Practices to improve production while reducing groundwater contamination

Clinton C. Shock, Professor and Superintendent

Oregon State University Malheur Experiment Station, 595 Onion Ave., Ontario, OR, 97914 e-mail <clinton.shock@oregonstate,edu>

Candace B. Shock, Chair

Scientific Ecological Services, 1059 SW 2nd Ave. Ontario, OR, 97914

Philip M. Richerson

Oregon Department of Environmental Quality, 700 SE Emigrant Suite 330, Pendleton, OR, 97801

Abstract. ***Agriculture in southeastern Oregon and southwestern Idaho 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 1987 groundwater had become contaminated with nitrate and residues of the herbicide 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 of years to see whether voluntary changes would improve contamination trends. Researchers, producers, and agencies cooperated to develop production options that had the possibility of being both environmentally protective and cost effective. Options to improve irrigation practices, increase N fertilizer use efficiency on several rotation crops, and find a cost effective replacement for DCPA were tested. Irrigation research demonstrated the opportunity for increased productivity through both irrigation scheduling and adoption of drip and sprinkler systems. Fertilization research demonstrated that N applications were more efficient with better timing and in smaller increments. 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.***

Introduction

Development of Irrigated Agriculture

Prior to the development of irrigation projects, agriculture in Malheur County was impossible due to arid conditions during the growing season. Agriculture was restricted to narrow strips of irrigated land along rivers. Some water could be diverted with water wheels or in-stream diversion structures. With the construction of dams for reservoirs in the early 1900s, irrigated agriculture expanded in Malheur County (BOR, 1997; BOR, 2011; Stene, 1996).

Today agriculture in Malheur County uses up to date practices producing diversified products. Family owned farms use crop rotation practices that keep soil healthy and reduce disease and weed pressures. Growers associations cooperate to improve the yield and quality of the products and foster sustainable agricultural practices. Many by-products of agricultural processing are recycled into the local agricultural sector.

A. Importance of irrigation water

Malheur County agriculture is dependent on irrigation. Since most precipitation falls during the time of the year when freezing temperatures prohibit crop growth and the soil dries before dryland crops can set seed, having irrigation water available during the growing season is indispensable to the economic health of the county. This water comes from snow melt and spring rains captured and stored behind dams. Having water available during the growing season is essential to maintaining agriculture's economic contribution to the county.

Good agricultural farm management can not only conserve scarce water resources, but can minimize agricultural contributions to sediment loss and water pollution.

A. Crops

The crops that have been grown in Malheur county have changed with changing economic opportunities over the years. In 1935 when the county agricultural agent made a survey of crop yields, the record shows the number of farms growing a crop, not the number of acres planted. The largest number of farms grew some alfalfa, wheat, or red clover seed, followed by corn, potatoes, and barley. There was also some production of oats, alfalfa seed, apples, and prunes. By 1944 the greatest number of acres produced wild hay, sugar beets, and potatoes. Acreages for wheat, corn, and lettuce were less, followed by onions and celery (Gregg, 1950). In 1961 the way of surveying crops changed; Malheur County Extension now estimates acreage and values of the major crops.

1. Forage crops

Over the last 45 years, alfalfa, other hay, and wheat have been grown on the most acreage in Malheur County. Hay is grown not only with irrigation below the dam, but is the principal crop on irrigated acreage in areas of the lower Owyhee subbasin above the dam. Eighty-five percent 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. Grass and rye hay are consumed locally (Schneider, 1990).

About 40,000 irrigated acres are devoted to pasture production. The majority of pasture is produced on ground that is not well suited for intensive farming. The ground may either be too steep, the growing season too short due to elevation, or the soil is too shallow for annual cropping but it still is quite productive for producing feed. The majority of irrigated pasture is utilized by beef cattle with some also being produced for dairies as well as sheep operations. 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).

1. Cereal crops

Wheat is the major cereal crop produced. Soft white wheat is famous in world markets for quality pasta and pastries. In addition to serving as a cash crop, wheat is also produced as a rotation crop with row crops in order to maintain soil with lower amounts of weeds and diseases of the cash crops. Over 90% of the wheat is raised on irrigated soil. Barley and field corn are raised primarily as feed grains and are utilized locally by feed lots and dairies (Schneider, 1990).

1. Row crops

Onions, 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. Recently, Amalgamated Sugar, the only processor of sugar beets, closed the Nyssa factory, and beets are now trucked to Nampa, ID. After being purchased by Heinz Foods, the Ore-Ida factory in Ontario quit producing some lines of products which had utilized local crops (sweet corn and onions).

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. The county's overall economy is impacted quite heavily by the fluctuating onion market. 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. Some are shipped fresh. Onions are packed locally and shipped by truck or rail (Schneider, 1990). The number of acres of onions has tended to increase over the years compared to the other row crops (Figure 1). The volatility of the onion market contributes to fluctuations in the amount of acreage planted. Onions are also processed into frozen chopped onions or onion rings at factories in Ontario, Oregon, Fruitland, Idaho, and Weiser, Idaho.

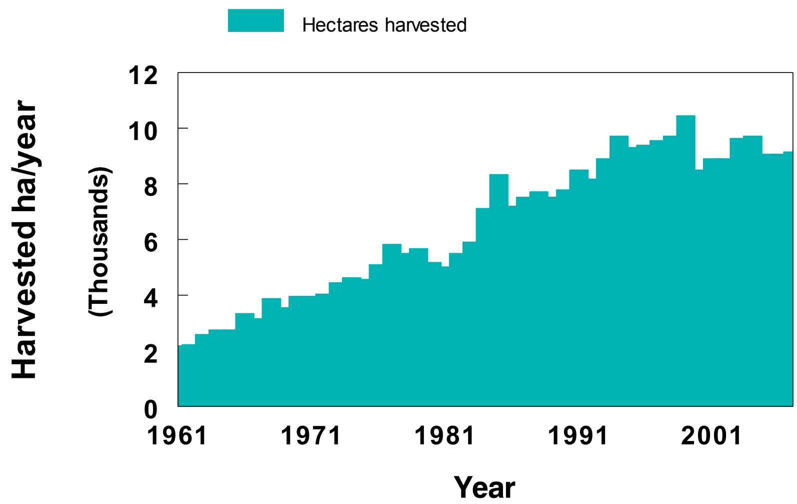

Figure 1. Increase in the cultivated area of onion production in the Treasure Valley over the last 50 years. Half of the area is in Malheur County and the other half is in the adjoining in Idaho.

Most of the potatoes in the county have been produced for processing under contract with Heinz and Simplot. 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. The beet company regulates the number of acres and subsequent production that can be produced based on the company's processing capacity and sugar market quotas. Sugar beets have been a relatively 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.

A. Irrigation, fertilization, and pesticide management

1. After the reservoir construction and before 1980

Most of the land that farmers settled had to be modified before it could be brought into production. The surface soil in the alluvial basins was very salty 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 dam became available it was first used to eliminate salt from the surface soil. A berm was built around a field and the field was flooded to leach the salt from the soil. 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 crops which required excellent weed control. Onions cannot compete well with weeds. Fields 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 a high user of nitrogen fertilizer and are sensitive to water deficits. Supplying the needed water and nitrogen probably caused nitrogen to leach into the vadose zone (the zone between the roots and above the ground water level) and into the shallow aquifers.

In early agriculture of the area, the only rotation crops used with onions were sugar beets and potatoes. Potatoes and sugar beets could also benefit from the dominance over weeds which had been established in the onion fields. High rates of nitrogen were also applied to sugar beets. Growers were paid by the ton, so growers disregarded the low percentage of sugar in highly fertilized beets and tried to achieve maximum tonnage per acre. Alfalfa, wheat or corn could have helped use up the excess or carry over nitrogen in the fields following row crops, but they were not used until the advent of effective herbicides which allowed growers to use most of the fields at their disposal in rotation with row crops.

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 created by the war effort and 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 management. Fewer cereal crops were grown because they were less profitable.

1. Situation about 1980

a. Irrigation

In 1980, irrigation in meadows and pastures was still dominated by surface flood irrigation from dirt ditches. Irrigation of crops was primarily 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.

Gated pipe, turbulent fountain weed screens, PAM, and straw mulch were not used. No soil moisture measurement tools or evapotranspiration estimates were used for irrigation scheduling.

b. Soil preparation and Dacthal 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 was becoming established through the adoption of herbicides in the 1970s, this innovation was 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 leading to the adoption of environmentally sound crop rotations. Crop rotations included onions, sugar beets, wheat, corn, dry beans, potatoes, alfalfa, alfalfa grown for seed, spearmint, peppermint, and other crops. Growers used many different crop rotations.

The herbicide Dacthal (DCPA) was widely used in Malheur County by onion and alfalfa seed growers to control a wide spectrum of weeds. Several chemicals such as Dacthal were applied at the full broadcast rate, 12 pounds per acre broadcast to prepare the ground for planting. Ample labor was usually available to help conduct supplemental hand weeding.

By the mid 1980's 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).

c. 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. Few soil analyses or follow-up plant tissue testing of root or petiole (the stem that supports the blade of a leaf) samples were taken. 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 1000 to 1500 pounds of 16-16-16 per acre for fall fertilizer. Fall fertilizer mixes containing 150 to 200 lb/acre of nitrogen were followed up in the spring with another 150 to 300 lb/acre of nitrogen sidedressed. Due to relatively high commodity prices and relatively low fertilizer prices, excess nitrogen was applied, trying to achieve maximum yields.

Two of the main reasons for fall applications were that the fertilizer was thought to act as a soil conditioner to help mellow the soil crust that builds up during the winter months and fall application helped avoid soil compaction from spring broadcast fertilizer application and other spring tractor work.

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 (Shock et al., 1996a,1996b, 1998c, 2004d; Feibert et al., 1998).

d. 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.

e. 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 percent 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.

2. Challenges in 1980

By the end of the 1970s, environmental concerns for irrigated agriculture in Malheur County included: 1) the reduction of soil loss and nutrient loss from crop land, 2) improvement in irrigation efficiency, 3) the reduction of nutrients added to groundwater, 4) preservation of soil structure, and 5) the transformation of 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 documented problems through the actions of a local citizen's committee (Malheur County Court, 1981).

Looking back we can see the types of changes which would solve the environmental challenges of the 1980s. The reduction of soil and nutrient losses from crop land would be managed with additional field leveling, better irrigation management, and the adoption of more efficient irrigation systems. Increases in irrigation efficiency would facilitate reductions in irrigation-induced erosion and excessive nitrate leaching. Irrigation management also would better time watering 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 would 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.

B. 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.

These changes have been made through a cooperative process led by the Malheur County Soil and Water Conservation District (SWCD), the Natural Resource Conservation Service (NRCS), the Farm Services Agency (FSA), the Malheur Watershed Council, the Lower Willow Creek Working Group, the Owyhee Watershed Council, and both the Malheur Agricultural Experiment Station (MES) and the Malheur Cooperative Extension Service (CES) of Oregon State University (OSU) with participation of growers' associations, growers, ranchers, other members of the community, and agency representatives. Research, education, and implementation funding was obtained to pursue long term environmental goals while respecting economic constraints faced by producers.

Agencies contributing to this cooperative endeavor included the Oregon Watershed Enhancement Board (OWEB), Oregon Department of Agriculture (ODA), Oregon Department of Environmental Quality (ODEQ), US Bureau of Reclamation (BOR), and the Agricultural Department of Treasure Valley Community College (TVCC).

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.

Incentives toward implementing change include 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.

1. Furrow irrigation

A wide array of practices were investigated to improve the efficiency of furrow irrigation and reduce irrigation-induced erosion.

a. Laser leveling

i. The challenge

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 to 0.7 or more feet per hundred feet 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 excessive water infiltration and associated with excessive deep leaching in other parts of the same field. 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.

ii. The changes

Dressing fields with laser leveling to a slope of 0.3 to 0.4 feet per hundred feet 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 4500 acres of cropland in Malheur County were laser leveled through cost share programs, improving irrigation efficiencies. Efficiency increases of 15 to 20 percent have been obtained from leveling alone. The practice became widely accepted by growers at their own initiative to the point that the practice now seldom receives cost share incentives.

b. Straw mulch

i. The challenge

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 on fields 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.

ii. The changes

One method of reducing soil movement within the field and loss of sediment and nutrients off the field is to use mechanical straw mulching techniques.[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 furrows that were compacted by tractor wheel traffic improved onion yield and size. The measurements made in onion fields showed that mechanical straw mulching had conservation benefits by reducing soil erosion and irrigation water runoff (Shock et al., 1993d, 1997). In addition, onion yield and market grade were improved, (Shock et al., 1999b) providing a financial incentive to growers to adopt this practice (Shock et al., 1993a).

From 1985 to 1999 growers applied straw mulch to approximately 4000 acres through cost share funds.

c. Gated pipe

Gated pipe was introduced to allow more uniform irrigation of many surface irrigated fields. The water set 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 60,000 acres of cropland. Gated pipe decreased water use by 35-40%.

d. 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. PAM use more than doubled in the following decade.

e. PAM to reduce irrigation-induced erosion

Polyacrylamide (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 percent reduction. Increases in infiltration rates varied from 20-60 percent. 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 3500 acres 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 (Nishihara and Shock, 2001; Iida and Shock, 2007a, 2009b).

f. 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 grower 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 (later the NRCS), ASCS, and SWCD. From 1990-1999 cost share assistance was provided for approximately 15 tail-water recovery sediment basin systems with water savings of 0.5 acre-foot of water per acre irrigated under each system. Current sedimentation ponds with pump back systems reduce irrigation water diversions to furrow-irrigated fields by 1/3 (1 acre-foot of water per acre) and can eliminate or nearly eliminate sediment loss off farm (Shock and Welch, 2011b).

2. Changes in irrigation systems

a. 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., 1989, 2007d). Solid set sprinkler systems are a means to cool the potato plant during hot weather and decrease water and nutrients loss from the plant's root zone. From 1990-1999 approximately 16,000 acres of cropland in Malheur County were converted from furrow irrigation to sprinkler irrigation through cost share programs.

Dick Tipton spearheaded a large scale demonstration project using gravity fed water to power sprinkler irrigation sponsored by the SCS, the SWCD and the Agricultural Research Service (ARS) on Morgan Avenue. 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. The successes of these projects are due to the cooperation of many growers and partners.

Over the last five years 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. Micro sprinklers have been used effectively in experiments (Shock et al., 2002c) and in growers fields for poplar production.

b. Drip irrigation

Starting in 1992, drip irrigation, sprinkler irrigation, and furrow irrigation were compared for onion bulb production on fields in Malheur County that were difficult to irrigate (Feibert et al., 1993, 1994, 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., 2004d) 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 uses approximately 28-32 acre-inches of water or about 60 to 65% as much as furrow irrigation with gated pipe (Shock et al., 2002b, 2004a, 2005).

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 (Shock et al., 2005c; Klauzer and Shock, 2005). The benefits to the growers mean that even though the concept of drip irrigation is relatively new in the region, by 2004 there were 1,800 acres of drip-irrigated onions in Malheur County and approximately 1,200 acres in adjoining areas of Idaho. These acres have vastly reduced N inputs and 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 percent 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 BLM has examined the use of drip irrigation for other crops. Potato 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, 2006b). Drip irrigation has been used effectively for poplar production (Shock et al., 2004c, 2005b), alfalfa seed production (Shock et al., 2003b, 2007b), and seed production from valuable native range plants for rangeland restoration (Shock et al., 2011).

3. Irrigation scheduling

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

Over-irrigation leads to a loss in water to runoff and subsurface aquifers and increases crop needs for nitrogen due to leaching. Nitrogen is lost to groundwater. Soil losses in terms of sediment in runoff are aggravated by over-irrigation. 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.

Under-irrigation of potato and onions may lead to losses in yield and quality (Eldredge et al., 1992, 1996; Shock and Feibert, 2002; Shock et al.,1993b, 1998b, 2000a, 2002a).

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.

a. 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). For Malheur County, the criteria for different crops have been developed at the Malheur Experiment Station of Oregon State University (Eldredge et al., 1992, 1996; Shock, 2003; Shock and Feibert, 2002; Shock et al., 1993b, 1998b, 2000a, 2002a, 2002c., 2007c, 2010; Shock and Wang, 2011; Thompson et al., 2008).

b. 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.

Watermark soil moisture sensors (GMS) Model 200 were introduced at the Malheur Experiment Station in 1986. Studies were initiated comparing various soil moisture monitoring techniques. Tensiometers were compared with Watermark soil moisture sensors, neutron probes, gypsum blocks and gravimetric soil water content (Eldredge et al., 1993; Shock, 1998; Shock et al., 1998a). New innovative GMS designs (models 200SS and 200SSXX) were evaluated at the Malheur Experiment Station (Shock, 2003). In 2001 and 2002 GMS model 200SS was compared to AquaFlex, Gopher, Gro-Point sensors, Measure-Point, Tensiometers, Neutron Probe and gravimetric soil moisture calculations (Shock et al., 2003a). GMS were effective at measuring soil water tension (Eldredge et al., 1993; Shock, 2003; Shock et al., 1998a; Shock and Wang, 2011). Meters to read the GMS data or log soil moisture change over time make these sensors a valuable tool for scheduling irrigation (Shock et al., 2005d).

Some of the growers in Malheur County have adopted GMS and automated data loggers to record soil water conditions and frequently use them in drip irrigated onions

(Shock et al., 2005d, 2010). Lower cost logging of GMS sensor readings has been accomplished by numerous companies. These systems have proven to be effective and reasonably easy for growers to use (Shock et al., 2004b; Pereira et al., 2008).

c. 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, lead 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 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.

d. Synergy of onion drip irrigation and irrigation scheduling

The combination of drip irrigation and irrigations scheduling for onion proved to be a powerful combination to increase onion yield (Figure 2) and marketable yield (Figure 3) in both Malheur County and the adjoining areas of Idaho, known collectively as the Treasure Valley.

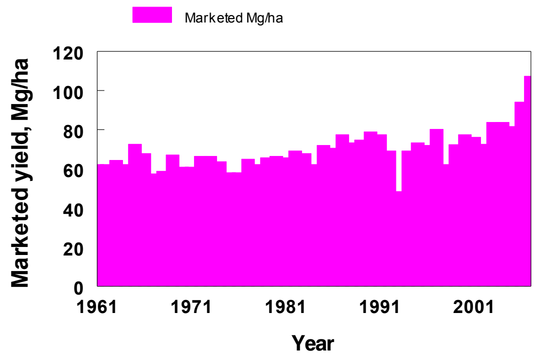

Figure 2. Average marketable yield on onion per cultivated hectare in the Treasure Valley. Marketable yields have increased in recent years, due to the expansion of drip irrigation coupled with careful irrigation scheduling.

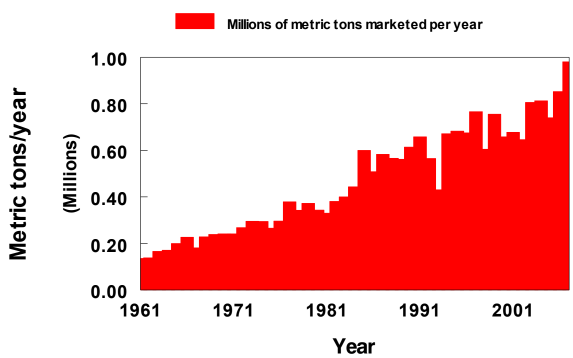

Figure 3. Total annual onion yield marketed from the Treasure Valley of Oregon and Idaho.

e. 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 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, 2007; Shock et al., 2006a**).**

1. Nutrition management

a. 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 completed by the OSU Malheur Experiment Station, the OSU Cooperative Extension Service, SWCD, NRCS, the Malheur Watershed Council, the Owyhee Watershed Council, United States Department of Agriculture programs such as Environmental Quality Improvement Program administered by the Farm Service Agency and NRCS, and others. The economics of fertilization and the cooperation of the local fertilizer dealers have played important roles in these changes. These changes occurred through cooperative financial and educational help from many partners. Some of those partners include United States Environmental Protection Agency (EPA), ODEQ, CES, MES, ODA, SWCD, FSA, NRCS, TVCC Agriculture Department, the watershed councils, and the local fertilizer dealers.

The improvements in nutrient management can be summarized as reducing the amount of nitrogen fertilizer used, budgeting the nitrogen to meet crop needs and account for all sources of nitrogen, and utilizing deep-rooted crops planted in rotation with shallow-rooted crops (Shock et al., 1993c, 1996a, 1998c; Stieber and Shock, 1993). 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 amount 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, 1998c, 2000b; Stieber and Shock, 1993).

Much less N fertilizer is now applied in the fall than 30 years 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 dramatic increases in practices such as soil testing, petiole testing, side dressing, banding, split applications, and converting from fall to spring nitrogen applications. Field acres where nutrient management practices are being applied in cooperation with the SWCD and NRCS steadily increased throughout the seven-year period of the HUA project from less than 5,000 in 1991 to over 44,000 acres by 1997, representing approximately 28% of the 157,000 acres in the HUA (Anon., 1997; Anon. 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, 1996a, 1998c, 2000b, 2004d; 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, 1996b, 1998c, 2000b, 2004d; Feibert et al., 1998). Growers are adjusting N application rates downward (Table 1). Reducing N application rates can reduce crop production costs, increase profits, and reduce nitrate leaching.

Table 1. N use efficiency of furrow- and drip-irrigated onion production for Malheur County, Oregon, and Idaho surveyed February 2008, compared to a 1989 survey and 1980 estimates.

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

b. Summary of N management practices

Fertilizer and chemical application practices in Malheur County have changed significantly over the past 25 years. 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 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 may be sampled 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 each small acreage needs. 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 ground water nitrate addition is being met by fertilizer management and the right amount of irrigation water applied at the right time.

1. 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 land fills 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 avid water contamination in CAFOs.

2. 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 (sold as Dacthal) is an effective herbicide to control weeds in onion fields and was commonly used in the past. DCPA metabolites, however, have been found in shallow aquifers underlying parts of the intensively farmed areas of Malheur County, Oregon (Bruch, 1986,Parsons and Witt, 1988). This product is not known to be in current usage.

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).

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 is no longer applied.

B. 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, on irrigation scheduling, and on drip irrigation (Shock, 2006; Shock et al.,2005b, 2005c, 2005d, 2006a., 2006b; Iida and Shock, 2007a, 2007b, 2009a, 2009b; Shock and Welch, 2011a, 2011b, 2011c).

Some challenges continue. Growers use many different crop rotations. Crop rotations with onions every third year tend to degrade the field with infestations of yellow nutsedge, compared with longer crop rotations.

C. 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 months 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 (Figure 4).

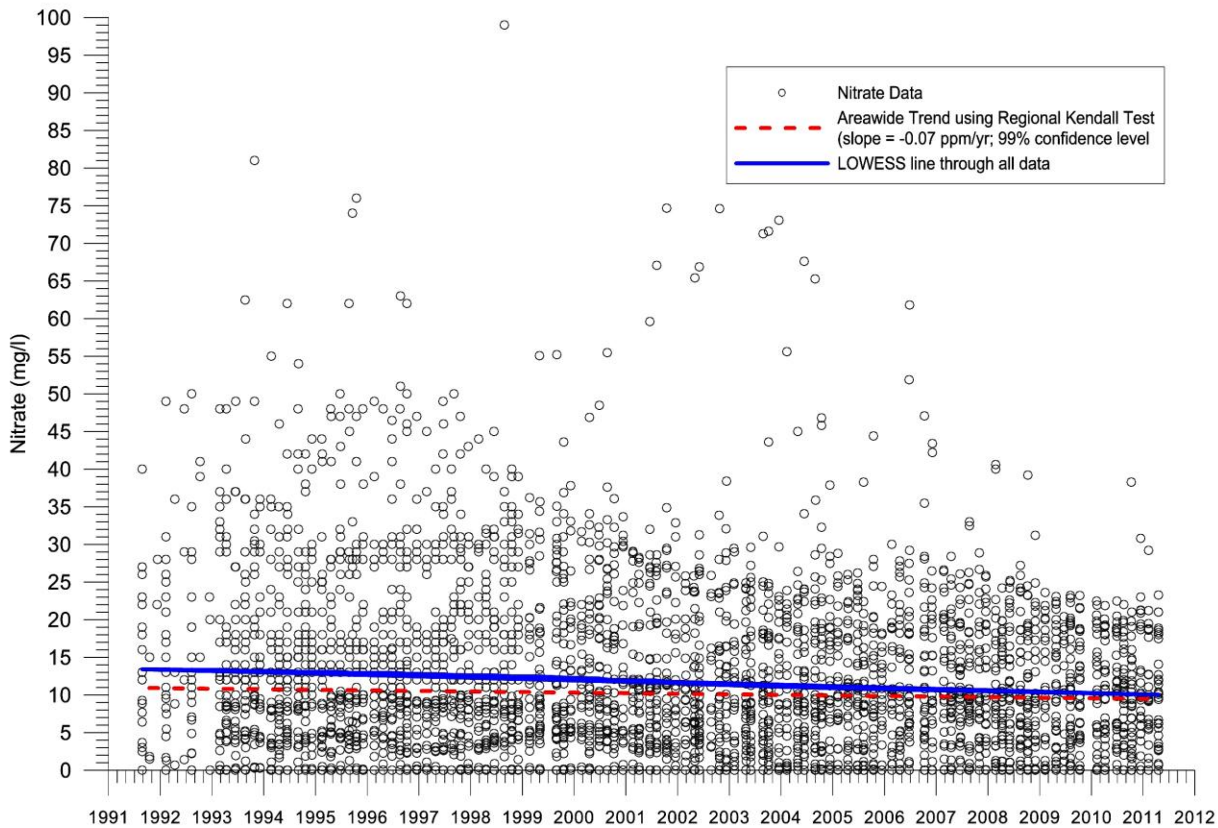

Figure 4. Decline in the groundwater nitrate content over the last two decades in all of the wells in the northeast Malheur County Groundwater Management Area (Richerson, 2010).

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

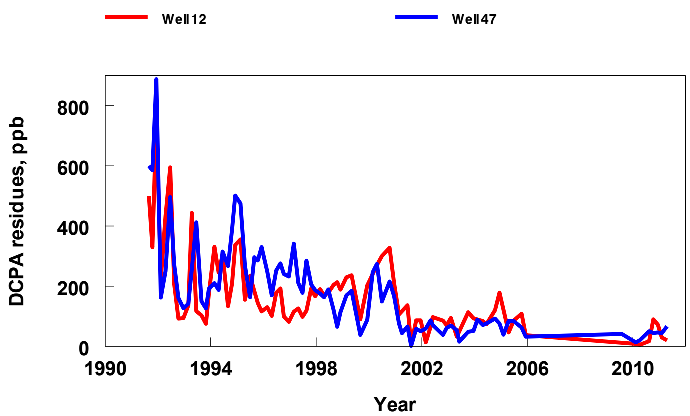

Figure 5. Decline in the groundwater DCPA residue content over the last two decades in two of the most contaminated wells in the northeast Malheur County Groundwater Management Area.

Progress on improving groundwater quality was 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.

D. Future uncertainties

1. Water availability and competition for water

Water is the grower's second most important resource after the land itself. Some years there is a serious irrigation water shortage due to nature's unpredictable ways. However, the growers also face increasing pressure to restrict their water use so that the water can be redirected to other purposes.

With the current power crises, there may be more and more pressure applied to use the water for power generation. Increased demands for water in the cities of the deserts of Nevada may place pressure upstream to divert water from the upper reaches of the Owyhee to uses in Nevada. There may be pressure to release irrigation water from storage for endangered species such as salmon.

A Bureau of Reclamation study concluded that "based on the historical period of record (1939-1992), the Owyhee River basin above Owyhee Reservoir would yield no additional water for storage in over 50 percent of the years."[4] Although the study was conducted to see if increased storage in Owyhee Reservoir would be a potential source of water for flow augmentation in the lower Snake River for salmon, the conclusion that extra "water would be available . . . only in good water years,"[4] means that any allocation for other purposes would remove water from that available to irrigated agriculture in the lower Owyhee subbasin and other areas benefiting from this irrigation water. In the last two years Idaho and Nevada have allocated more water upstream of the Treasure Valley in the Owyhee subbasin for additional irrigation use.

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. Any allocation for other purposes would be detrimental to the health of irrigated agriculture in Malheur County.

1. Population growth

Reallocation of land in Malheur County to residential and industrial purposes will have a concomitant reallocation of water away from agriculture.

1. 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 run off from farm ground, vast capital investments in irrigation infrastructure will be required by the rules adopted by the Oregon 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 in a “level playing field” in the global economy.

Acknowledgments

The development of this discussion was aided by previous writing of the Lower Owyhee Watershed Assessment for the Owyhee Watershed Council with support from the Oregon Watershed Enhancement Board (Shock, C.B. et al., 2007)

References

Anon. 1983. Water-Related Technologies for Sustainable Agriculture in U.S. Arid/Semiarid Lands. (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-F-2I2, October 1983).

Anon. 1997. Ontario HUA Final Report 1990-1997. Malheur County SWCD and NRCS. Ontario, OR.

Anon. 1998. Malheur County Soil and Conversation District Annual Report and Financial Statements.

Bruch, G. 1986. Pesticide and nitrate contamination of ground water near Ontario, Oregon. Impacts on Groundwater Conference, Proc. Am. Water Well Assn. 11-13 Aug. 1986. Omaha, NE.

Bureau or Reclamation. 1997. *Owyhee Project Storage Optimization Study Oregon*: Information Report. United States Department of the Interior, Bureau or Reclamation, Boise, Idaho.

Bureau of Reclamation. 2011. Owyhee project. Available at http://www.usbr.gov/projects/Project.jsp?proj_Name=Owyhee+Project (verified 21 Sept. 2011).

Burton, D., J. Trenkel, and C. C. Shock. 1996. Effects of Polyacrylamide Application Method on Soil Erosion and Water Infiltration. OSU, Malheur Experiment Station Special Report 964: 186-191.

Cleveland, W.S. 1979. Robust Locally Weighted Regression and Smoothing Scatterplots: J. Am. Stat. Assoc. 74, 829-836.

Eldredge, E.P., C.C. Shock, and L.D. Saunders. 2003. Early and late harvest potato cultivar response to drip irrigation. In Yada, R.Y. (eds) *Potatoes - Healthy Food for Humanity*. Acta Horticulturae. 619:233-239.

Eldredge, E.P., C.C. Shock, and T.D. Stieber. 1992. Plot sprinklers for irrigation research. Agron. J. 84:1081-1984.

Eldredge, E. P., C. C. Shock and T.D. Stieber. 1993. Calibration of Granular Matrix Sensors for Irrigation Management. *Agronomy* 85:1228-1232.

Eldredge, E.P., Z.A. Holmes, A.R. Mosley, C.C. Shock, and T.D. Stieber. 1996. Effects of transitory water stress on potato tuber stem-end reducing sugar and fry color. *Am Potato J.* 73:517-530.

Feibert, E.B.G., C.C. Shock, and L.D. Saunders. 1993. A preliminary comparison of sprinkler, subsurface drip and furrow irrigation of onions. Oregon State University Agricultural Experiment Station, Special Report 924. pp. 62-70.

Feibert, E.B.G., C.C. Shock, and M. Saunders. 1994. A comparison of sprinkler, subsurface drip, and furrow irrigation of onions. Oregon State University Agricultural Experiment Station, Special Report 936. pp. 27-35.

Feibert, E.B.G., C.C. Shock, and L.D. Saunders. 1995. A comparison of sprinkler, subsurface drip, and furrow irrigation of onions. Oregon State University Agricultural Experiment Station, Special Report 947. pp. 59-67.

Feibert, E.B.G., C.C. Shock and L.D. Saunders. 1998. Nitrogen fertilizer requirements of potatoes using carefully scheduled sprinkler irrigation. HortSci. 32:262-265.

Gregg, Jacob Ray. 1950. *Pioneer Days in Malheur County*. Lorrin L. Morrison, Los Angeles.

Helsel, D.R., and L.M. Frans. 2006. Regional Kendall Test For Trend, Environmental Science & Technology, Vol. 40, No. 13, pg 4066-4073.

Helsel, D.R. and R.M. Hirsch, 1992. Statistical Methods in Water Resources. Studies in Environmental Science 49, Elsevier Science B.V. Amsterdam. 529 pgs.

Helsel, D.R., Mueller, D.K., and Slack, J.R. 2006. Computer Program for the Kendall Family of Trend Tests. U.S. Geological Survey Scientific Investigations Report 2005-5275, 4 p.

Iida, C.L. and C.C. Shock. 2007a. Make polyacrylamide work for you! Sustainable Agriculture Techniques. Oregon State University Extension Service, Corvallis. 6p.

Iida, C.L. and C.C. Shock. 2007b. The phosphorus dilemma: Sustainable Agriculture Techniques. Oregon State University Extension Service, Corvallis. 4p.

Iida, C.L. and C.C. Shock. 2009a. El dilema del fósforo. Tecnicas para la agricultura sostenible, Oregon State University Extensión Service, EM 8939-S-E http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/20521/em8939-s-e.pdf

Iida, C.L. and C.C. Shock. 2009b. La poliacrilamida: Una solución para la erosión. Tecnicas para la agricultura sostenible, Oregon State University Extensión Service, EM 8958-S-E • enero de 2009. http://extension.oregonstate.edu/catalog/pdf/em/em8958-s-e.pdf

Jensen, L. 1997. Nitrogen mineralization from potato sludge. Oregon State University Agricultural Experiment Station, Special Report 978:68-70.

Jensen, L. 1998. Nitrogen mineralization from potato sludge and onion sludge. Oregon State University Agricultural Experiment Station, Special Report 988:29-31.

Jensen, L. and B. Simko. 1991. Malheur County crop survey of nitrogen and water use practices. Oregon State University Agricultural Experiment Station, Special Report 882, pp. 187-198. Malheur Experiment Station. Ontario, OR.

Jones, J.P. and C.G. Painter. 1974. Tissue analysis: A guide to nitrogen fertilization of Idaho Russet Burbank Potatoes. University of Idaho, College of Agriculture, Cooperative Extension Service, Agricultural Experiment Station, Current information series # 240, June 1974.

Klauzer, J. and C.C. Shock. 2005. Growers use less nitrogen fertilizer on drip-irrigated onion than furrow-irrigated onion. p 94-96. Oregon State University Agricultural Experiment Station, Special Report 1062.

Lentz, R.D., I. Shainberg, R.E. Sojka and D.L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. *Soil Sci. Soc. Am. J.* 56:1926-1932.

Lovell, B.B. 1980. Soil survey report of Malheur County Oregon, Northeastern Part. September 1980. Soil Conservation Service, United States Department of Agriculture, Soil Conservation Service, in cooperation with the Oregon Agricultural Experiment Station.

Malheur County Court. 1981. Two-Year Sampling Program, Malheur County Water Quality Management Plan. Malheur County Planning Office, Vale, Oregon.

Mountfort, R.F. 1988. DCPA (Dacthal) Herbicide Profile 6/88. Office of Pesticide Programs. Environmental Protection Agency. Available at http://pmep.cce.cornell.edu/profiles/herb-growthreg/dalapon-ethephon/dcpa/herb-prof-dcpa.html (verified 10 Aug. 2007).

Nishihara, A. and C.C. Shock. 2001. Benefits and Costs of Applying Polyacrylamide (PAM) in Irrigated Furrows. Available at http://www.cropinfo.net/bestpractices/bmppamreport.html (verified 21 Sept. 2011).

Parsons, D.W., and J.M. Witt. 1988. *Pesticides in groundwater in the United States of America*. A report of a 1988 survey of state lead agencies. pp. 12, 17-18.

Pereira, A. B., C.C. Shock, . B. G. Feibert, and N. A. V. Nova. 2008. Performance of "Irrigas" for onion irrigation scheduling compared to three soil water sensors. Engenharia Rural. 18:109-114.

Richerson, P.M. 2010. Third Northern Malheur County Groundwater Management Area nitrate trend analysis report. Oregon Department of Environmental Quality.

Schneider, G. 1990. Malheur County Agriculture. Oregon State University Extension Service. Malheur County office.

Shock, C.B., M.P. Shock, and C.C. Shock. 2007. Lower Owyhee Watershed Assessment. Prepared for the Owyhee Watershed Council, prepared by Scientific Ecological Services.

Shock, C.C. 1997. Application of onion sludge as a fertilizer supplement. Oregon State University Agricultural Experiment Station, Special Report 978:50-53.

Shock, C.C. 1998. Instrumentos para determinação da humidade do solo. Simpósio de Energia, Automação e Instrumação. XXVII Congresso Brasileiro de Engenharia Agricola, Poços de Caldas, MG, Brasil. pp 137-149.

Shock, C.C. 2003. Soil water potential measurement by granular matrix sensors. *In* Stewart, B.A. and Howell, T.A. (eds) *The Encyclopedia of Water Science*. Marcel Dekker. p 899-903.

Shock, C.C. 2006. Drip Irrigation: An Introduction. Oregon State University Extension Service, Corvallis. EM 8782-E (Revised October 2006) 8p.

Shock, C.C. 2007. Efficient irrigation scheduling. Available at http://www.cropinfo.net/irrigschedule.htm (verified 21 Sept. 2011)

Shock, C.C., A. I. Akin, L. A. Unlenen, Erik B. G. Feibert, and Cedric A. Shock. 2003a. Precise irrigation scheduling using soil moisture sensors. International Irrigation Show 2003 Proceedings, The Irrigation Association. San Diego, CA. November 18-20. p. 25--262.

Shock, C. C., J. Barnum, and M. Seddigh. 1998a. Calibration of Watermark soil moisture sensors for irrigation management. Irrigation Association. Proceedings of the International Irrigation Show pp. 139-146. San Diego, CA.

Shock, C.C., E.P. Eldredge, and L.D. Saunders. 2002a. Irrigation Criteria and Drip Tape Placement for 'Umatilla Russet' Potato Production. International Irrigation Show 2002 Proceedings, The Irrigation Association. New Orleans, LA. October 24-26. p 8.

Shock, C.C. and E.B.G. Feibert. 2002. Deficit irrigation of potato. In P. Moutonnet (ed) *Deficit Irrigation Practice*s. Food and Agriculture Organization of the United Nations, Rome. Water Reports 22:47-55.

Shock, C.C., E. B. G. Feibert, E. P. Eldredge, L. D. Saunders, A.B. Pereira, and C.A. Shock, and J. Klauzer. 2004a. Progress report on microirrigation in Oregon, 2004. Western Region Project W-128: Microirrigation: Management Practices to Sustain Water Quality and Agricultural Productivity, Tampa, FL, November 17-19, 2004.

Shock, C.C., E.B.G. Feibert, L.B. Jensen, R.L. Jones, G.W. Capps and E. Gheen. 2001. Changes toward sustainability in the Malheur-Owyhee watershed. In W.A. Payne, D.R. Keeney, and S. Rao (eds). *Sustainability in Agricultural Systems in Transition Proceedings*, ASA Special Publication. American Society of Agronomy, Madison, WI. pp. 97-106

Shock, C.C., E.B.G. Feibert, L.B. Jensen and J. Klauzer. 2010. Successful Onion Irrigation Scheduling. Oregon State University Extension Service, Corvallis. SR 1097. http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/18398/sr1097.pdf?sequence=1

Shock, C.C., E.B.G. Feibert, A.B. Pereira, and C.A. Shock. 2004b. Automatic collection, radio transmission, and use of soil water data. International Irrigation Show 2004 Proceedings, The Irrigation Association. Tampa Bay, FL. November 14-16, 2004.

Shock, C.C., E. B. G. Feibert, and L. D. Saunders. 2000a. Irrigation criteria for drip-irrigated onions. *HortScience* 35:63-66.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1996a. Re-examination of university nitrogen fertilizer guides. Potato Association of America. Abstract.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998b. Onion yield and quality affected by soil water potential as irrigation threshold. *HortScience* 33:1188-1191.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1999a. Residual effects of potato and onion sludge on wheat yield. Oregon State University Agricultural Experiment Station, Special Report 1005:183-186.

Shock, C.C., E.B.G. Feibert, L.D. Saunders. 2002b. Plant population and nitrogen fertilization for subsurface drip-irrigated onion. 26th International Horticultural Congress and Exhibition. Toronto, Canada. August. p 97-98 (abstract).

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2004c. Micro-irrigation alternatives for hybrid poplar production, 2003 trial. Oregon State University Agricultural Experiment Station, Special Report 1055. pp 121-129.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2004d. Plant population and nitrogen fertilization for subsurface drip-irrigated onion. *HortScience* 39:1722-1727.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2005a. Onion response to drip irrigation intensity and emitter flow rate. *HortTechnology* 15:652-659.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2007a. Short duration water stress produces multiple center onion bulbs. HortScience. 42:1450-1455.

Shock, C.C., E.B.G. Feibert, L.D. Saunders, and J. Klauzer. 2007b. Deficit irrigation for optimum alfalfa seed yield and quality. Agron J. 99: 992-998.

Shock, C.C., E.B.G. Feibert, L.D. Saunders and G. Schneider. 1998c. Nitrogen value of potato and onion sludge for corn production. Oregon State University Agricultural Experiment Station, Special Report 988:23-28.

Shock, C.C., E.B.G. Feibert, L.D. Saunders, N.L. Shaw and R.S. Sampangi. 2011. Native Wildflower Seed Production with Low Levels of Irrigation. p 158-178. In Shock C.C. (Ed.) Oregon State University Agricultural Experiment Station, Malheur Experiment Station Annual Report 2010, Department of Crop and Soil Science Ext/CrS 132.

Shock, C.C., E.B.G. Feibert, M. Seddigh, and L.D. Saunders. 2002c. Water requirements and growth of irrigated hybrid poplar in a semi-arid environment in Eastern Oregon. *Western Journal of Applied Forestry* 17:46-53.

Shock, C.C., E.B.G. Feibert, and D. Westermann. 1998d. "On farm" implementation of lower nitrogen fertilizer inputs through nitrogen accounting and validation of organic matter mineralization. pp. 126-134. Oregon State University Agricultural Experiment Station, Special Report 988.

Shock, C.C., E.B.G. Feibert, D. Westermann, D. Traveler, T. Tindall, S. Camp, B. Walhert, B. Huffaker, D. Bowers, D. Elison, S. Lund, C. Millard, and T. Miller. 1996b. "On farm" validation of nitrogen fertilization recommendations for sugar beets. pp. 126-133. Oregon State University Agricultural Experiment Station, Special Report 964.

Shock, C.C., R.J. Flock, E.P. Eldredge, A.B. Pereira, L.B. Jensen. 2006a. Successful Potato Irrigation Scheduling. Oregon State University Extension Service, Corvallis. EM 8911-E. 8p. http://extension.oregonstate.edu/catalog/pdf/em/em8911-e.pdf

Shock, C.C., R.J. Flock, E.P. Eldredge, A.B. Pereira, and L.B. Jensen. 2006b. Drip Irrigation Guide for Potatoes in the Treasure Valley. Oregon State University Extension Service, Corvallis. EM 8912-E. 6p. http://extension.oregonstate.edu/catalog/pdf/em/em8912-e.pdf

Shock, C.C., R.J. Flock, E.B.G. Feibert, A.B. Pereira, and M. O'Neill. 2005b. Drip irrigation guide for growers of hybrid poplar. Oregon State University Extension Service. EM 8902 6p.

Shock, C.C., R.J. Flock, E.B.G. Feibert, C.A. Shock, L.B. Jensen, and J. Klauzer. 2005c. Drip irrigation guide for onion growers in the Treasure Valley. Oregon State University Extension Service. EM 8901 8p.

Shock, C.C., R.J. Flock, E.B.G. Feibert, C.A. Shock, A.B. Pereira, and L.B. Jensen. 2005d. Irrigation monitoring using soil water tension. Oregon State University Extension Service. EM 8900 6p.

Shock, C.C., H. Futter, R. Perry, J. Swisher, and J. Hobson. 1988a. Effects of Straw Mulch and Irrigation Rate on Soil Loss and Runoff. OSU, Malheur Experiment Station Special Report 816:38-47.

Shock, C.C., J.H. Hobson, J. Banner, L.D. Saunders, and T.D. Stieber. 1993a. Research shows straw mulching pays. *Onion World* 9:35-37.

Shock, C.C., J.H. Hobson, M. Seddigh, B. M. Shock, T. D. Stieber, and L. D. Saunders. 1997. Mechanical straw mulching of irrigation furrows: soil erosion and nutrient losses. *Agronomy Journal* 89:887-893.

Shock, C.C., Z.A. Holmes, T.D. Stieber, E.P. Eldredge, and P. Zhang. 1993b. The effect of timed water stress on quality, total solids and reducing sugar content of potatoes. *Am Potato J.* 70:227-241.

Shock, C.C., L. Jensen, T.D. Stieber, E.P. Eldredge, J.A. Vomocil and Z.A. Holmes. 1989a. Introduction: Cultural practices that decrease potato dark-ends. Oregon State University Agricultural Experiment Station, Special Report 848. pp. 1-4.

Shock, C.C., L.B. Jensen, J.H. Hobson, M. Seddigh, B.M. Shock, L.D. Saunders, and T.D. Stieber. 1999b. Improving onion yield and market grade by mechanical straw application to irrigation furrows. *HortTechnology* 9:251-253.

Shock, C.C., J.G. Miller, L.D. Saunders, and T.D. Stieber. 1993c. Spring wheat performance and nitrogen recovery following onions. pp. 233-239. Oregon State University Agricultural Experiment Station, Special Report 924.

Shock, C.C., A.B. Pereira, B.R. Hanson, and M.D. Cahn. 2007c. Vegetable irrigation. p. 535--606. In R. Lescano and R. Sojka (ed.) Irrigation of agricultural crops. 2nd ed. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI.

Shock, C.C., A.B. Pereira, and E.P. Eldredge. 2007d. Irrigation Best Management Practices for Potato. *In* C. Rosen and M. Thornton (Eds.). Symposium on Best Management Practices for Nutrients and Irrigation: Research, Regulation, and Future Directions. Submitted to Amer. J. Potato Res. 84:29-37.

Shock, C. C., L.D. Saunders, B.M. Shock, J. H. Hobson, M. J. English, and R.W. Mittelstadt. 1993d. Improved Irrigation Efficiency and Reduction in Sediment Loss by Mechanical Furrow Mulching Wheat. OSU, Malheur Experiment Station Special Report 936:187-190.

Shock, C.C., L.D. Saunders, G. Tschida, L.D. Saunders, and J. Klauzer. 2003b Relationship between water stress and seed yield of two drip-irrigated alfalfa varieties 2002. Oregon State University Agricultural Experiment Station, Special Report 1048. pp 18-30.

Shock, C.C., M. Seddigh, J.H. Hobson, I.J. Tinsley, B. M. Shock, and L.R. Durand. 1998e. Reducing DCPA losses in furrow irrigation by herbicide banding and straw mulching. *Agronomy Journal* 90:399-404.

Shock, C.C., M. Seddigh, L.D. Saunders, T.D. Stieber, and J.G. Miller. 2000b. Sugarbeet nitrogen uptake and performance following heavily fertilized onion. *Agronomy Journal* 92:10-15.

Shock, C.C. and B.M. Shock. 1997. Comparative effectiveness of polyacrylamide and straw mulch to control erosion and enhance water infiltration. In Wallace, A. *Handbook Of Soil Conditioners*. Marcel Dekker, Inc. New York, NY. pp. 429-444.

Shock, C.C., C. E. Stanger, and H. Futter. 1988b. Observations on the Effect of Straw Mulch on Sugar Beet Stress and Productivity. OSU, Malheur Experiment Station Special Report 816:103-105.

Shock, C.C. and F.X. Wang. 2011. Soil Water Tension, a Powerful Measurement for Productivity and Stewardship. HortScience 46: 178-185.

Shock, C.C. and T. Welch. 2011a. Surge Irrigation, Sustainable Agriculture Techniques. Oregon State University, Department of Crop and Soil Science Ext/CrS 135.

Shock, C.C. and T. Welch. 2011b. Tailwater Recovery Using Sedimentation Ponds and Pumpback Systems, Sustainable Agriculture Techniques, Oregon State

University, Department of Crop and Soil Science Ext/CrS 134. http://cropinfo.net/bestpractices/TailwaterRecoveryExtCrS134July2011.pdf

Shock, C.C. and T. Welch. 2011c. TMDLs and Water Quality in the Malheur Basin: A Guide for Agriculture, Sustainable Agriculture Techniques, Oregon State University, Department of Crop and Soil Science Ext/CrS 133. http://cropinfo.net/bestpractices/TMDLsAnd%20WaterQualityExtCrs133July2011.pdf

Stanger, C.E., and J. Ishida. 1990. An evaluation of herbicide treatments for onion tolerance and weed control. Oregon State University Agricultural Experiment Station, Special Report 862, pp. 30-37. Malheur Experiment Station. Ontario, OR.

Stanger, C.E., and J. Ishida. 1993. Weed control in seedling onions with herbicides applied as preplant and postemergence applications. Oregon State University Agricultural Experiment Station, Special Report 924, pp. 32-42. Malheur Experiment Station. Ontario, OR.

Stene, Eric A. 1996. The Owyhee Project. *Dams, Projects & Powerplants: Bureau of Reclamation*. Available at http://www.usbr.gov/dataweb/projects/oregon/Owyhee/history.html (verified 10 Nov. 2006).

Stieber, T.D. and C.C. Shock. 1993. Budget approach to nitrogen fertilizer recommendations. Malheur County Groundwater Symposium Proceedings. p. 52.

Thompson, A.L., S.L. Love, J.R. Sowokinos, M.K. Thornton, and C.C. Shock. 2008. Review of the sugar end disorder in potato (*Solanum tuberosum*, L.). Am J Potato Res. 85:375-386.

Trenkel, J., D. Burton, and C. Shock. 1996. PAM and/or low rates of straw mulching to reduce soil erosion and increase water infiltration in a furrow-irrigated field, 1995 trial. OSU, Malheur Experiment Station Special Report 964:167-175.