigate the row. The extra water promotes irrigation induced erosion and excessive leaching of nitrates to groundwater. With cleaner water, gates and siphon tubes can be set with greater accuracy insuring that the furrow irrigation will continue to run as set without clogging.

Herb Futter of the SCS introduced weed screens to Malheur County to clean irrigation water. Several small weed screens were installed at the Malheur Experiment Station and were highly visible near other trials and helped show growers their advantages. Adoption of weed screens followed the 1985 Malheur Experiment Station field day when Herb Futter promoted the use of bubbler weed screens to remove weed seed and trash from irrigation water. Growers started building and installing weed screens on their own, with fabrication by local irrigation dealers. Especially noteworthy were the efforts of Dale Cruson in Ontario, who gave a big boost to screen adoption by manufacturing many of the screens.

In 1990, cost sharing was implemented to promote weed screens. By 1999, the practice had become wide spread enough that cost share incentives were only being used in large scale projects where the size of the weed screen might be cost prohibitive.

Polyacrylamide (PAM) to reduce irrigation-induced erosion PAM is a synthetic water-soluble polymer made from monomers of acrylamide. It binds soil particles to each other in the irrigated furrow. PAM is highly effective in reducing soil erosion off of fields and can increase water infiltration into irrigated furrows (Lentz *et al*. 1992; Trenkel *et al*. 1996). PAM was shown in experiments done at the Malheur Experiment Station to significantly reduce sediment loss, generally a 90-95% reduction. Increases in infiltration rates varied from 20-60%. PAM added to irrigation water in either liquid or granular form reduced sediment losses and increased water infiltration into the soil (Burton *et al.* 1996; Shock and Shock 1997). From 1990 to 1999, irrigation systems serving approximately 1 400 ha of cropland in Malheur County were treated with PAM via cost sharing. Use of PAM diminished both soil losses and concomitant nutrient losses to streams (Iida and Shock 2007a).

Sedimentation basins and pump back systems A sedimentation basin is a pond at the bottom of an irrigated field to catch water runoff. Water can be pumped back uphill to reuse in irrigation (Shock and Welch 2011b). Sediment in the pond can be dredged and added back to the fields it came from.

Some of the first sedimentation basins promoted by the SCS in Malheur County were designed as demonstration-education systems. They demonstrated to growers the dimensions of their irrigation-induced erosion problem. Many functional sedimentation basins with pump back features were built in the late 1980s and 1991 and 1992 with active participation of the SCS, ASCS, and SWCD. From 1990-1999, cost share assistance was provided for approximately 15 tail-water recovery sediment basin systems with water savings of 150 mm. Current sedimentation ponds with pump back systems reduce the diversion of irrigation water to furrow-irrigated fields by 1/3 (300 mm) and can eliminate or nearly eliminate sediment loss off farm (Shock and Welch 2011b).

Changes in irrigation systems

Sprinkler irrigation Prior to 1985, very little sprinkler irrigation was used on row crops in Malheur County. Research and demonstrations were conducted in 1987 and 1988 to compare the efficiency of sprinkler irrigation to surface irrigation and to determine the effectiveness of sprinkler irrigation in producing better quality potatoes. Water was used more efficiently and potato quality was improved through the use of sprinkler irrigation (Shock *et al*. 2007d). Solid set sprinkler systems are a means to cool the potato plant during hot weather and decrease water and nutrient loss from the plant's root zone. From 1990-1999, approximately 6 500 ha of cropland in Malheur County were converted from furrow irrigation to sprinkler irrigation through cost share programs.

Dick Tipton, a local Ontario, Oregon grower, spearheaded a large scale demonstration project on Morgan Avenue using gravity fed water to power sprinkler irrigation sponsored by the SCS, the SWCD and the FSA. Alfalfa, small grains, pasture, and sugar beets were successfully grown by the project. Other gravity pressured systems were built following Tipton's example. In 2002-2003, a gravity pressured system to power sprinkler irrigation was installed by the South Board of Control and cooperating growers south of Adrian. Large cooperative piping projects have recently been installed northeast of Mitchell Butte in the lower Owyhee subbasin and in lower Willow Creek, USA. The successes of these projects are due to the cooperation of many growers and partners.

Over the last 5 yr there has been a vigorous expansion of gravity fed sprinkler irrigation, especially by the Lower Willow Creek Working Group in concert with the Malheur Watershed Council with the support of OWEB, BOR, and others.

Drip irrigation Starting in 1992, drip, sprinkler, and furrow irrigations were compared for onion bulb production on fields in Malheur County that were difficult to irrigate (Feibert *et al*. 1995). Drip irrigation was very promising in terms of bulb yield, bulb quality, water use efficiency, and apparent nitrogen (N) fertilizer use efficiency. In 1993, the first Treasure Valley grower adopted drip irrigation for onion production. The success of these efforts prompted further research to optimize the irrigation criteria for drip-irrigated onions (Shock *et al*. 2000a), determine the duration of irrigation sets (Shock *et al*. 2005a), use ideal plant populations and N fertilizer rates with drip irrigation (Shock *et al*. 2004), and understand the timing of water stress that leads to the defect of internal bulb multiple centers (Shock *et al*. 2007a). Drip irrigation for onion in the Treasure Valley uses approximately 710-810 mm of water or about 60-65% as much as furrow irrigation with gated pipe.

Drip irrigation has been shown in Malheur County to combine the environmental advantages of less leaching of nutrients into the aquifer, less use of scarce water, and less nitrogen application with the financial advantages of higher onion yields and quality (Klauzer and Shock 2005; Shock *et al*. 2005c). The benefits to the growers mean that even though the concept of drip irrigation is relatively new in the region, by 2004 there were 700 ha of drip-irrigated onions in Malheur County and approximately 500 ha in adjoining areas of Idaho. The conversion to drip irrigation has vastly reduced N inputs with no irrigation-induced erosion and associated pollutant runoff. The drip irrigation techniques developed for onion in Malheur County have been rapidly adopted by onion growers in other parts of the country. By 2011, 42% of the onion acreage in Malheur County and the adjoining six counties of Idaho were produced using drip irrigation.

Research work on other crops in Malheur County supported by ODEQ, OWEB, US Forest Service, and the Bureau of Land Management has examined the use of drip irrigation for other crops. Potato research includes variety performance with drip irrigation (Eldredge *et al*. 2003), irrigation criteria for drip-irrigated potato, and potato plant populations and planting configurations under drip (Shock *et al*. 2002a, 2006a, b). Drip irrigation has been used effectively for poplar production (Shock *et al*. 2005b, 2009), alfalfa seed production (Shock *et al*. 2007b), and seed production of valuable native range plants for rangeland restoration (Shock *et al*. 2011).

Irrigation management

Irrigation scheduling consists of applying the right amount of water at the right time. Irrigating only when crops need water avoids both under- and over-irrigation. Crops highly sensitive to water stress, like potatoes, onions, and many vegetable crops, require precision irrigation scheduling determining both irrigation frequency and duration (Shock *et al*. 2006a, 2010).

Over-irrigation leads to a loss in water to runoff and subsurface aquifers and increases crop needs for nitrogen due to leaching. Nitrogen loss to groundwater and soil losses in terms of sediment in runoff are aggravated by over-irrigation. Under-irrigation of potato and onions leads to losses in yield and quality (Eldredge *et al*. 1992, 1996; Shock and Feibert 2002; Shock *et al*. 1993b, 1998b, 2000a, 2002a). Irrigating only when a crop needs water means that less water is used, less energy is used for pumping, less nitrogen is leached preventing additional groundwater pollution, and both crop yield and quality can be higher.

In 1984, irrigation scheduling in Malheur County was based exclusively on intuition and a calendar, specifically the number of days since the last irrigation. Although growers had tried to use tensiometers these meters were cumbersome. No instruments were used to measure soil moisture to assure that irrigations were applied at the right time for the plants.

Criteria for irrigation Soil water criteria for irrigating vary depending on the crop, the type of soil, and the type of irrigation (Shock *et al*. 2007c; Shock and Wang 2011). For Malheur County, the criteria for different crops' needs have been developed at the Malheur Experiment Station of Oregon State University (Eldredge *et al*. 1992, 1996; Shock and Feibert 2002; Shock *et al*. 1993b, 1998b, 2000a, 2002a, b, 2007c, 2010; Thompson *et al*. 2008).

Soil moisture monitoring devices When irrigation criteria based on soil moisture have been established, an easy, reliable method of measuring soil water is essential for grower adoption of this irrigation scheduling technique.

Studies were initiated comparing various soil moisture monitoring techniques. Tensiometers were compared with Watermark soil moisture sensors (GMS, Irrometer Co. Inc., Riverside, CA), neutron probes, gypsum blocks and gravimetric soil water content (Eldredge *et al*. 1993; Shock *et al*. 1998a). GMS were effective at measuring soil water tension (Eldredge *et al*. 1993; Shock *et al*. 1998a; Shock 2003; Shock and Wang 2011). Inexpensive data loggers to record soil moisture change over time made these sensors a valuable tool for scheduling irrigation (Pereira *et al*. 2008; Shock *et al*. 2005d, 2010).

Irrigation scheduling Starting in 1988, after the initiation of a successful research program at the Malheur Experiment Station, GMS soil water potential readings made in growers' fields were used to schedule irrigations. In the beginning, the potato extension specialist, Lynn Jensen (OSU), led the program. As the experimental trials went forward, Lynn Jensen started demonstrating the effectiveness of these scheduling practices on grower fields through funding from the US Department of Agriculture (USDA). This effort was later expanded by Ron Jones of the SWCD through funding from the Oregon DEQ. The program evolved to the point where 87 Malheur County potato fields were monitored in 1995 by the Soil Water Conservation District under the management of Ron Jones. The cost was paid for by the growers. Actual readings were made and graphed by student summer labor.

Eventually the Malheur County Potato Growers Association directed the program in conjunction with their potato integrated pest management program until the growers were familiar enough with the program to conduct irrigation scheduling on their own.

The advent of the Hansen Meter (A.M. Hansen Co., Wenatchee, WA) to read GMS installations eliminated the need for students to manually read and graph soil moisture since a series of GMS could be attached to the meter and could then be read and graphed three times per day. The process was simplified to the point that a grower could readily install the sensors and meter and track soil moisture with a minimum of training. Currently most soil moisture monitoring is being conducted by growers, especially those using drip irrigation, with the aid of Hansen Meters or Watermark Monitors (Irrometer Co. Inc.).

Synergy of onion drip irrigation and irrigation scheduling The combination of drip irrigation and irrigation scheduling for onion proved to be powerful in increasing onion yield (Fig. 2) and marketable yield (Fig. 3) in the Treasure Valley.

Crop evapotranspiration Crop evapotranspiration is a fancy word for the consumptive use of water. Consumptive water use is composed of evaporation of water off of the soil surface, transpiration of water through plant tissue to the air, and the small amount of water incorporated into a crop's tissues. Crop evapotranspiration is estimated using weather station data or an atmometer. Excellent estimates of crop water use can be provided by automated weather stations and local knowledge about when crops emerged, how quickly they developed, and when they matured.

In 1992, an AgriMet weather station (BOR) was installed at the Malheur Experiment Station to provide evapotranspiration measurements. The annual maintenance costs are paid by the agricultural experiment station. The data are especially useful for the management of sprinkler and drip irrigation. Growers in Malheur County who use crop evapotranspiration to schedule irrigation have local data on which the calculations are based. Written explanations are available on how to use evapotranspiration data to schedule irrigations (Shock *et al*. 2006a, 2010).

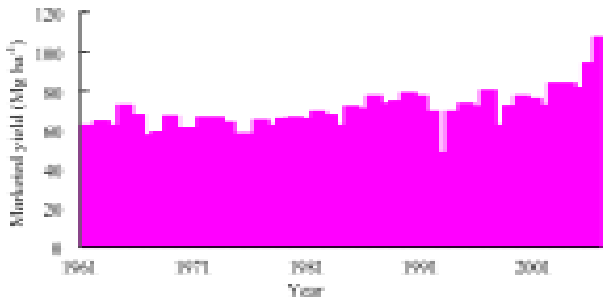

Fig. 2 Average marketable yield on onion per cultivated hectare in the Treasure Valley. Marketable yields have increased in recent years, due to the expansion of drip irrigation coupled with careful irrigation scheduling.

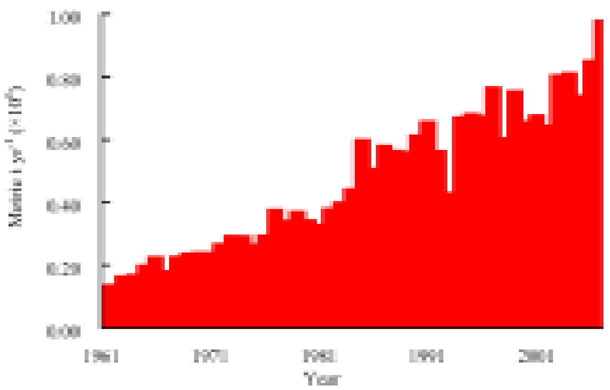

Fig. 3 Total annual onion yield marketed from the Treasure Valley of Oregon and Idaho.

Nutrition management

Changes to nitrogen fertilization management Nitrogen fertilizing practices have changed in Malheur County. Current practices are much more environmentally sound than traditional fertilization practices. These changes have come about due to the research and outreach/demonstration projects. The economics of fertilization and the cooperation of the local fertilizer dealers have played important roles in these changes. The improvements in nutrient management can be summarized as reducing the amount of nitrogen fertilizer used, budgeting the nitrogen to meet crop needs and to account for all sources of nitrogen, and utilizing deep-rooted crops planted in rotation with shallow-rooted crops (Stieber and Shock 1993; Shock *et al*. 1993c, 1996, 2000b). All of these improvements decrease the amount of nitrogen available for leaching into the groundwater and decrease the amount of nitrogen that a grower must purchase. These improvements have been made without damage to crop quality and productivity.

The amount of nitrogen fertilizer applied to a crop can be reduced through determination and utilization of optimal timing, placement, and rate of fertilizer. Budgeting nitrogen allows a better match to be made between the amounts needed to be applied during a year to the amount used by the crop while it is growing. To do this, the growers can incorporate soil testing results (how much nitrogen is already in the field from previous crops), plant tissue testing results (how much nitrogen the plant has taken up), and nitrogen mineralization (knowledge of how nitrogen will be freed by the soil during the summer and become available) into the budget. Growing deep-rooted crops (e.g., sugar beets and wheat) after onions and potatoes allows the deeper rooted crops to recover residual soil nitrate and mineralized nitrogen that the previous shallowly rooted crops did not use (Shock *et al*. 1993c, 1996, 2000b; Stieber and Shock 1993).

Much less N fertilizer is now applied in the fall than 30 yr ago. Fall nitrogen is more apt to be leached and interfere with crop seeding establishment. Soil samples are now commonly analyzed prior to any fertilizer application, and the amount of residual nitrogen in the soil as nitrate and ammonium is factored into the total amount of fertilizer to be applied to the next crop. Nitrogen applications are typically applied in the spring, with split applications starting in March and ending in July. After the plants reach a prescribed maturity, tissue samples are taken to see if more nutrients are needed for the plants to continue to be productive through full maturity. Routinely petiole samples are taken from potato (Jones and Painter 1974) and sugar beet plants, root samples are taken from onion, and less frequently, flag leaf samples are taken from wheat.

The Ontario Hydrologic Unit Area (HUA) Final Report indicated that traditional nitrogen application rates had been reduced by 1997 (Anon 1997). The report also explained that nitrogen was being applied more efficiently and at rates closer to plant needs. Since 1990, information and education activities targeting awareness of how much nitrogen is needed for crops as well as more efficient application methods have resulted in increases in practices such as soil and petiole tests, side dressing, banding, split applications, and converting from fall to spring nitrogen applications. The areas where nutrient management practices are being applied in cooperation with the SWCD and NRCS steadily increased throughout the 7-yr period of the HUA project from less than 2 000 ha in 1991 to over 18 000 ha by 1997, representing approximately 28% of the 63 500 ha in the HUA (Anon 1997, 1998). Many other areas had careful nutrient management based entirely on private initiative.

Crops grown in Malheur County without N fertilizer consistently obtained more residual and mineralized (RAM) N from the soil environment than predicted by soil tests (Shock *et al*. 1993c, 1996, 1998c, 2000b, 2004; Stieber and Shock 1993). Large amounts of RAM-N complicate fertilizer recommendations because it is difficult to predict the mineralized N and its timing. Since large RAM-N supplies can occur, crop responses to applications of N fertilizer may be small in many fields (Shock *et al*. 1993c, 1996, 1998d, 2000b, 2004; Feibert *et al*. 1998). Growers are adjusting N application rates downward (Table). Reducing N application rates can reduce crop production costs, increase profits, and reduce nitrate leaching.

Summary of N management practices Fertilizer and chemical application practices in Malheur County have changed significantly over the past 25 yr. Large amounts of fertilizer are no longer being applied to assure high yields without regard for plants' usage or the fate of excess fertilizer.

In the mid 1980s, more growers started soil sampling and tailored their fertilizer rates according to the soil sample recommendations. Following recommendations by the Malheur Experiment Station in 1990 to reduce nitrate leaching, growers cut down on the amount of fertilizer applied in the fall. In the spring, they put the rest of their fertilizer needs on by

Table N use efficiency of furrow- and drip-irrigated onion production for Malheur County, Oregon, and Idaho surveyed in February 2008, compared to a 1989 survey (Jensen and Simko 1991) and 1980 estimates

	Malheur County, 1980	Malheur County, 1987	Malheur County, 2008	Idaho, 2008
Furrow-irrigated				
Yield (Mg ha^{-1})	26.7	30.2	44.2	43.8
Total N applied (kg ha^{-1})	448	318	288	291
kg onions kg^{-1} N applied	120	190	307	301
Drip-irrigated				
Yield (Mg ha^{-1})			45.6	44.1
Total N applied (kg ha^{-1})			196	181
kg onions kg^{-1} N applied			485	486

sidedressing one to three times.

In the early 1990s, many farmers cut out most of the fall nitrogen except for the nitrogen required to break down crop stubble. The remainder of the fertilizer was often spoon fed over three sidedress applications determined by plant tissue sampling before each application.

Today, a few growers are experimenting with sampling the soil in one to two acre grids in the fall to determine what each acre's fertility needs are. GPS technology is then used to help variable fertilizer applicators apply only what the crop needs in each small acreage. Simplot Growers Services (Ontario, Oregon) and Western Laboratories (Parma, Idaho) are local leaders in precision fertilization.

Efficient use of soil nitrate and the other available N sources listed above depends on irrigation being roughly in balance with crop water needs so that nitrate leaching is minimal. The first furrow irrigation has great potential to leach nitrate because the loose soil and often dry subsoil has a high infiltration rate and water plus nitrate is carried beyond the reach of most of the roots of plants. Applying nitrogen after the first irrigation dramatically reduces the potential of leaching. This technique alone has allowed onion growers to reduce nitrogen applications by about 25% without reducing yield or quality. The goal of reducing nitrate movement to groundwater is being met by fertilizer management and the right amount of irrigation water applied at the right time.

Use of crop residues and animal waste

Organic agricultural wastes are recycled as fertilizers and soil conditioning agents. Potato and onion wastes from processing facilities were not utilized as fertilizer until recently. These materials are now being used in partial substitution for commercial fertilizers. Nitrogen release curves were developed for potato and onion sludge by local OSU extension and research (Jensen 1997, 1998; Shock 1997; Shock *et al*. 1998c, 1999a). Following testing by OSU MES and Oregon Trail Mushrooms (Vale, Oregon), alfalfa seed screenings were no longer hauled to the landfills but were being used as an ingredient in the compost used to grow mushrooms. Spent mushroom compost was no longer accumulating as waste but was utilized as a soil conditioner, largely for landscape purposes. Animal manures from confined animal feeding operations are being used extensively for their nutrients on crop and pasture lands, through well defined nutrient management plans.

Major initiatives by growers, ranchers, ODA, SWCD, NRCS, and others have resulted in the capture and reuse of most of the waste from confined animal feeding operations (CAFOs) in Malheur County. Many individuals and groups have help to reroute or pipe irrigation and drainage water to avoid water contamination in CAFOs.

Transformations in agricultural chemical use

Agricultural chemicals and their uses have changed in the entire Snake River Plain with our greater understanding of chemistry and the environment. From the inception of modern agriculture through the 1950s, little attention was paid to the persistence and unintended effects of pest control products. In recent decades the pesticide industry has been transformed by the adoption of products, including herbicides, with much narrower target species and short half lives so the products break down more quickly.

Onions are one of the most important irrigated crops in this valley. Onions compete poorly with weeds and efficient weed control is essential to maintain an economically viable onion industry. DCPA is an effective herbicide to control weeds in onion and alfalfa fields and was commonly used in the past.

DCPA was first registered as a pesticide in the US in 1958 as a selective preemergence herbicide for weed control on turf grasses. This herbicide is effective in other situations such as onion fields. When it was reregistered in 1988, the EPA concluded that "DCPA and its metabolites do not currently pose a significant cancer or chronic non-cancer risk from non-turf uses to the overall US population from exposure through contaminated drinking water". However, they also stated that DCPA "impurities have chronic toxicological properties (including oncogenic, teratogenic, fetotoxic, mutagenic or adverse effects on immune response in mammals) that are of particular concern in the reregistration of DCPA pesticide products" (Mountfort 1988).

DCPA metabolites, however, were found in shallow aquifers underlying parts of the intensively farmed areas of Malheur County, Oregon (Bruch 1986; Parsons and Witt 1988). Due to concerns about residues of DCPA and its metabolites in surface water and sediment runoff from furrow-irrigated crop land, as well as through deep percolation through the soil profile, MES conducted intensive studies to trace the fate of DCPA and DCPA metabolites' with both banding and broadcast DCPA application techniques (Shock *et al*. 1998e).

The method of herbicide application has a role in how much herbicide leaves the field. Under traditional furrow irrigation, banded applications were better. The quantities of DCPA and its metabolites in transported sediment was 33% less when banded than when broadcast. In surface water runoff, the difference was greater with 41% less of the herbicide lost from banded applications. For both application methods, straw mulch reduced DCPA and DCPA metabolite losses in transported sediment by about 90% from losses in traditional furrow irrigation. Straw mulch also reduced DCPA and its metabolite losses in surface water runoff by 30% for banded application and by 50% for broadcast application. The benefits of straw mulch were primarily achieved by reductions in soil erosion and volume of runoff water.

In the mid 1980s, farmers started banding all the post emergence chemicals on onions.

Even without a product to substitute for DCPA, it was possible to lower the amount of chemical loading by banding DCPA in a narrow band directly where the onions would grow, rather than broadcasting DCPA over the entire soil surface. Less DCPA was applied. The area of soil between the banded DCPA did not need the product because weeds were controlled there by cultivation. Growers were quick to adopt the banding of DCPA, because costs were reduced with no loss in weed control. By 1990, many growers using DCPA banding were saving two thirds of the DCPA expense (Jensen and Simko 1991).

Malheur Experiment Station studies concluded that omitting DCPA or banding DCPA during onion production immediately reduced the losses of DCPA residues through downward leaching or runoff. One objective of the Ontario HUA had been to reduce DCPA application by 30%. Surveys conducted by the Malheur Extension Service showed that this goal was easily met by the end of 1997.

Additional research at MES and "on farm" demonstrations by Lynn Jensen of OSU Cooperative Extension have shown that other herbicides with shorter half-lives could control weeds in onions on a wide range of fields at lower cost (Stanger and Ishida 1990; Stanger and Ishida 1993). The use of DCPA was no longer necessary. With the registration of pendimethalin (sold under the trade name of Prowl) in about 1993 or 1994, growers rapidly switched to pendimethalin because it was lower in cost, more effective, and did not have the undesirable environmental effects of DCPA. DCPA inventories in Malheur County were depleted by the 1998 growing season and DCPA is no longer applied.

IMPLEMENTATION OF NEW PRACTICES

Major changes in agricultural practices have occurred since groundwater contamination was identified in the Malheur River area in the late 1980s (Shock *et al*. 2001). The method of nitrogen application in this area has been changed. Reduced nitrogen loading has been accomplished by changes in the timing and the application of nitrogen as well as the rate of application. Plant tissue and soil sampling have also played a major role in modifying practices for the application of nitrogen and other nutrients, enabling producers to apply only the amount of nutrient needed and only when that nutrient is needed. Changes in irrigation management practices have also occurred that increase the protection of groundwater quality.

Many best management practices (BMPs) have been implemented in the Northern Malheur County Groundwater Management Area (GWMA) that are protective of groundwater quality. Some of this progress is documented in the Ontario Hydrologic Unit Area Final Report 1990-1997 (Anon 1997).

Extension brochures have been prepared to help growers effectively implement many of the newer BMPs. Oregon State University publishes extension brochures on the use of PAM, irrigation scheduling, drip irrigation, and other topics (Shock *et al.* 2005b, c, d, 2006a, b; Shock 2006; Iida and Shock 2007a, b; Shock and Welch 2011a, b, c).

Growers have made and are making many changes to conserve water. These changes will help cushion the effect on irrigated agriculture from drought years. These changes can not generate a reliable source of water for allocation to other uses.

PROGRESS ON WATER QUALITY

Water quality was measured over time by establishment of a well sampling network and well sampling protocols by ODEQ. Wells were sampled every 2 mon or less often as resources allowed. Analyses of nitrate and DCPA plus metabolites were conducted by ODEQ.

Nitrate trend analyses were conducted by Phil Richerson of ODEQ (Richerson 2010) using season and regional Kendal statistical methods (Helsel and Hirsch 1992; Helsel and Frans 2006; Helsel *et al*. 2006) and robust locally weighted regression and smoothing scatterplots (LOWESS) (Cleveland 1979). Groundwater nitrate trends are slowly but significantly negative (Fig. 4).

DCPA and its metabolites were not analyzed in the water on all water sampling dates. The reduced contamination is evident by graphing the concentration of two of the most contaminated sites over time (Fig. 5).

Progress on improving groundwater quality is being accomplished entirely through voluntary cooperative action. Irrigation, nutrient management, and groundwater contamination are inherently complex and spatially variable. At the start of the groundwater efforts, onion production, nitrate contamination, and DCPA contamination were shown to be closely linked (Bruch 1986). As onion acreage increased, onion productivity and N use efficiency rose, and groundwater quality has slowly improved. These improvements have only been possible through innovations in practices and the implementation of improved practices.

Uncertainty exists as to the effect of regulations. Since the water which growers use contains more nutrients and has a higher temperature than is allowed by the total maximum daily load (TMDL) to return to the Snake River, once this water is used on farms it will continue to exceed TMDL parameters for the Snake River. To reduce or eliminate water runoff from farm ground, vast capital investments in irrigation infrastructure will be required by the rules adopted by the Oregon

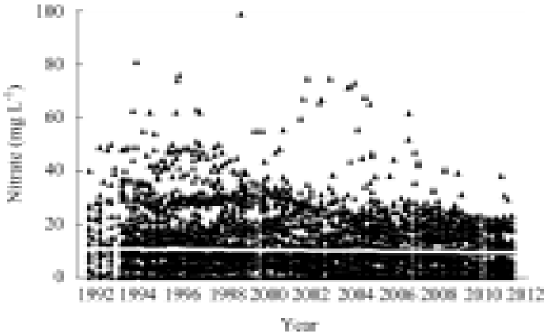

Fig. 4 Decline in the groundwater nitrate content over the last two decades in all of the wells in the northeast Malheur County Groundwater Management Area (Richerson 2010). The trend line is the regional Kendal test with slope of -0.07 mg yr^{-1} and 99% confidence.

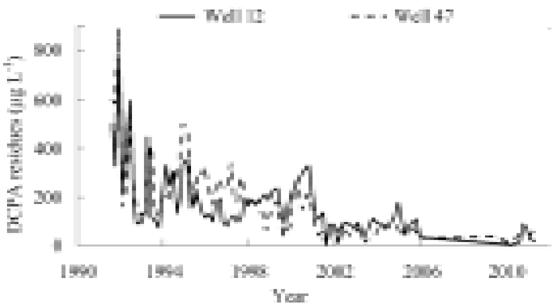

Fig. 5 Decline in the groundwater DCPA residue content over the last two decades in two of the most contaminated wells in the Northeast Malheur County Groundwater Management Area.

Department of Environmental Quality and the Environmental Protection Agency. It is not known whether the rules for agriculture that are being adopted by many governmental agencies will allow growers to operate on a "level playing field" in the global economy.

CONCLUSION

Cooperation between agencies and producers led to a wide range of research and demonstration projects aimed at pursuing long term environmental goals. As best management practices were developed, growers implemented those which improved production efficiency and respected the economic constraints faced by producers. Changes in farming practices have led to progress being made in reducing groundwater contamination, reducing soil and nutrient loss in runoff, and improving water and N use efficiency.

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