Opportunities to Improve the Water Use Efficiency of Irrigated Alfalfa

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Abstract: Water managementis perhaps the key limiting factor for irrigated alfalfa production worldwide. Although there are several important advantages of alfalfa with regards to water, we must further improve water-use efficiency (WUE) of alfalfa to meet the food needs of a growing world population, to mitigate drought events, and to lessen demands on water resources. There are several basic strategies for improving the water-use efficiencyand resiliency of alfalfa: 1) Yield improvement, including genetic modification, 2) Improvement in water system delivery technologies, 3) Improved irrigation management systems, and 4) Deficit water strategies for periodic droughts. The most important of these are strategies to enhance yield and stand persistence with genetic improvement and better agronomic and irrigation practices. Plant adaptation to deficit water situations and to saline conditions must be considered. Secondly, technological solutions to improved water application methods, e.g.switching from flood to advanced sprinkler or to drip irrigation hold promise as technological advances. Thirdly, management strategies such as ET monitoring, soil moisture monitoringand sensor technology which improve the ability of growers to more closely match true water demand are important regardless of which irrigation technology is utilized. Lastly, alfalfa is well-suited to 'deficit irrigation' strategies when water supplies are insufficient. A range of practices which include plant genetic, crop management, irrigation technology, and water management elements are required to improve WUE in alfalfa. Envisioning more water-use efficient systems is critical to meeting future needs for forage crops in a more water-limited future.

Introduction

Alfalfa (*Medicago sativa L.),*is the fourth largest economic crop in the United States. The majority of alfalfa is grown in the northern Midwest, or in the arid West region of the US (Table 1). Nearly 50% of the US alfalfa hay or haylage is grown in western states (Table 1) and nearly allof this is grown under irrigation. The most common methods of irrigation for alfalfa are sprinkler irrigation of various types (pivots, wheel lines, movable pipe) and flood methods of irrigation. Alfalfa has significant impacts upon agricultural water use in all western US states.

Although alfalfa is considered to have high seasonal water use, it is one of the most water-efficient crops due to its high yield, perennial nature, deep roots, and the fact that the entire above-ground portion is harvested as an economic product. High seasonal water use is primarily due to its year-long growth patterns, and the area planted, which dominates many irrigated regions.

Water supplies are a key limiting factor for all countries including the US. In some regions, such as the UAE and Saudi Arabia, agricultural water use has been severely curtaileddue to the diminishing reserves. Thereis little question thatgrowers and scientists must improve water use efficiency (WUE) in the future, given water demands by an expanding population and intense competition for water resources, as well as climate change. Here, several strategies for improvement of water use efficiency and productivity in irrigated alfalfa forage systems are considered.

Table 1. Alfalfa Hay & Alfalfa Forage (hay+silage+greenchop) production of different regions of the US. Yields expressed on hay equivalent basis (13%DM). Data from 2012 USDA Agricultural Ag. Census.

Region	Alfalfa Hay	Alfalfa Forage (Hay+Silage+Greenchop)	Alfalfa Forage (% of US)
	tons per year	tons per year	%
MidWest	18,498,320	21,525,155	39.4%
Northeast	2,224,016	3,501,677	6.4%
South	3,134,823	3,286,645	6.0%
West	25,612,012	26,254,223	48.1%
Total US	**49,469,171**	**54,567,699**	**100%**

HOW MUCH WATER DOES ALFALFA REQUIRE?

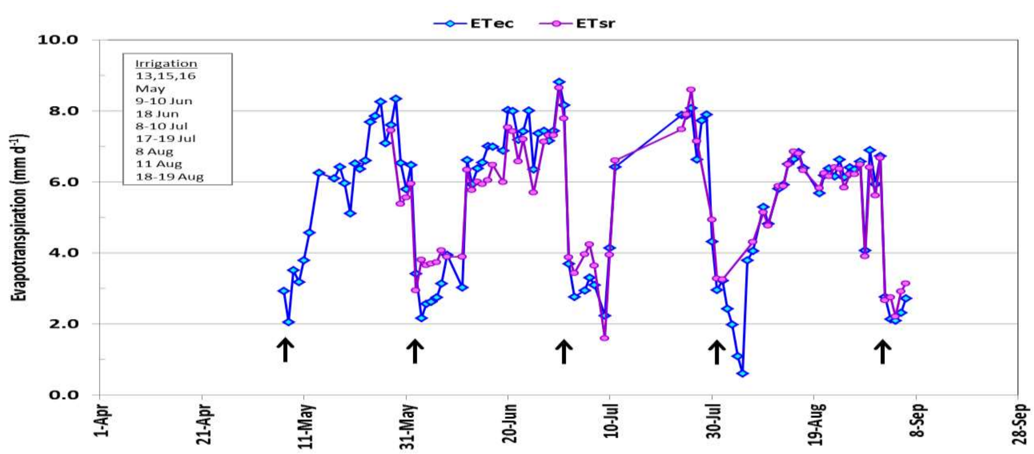

Figure 1. Evapotranspiration (ET) of a sprinkler-irrigated alfalfa field as measured by Eddy Covariance (ETec) and Surface Renewal systems (ETsr), Davis, CA, 2014. Vertical arrows indicate harvests. (R. Snyder, A. Montazar, D. Zaccaria, D. Putnam, unpublished data).

The first step for improving water use efficiency is to understand the true water requirements for that crop. Water Use Efficiency (WUE) is typically defined as the productivity of the crop (measured as dry matter or economic return) per unit of water utilized (or applied). Alfalfa is a herbaceous crop with rapid growth characteristics, and its yield is directly linearly related to Evapotranspiration (ET). ETc is an estimation of the true use of water by a specific crop, which includes evaporative losses from soil, as well as transpired water through leaf tissue. Alfalfa production is basically a linear function of plant transpiration and stomatal conduction which allows the plant to absorb CO_2, to build plant carbohydrates and plant biomass, and so understanding the true ETc is the first step to manage irrigation in alfalfa. ETc for a region is primarily a function of the temperature, solar radiation, humidity, length of season, and other factors such as wind and soil type, so seasonal demand is a function of the environment. In North America, the full water requirement (assuming no deficit irrigation) for alfalfa will range from about 2 Acre Feet per acre (6,000 m^3 per hectare) in short-season colder environments to nearly 6.5 acre feet/acre (19,000 m^3 per hectare) in long-season desert environments (such as Mexico or Arizona). Thus the requirement of alfalfa for water in a long-season desert environment will be much greater, whereas ET in a short-season northern environment will be lower. ETc is not necessarily equal to irrigation applied, since rainfall and residual soil moisture contribute to ETc.

Figure 2. Irrigated alfalfa is widely beneficial to wildlife, such as egrets, due to the presence of water, cover, and food.

Plant canopy also affects ET. The amount of water that alfalfa used, measured in the fieldover 5 cuttings,is shown in Figure 1. Note increases in ET when the crop grows to full canopy over a 28-30 day period, and declines during harvest, when only stubble remains.

POSITIVE FEATURES OF ALFALFA WITH REGARDS TO WATER

There are some important but not widely-understood biological values of alfalfa with regards to water use in agriculture. These are:

- **High Water Use Efficiency (WUE).**Alfalfa has very high water use efficiency (WUE) as defined by unit of economic dry matter production per unit water. This is primarily a function of high annual yield and Harvest Index (HI), or the percent of the dry matter of the crop which is harvested and utilized. Unlike many crops, of which only 10-50% of the above-ground biomass is harvested, 100% of the above ground biomass of alfalfa is harvested and yields are high, so WUE is high.
- **Deep-Roots and Perennial Characteristics Enable Alfalfa To Be An Efficient User Of Residual Rainfall And Subsurface Moisture.** After establishment, perennial crops generally do not require much irrigation to begin growing and establish a plant canopy– this enables early season yields with little or no irrigation. Alfalfa roots are typically 3-6 feet (1-2 m) in depth, and it is more difficult to irrigate past the root zone than with annual crops.

- **Positive Impacts on Water Quality.** Alfalfa fields essentially act as a 'filter crop' in cleaning up particulates from agricultural fields, and takes up nitrate from polluted waters. Tail water from alfalfa fields contains lower particulate levels compared with source water when initial levels are high (Long et al., 2002), Alfalfa fields can absorb nitrates from soil water, mitigating nitrate pollution of high N-containing waters such as manures or municipal wastes (Nebeker, 2001).
- **Value of Alfalfa Water to Wildlife.** Migratory water birds and raptors (e.g. Swainson's Hawk) especially benefit from alfalfa habitats (Hartman and Kyle, 2010). Surface irrigation in particular is beneficial for many species of birds, insects, and predators (Putnam, 2011, Figure 2).
- **Ability to be Deficit Irrigated**. In drought years, alfalfa can be only partially irrigated to produce a high percentage of annual yields. Yields are typically reduced, but the alfalfa can be temporarily deficit irrigated, and most of the time will recover and to produce normally when re-watered (Ottman, 2011). Thus, with only 50% of the water applied, often 60-75% of full production can be accomplished. This enables economic decisions to be made to move water to a different crop or use without completely destroying forage crop production or long-term production in a region or on a farm (Hanson et al., 2009).

In spite of these advantages, there is a strong need to envision much more efficient and water efficient irrigated alfalfa forage systems for the future. Several approaches are suggested here, some of which are short term, and some long term.

I. PLANT STRATEGIES TO IMPROVE ALFALFA WATER USE EFFCIEINCY

One of the most important strategies for the improvement of water management in alfalfa is to increase yields. Water Use Efficiency (WUE) is dry matter production divided by the amount of water used, so increasing alfalfa yield improves WUE as does decreasing the amount of water used. This is a concept which is frequently missed by water policy professionals and irrigation engineers.

The genetic yield potential of alfalfa in some long-season environments is likely currently at least in the 12-16 tons/acre range(27 to 36 Mg/ha). We have routinely recorded these yields on UC Experiment Stations and in Arizona trials in favorable environments. However, average on-farm yields are closer to ½ this amount or 5.0-8.5 tons/acre (11 to 19 Mg/ha) reported from farmer's fieldsfrom the highest yielding US states, Arizona and California. Although the yield potential is lower in other regions due to season length, cold or other factors, there is little doubt that alfalfa yields can be much higher than commonly recorded. Reducing the gap between potential yields and average yields could result in dramatic increases in WUE. Mechanisms for increases in yields may be genetic or changes in agronomic practices, of which agronomic practices are likely to bemore important. Better irrigation management is one of the key agronomic practices to increase yields.

Variety Improvement. Improved varieties are a key aspect of improved WUE, largely due to higher yields. Over the past 35 years of UC variety trials, the average impact of variety on yield has been approximately 30% of the mean value (Putnam, et al., 2010). There are also innovative genetic strategies for improvement of alfalfa in the future, including biotech solutions and traditional plant breeding, which could contribute to higher WUE. These may include:

- **De-linking the negative relationship of yield and quality.** Growers frequently harvest early for improved quality to meet the demands of dairy nutritionists. However, cutting at the vegetative stage often reduces yields by 0.5-2tons/acre (1 to 4.5 Mg/ha). Genes such as the low-lignin trait or delayed flowering genes may contribute to better quality at longer harvest schedules, combining higher quality with higher yields. Unscrambling the yield-quality tradeoff in alfalfa (producing high quality at maximum yield harvest schedules) would significantly contribute to higher WUE by improving yield without loss of quality, with little or no increase in water applications.
- **Stand Persistence-Resistance to Winterkill, Traffic, Stand Loss.** Low alfalfa yields frequently occur during the last years of a stand. Stand persistence is a complex trait, and may include tolerance to flooding and disease, resistance to winterkill, and ability to withstand frequent field traffic, and tolerance of heat stress. Stands that last longer with little loss in stand density during a 3-8 year period will improve WUE.
- **Root Characteristics.** The ability of roots to extract moisture from deeper in the profile would enable alfalfa to sustain yields under water limiting conditions. Perhaps branching patterns and the ability to generate and re-generate fine root hairs for full exploration of the soil profile may be important. Improvement in crown characteristics (the top of the root where multiple buds for regrowth are located) may also be important, along with roots that resist nematodes and diseases.
- **Stress And Salinity ToleranceAnd Ability To Be Deficit Irrigated.** The ability of alfalfa to sustain temporary droughts without stand loss should be amenable to selection pressure, or perhaps through genetic engineering. Alfalfa already has this characteristic to a considerable degree (Putnam et al., 2014). Since alfalfa must be frequently harvested, periodic droughts are typically unavoidable (during a 10-17 day period), depending upon system, and often limit full expression of yield potential. The ability of a crop to be deficit irrigated for weeks or months, and re-watered to full yield potential is an important characteristic and a method of dealing with future droughts. Similarly, the ability to use degraded water sources (manures, saline wastewaters) is an important strategy to preserve fresh water for other uses.

Agronomic Management Factors to Improve Yield. There are a wide range of management factors that can increase yields. The first of these is excellent stand establishment procedures, but also weed management, harvest management, insect control, and soil fertility.Although these are not discussed extensively here, in general, management factors are more important than genetic factors in limiting (or increasing) yields on farms. Any soil limitation (phosphorus and potassium and sulfur are the most common, along with soil pH) can reduce WUE and should be corrected.

One of the important points is irrigation management itself. Applications ofmorewater may be necessary to improve yields in some situations and thereby improve water use efficiency. Irrigation has such a profound effect on yield that better water management (possibly even more water applied per acre) may be necessary to improve overall WUE, since yields are increased.

Control of Traffic. One technique worth mentioning is the utilization of GPS technology to control wheel traffic in alfalfa. It has been found that yield losses of at least 25% are observed with only 2 trips across the field (Putnam, unpublished data). Compaction also has a large effect on soil water infiltration as well, and thus on the ability to water deeply in the profile and to maintain stand life. This could be an innovated way to improve WUE in alfalfa due to both improved infiltration, and higher yields due to less plant damage.

II. CHANGE IN IRRIGATION TECHNOLOGY TO IMPROVE WUE

Improvement or wholesale changein irrigation systems (water delivery systems on farm fields) is an important strategy to improve WUE in alfalfa. This is especially true of some border-strip-flood systems, some of which may have been in place for decades without improvement. However, it is also true of sprinkler irrigation systems which can go unexamined for decades without improvement. Improving irrigation delivery systems on an area basis is a key strategy for improvement of alfalfa water-use efficiency.

What's the Best Irrigation System?The principle behind ideal irrigation delivery system is to provide the crop with water to meet the crop ET at a time that the crop needs it, and to provide water uniformly across a field. The best irrigation system for alfalfa is one that:

- Maximizes Distribution Uniformity (DU), approaching 100%, so that every cm^2 of soil gets the same amount.
- Allows operators to very closely match applied water with the seasonal crop ET demand.
- Can fully fill the soil profile with moisture for crop growth.
- Minimizes water losses below the root zone, off-site surface runoff, and evaporation.
- Minimizes energy requirements.
- Requires less labor.
- Maintains sufficient oxygen in root zone (not excessive saturation).
- Is able to adjust for the requirements of frequent harvests (drying periods).
- Does not worsen pest problems (particularly rodents, weeds, nematodes and diseases).
- Can help manage salts.
- Is inexpensive - minimizes cost.

It should be immediately obvious that not all systems will fully meet all of these conditions, but each has advantages and disadvantages and strengths for each criterion. Choice of the best irrigation system for an individual farm must be carefully analyzed using water supply, soil, logistical and economic criteria.

Irrigation systems appropriate for alfalfa include **surface systems** (border-strip, dead level basin, and bedded furrow), **sprinklers** (solid set, movable pipe, wheel lines, center pivots and linear systems), and **drip irrigation** (Subsurface drip or SDI). Surface drip or microsprinklers are not appropriate for alfalfa given the frequent harvest periods. Each of these can be improved; each holds innate advantages and disadvantages for water management (Table 3).

Surface Systems – Border-Strip, Bedded, and Dead-level basin Irrigation.

Description: Laser or GPS-leveled fields with alfalfa planted on the flat, utilizing 30'-100' (10m to 30 m) wide levies (check flood) to guide the water, utilizing 'checks from 500 through ½ mile runs (Figure 3). 'Bedded' alfalfa involves furrow-irrigated beds which are sub-irrigated, similar to tomato or cotton beds (Figure 4). Dead level basins are smaller flooded basins (e.g. 200' x 500' or 60 x 150 m) that can be filled quickly (Figure 5).

Where it is most appropriate: These surface systems are appropriate where high flow rates are feasible (e.g. surface water sources), the soils have excellent water-holding capacity and moderate infiltration rates (e.g. medium to heavy textured soils), good internal drainage, but with little risk of irrigating past the root zone. These are not as appropriate for lighter soils, highly variable soils, or very poorly drained soils, or for areas with scarce water, or low flow rates.

Key Advantages: The majoradvantage of this system is the low cost, which is usually lower than pressurized systems, since no pumps or pressurized systems are required –it's a gravity fed system. Less purchased hardware is required, but careful land leveling or field design is required. The low energy requirement of surface irrigated systems is a major advantage in reducing energy demand of agriculture. Additionally, flood-type systems, if properly designed, can move water to deeper in the profile than sprinklers, depending upon soil type. Thiswatercan then be used by the crop during harvest or short-term droughtfor deep-rooted alfalfa crops. Distribution uniformity for bedded alfalfa and dead-level basin can be excellent, depending upon soil type. Rodents (gophers) aremanaged through frequent flooding of burrows. Bedded alfalfa configurations have advantage isolating traffic only in the furrows, and allowing water

Figure 3. Check flood irrigation is typically designed with 0.1-0.2% laser-levelled slopes with small levies from 8 m to 30 meters apart that allow water to move across the field. Substantial quantities are required to 'push' water down the field. ***KeyOpportunities for improvement*** are shorter runs, better land-levelling, and automated surface water delivery using sensors and automatic gates.

drainage off of alfalfa crowns, both of which benefit plant growth.Surface irrigations are highly beneficial to wildlife. When used on the right soil type, dead level basins can have very high distribution uniformity and prevent off-site water movement.

*Key Disadvantages:*Distribution uniformity is typically less than well-designed pivot or drip systems, and requires high quantities of water just to move the water down the field.Stand loss and waterlogging are frequent problems in the tail-ends of alfalfa fields with flood irrigation. Lack of oxygen in the root zone during and following irrigation events often damages plants, resulting in scald (death of plants) during hot weather. On sandy soils or variable soils, water loss below the root zone can be very high.Check flood requires significant initial land leveling before planting, and ditch maintenance throughout production and significant labor for irrigation. Off-site movement of tailwater from surface systems can contain pollutants – a major problem in some areas. In poorly-designed surface irrigation systems (lack of land leveling, long runs, poor tail end design), distribution uniformity can be poor. Surface systems often result in more water stress during harvest periods, since small amounts cannot be applieddue to the need for drying the fields for harvest. Evaporative losses in surface systems are greater than buried drip, but less than sprinkler systems. Labor costs of gravity-fed systems are greater than center pivot or drip systems, due to the opening and closing of gates, placement of siphons, maintenance of ditches.

*Key Opportunities for Improvement:*Tailwater

Figure 4. 'Bedded' alfalfa involves sowing the crop on top of small beds from 40 cm to 100 cm apart. Ditches move water off the crop and down the field, appropriate for very heavy clay soils. ***Opportunities for improvement:*** shorter runs, automated delivery systems, equipment modification to avoid wheel traffic.

Figure 5. Dead level basins are not common in alfalfa but can be very high in distribution uniformity. Requires small fields, very high flow rates and good internal drainage.***Opportunities for Improvement:*** Laser levelling, high delivery rates, subsurface tile drains.

return systems, automation of delivery,improved flow rate, analysis of cutoff time, and improvement in field design could result in significantly greater WUE with surface systems (Bali et al., 2014). The goal is to reduce deep percolation (a major problem with light soils and even some heavy soils)-toreduce, eliminate, or recycle surface runoff, and to improve Distribution Uniformity (DU). Low DU is a major limitation of many check flood systems, as well as tailwater runoff (Sanden et al, 2011). Automation (automatic off- and on- mechanisms) would be highly beneficial since human error is one of the key problems with optimization of this system (K. Bali, pers. Comm.), and would reduce labor costs. Better tail-end designs and field designs to recycle, allow drainage, and contain surface runoff is needed. Shorter runs and better land leveling, often improve uniformity greatly, and holding ponds which return water to the same or neighboring field may be helpful in conserving runoff.Soil moisture monitoring to assist in scheduling irrigation would be highly beneficial to detect when fields are under- or over-irrigated(Sanden et al., 2003). The use of controlled traffic using GPS would be useful to improve infiltration and increase yields. Ultimately, electronic monitoring with soil moisture sensors, fully- or partially- automated systems could be envisioned for surface systems.

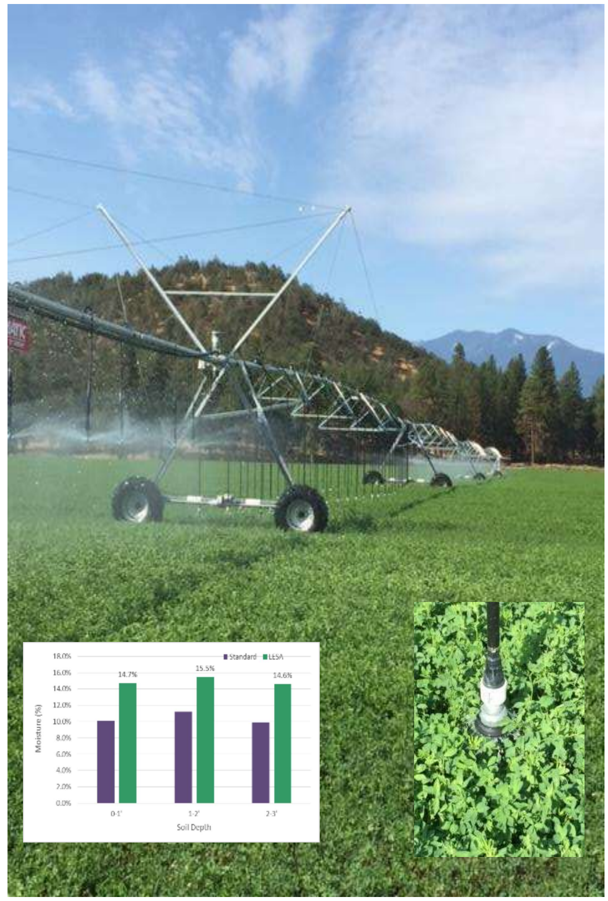

Figure 6. Center Pivots are a very common and effective method of irrigation delivery to fields and appropriate for regions with limited water and less land limitation. ***Key opportunities for improvement***: better nozzle designs and closer spacing to improve distribution uniformity, reduce evaporation losses. Drop nozzles like this LESA system deliver water much closer to the soil (center of photo and inset), and improve moisture in this experiment in California (Steve Orloff, Univ. of California, data & photo).

Sprinkler Systems (Center Pivot, Linear, Wheel line, Moveable Pipe, Solid Set).

Description: There are a range of sprinkler systems that are available and appropriate for use in alfalfa, ranging from aluminum or PVC hand-lines, to solid set (buried pipe with risers), to linear and pivot (Figure 6) overhead systems (Table 2).

Where it is most appropriate: Sprinklers have the best fit where soils cannot be sufficiently leveled for surface irrigation, where soil texture is light (sandy or sandy loams), where water is pumped and pressurized anyway, and where water quantities are limited.

Center pivots are often the sprinkler of choice in larger fields where land is not as limiting (Figure 6). Linear moves are appropriate for higher land-value areas and for rectangular fields. Moveable hand lines, solid set or wheel lines are appropriate for smaller fields.Some overhead systems, pivots and linear systems, have major labor-saving advantages compared with other sprinkler systems.

Advantages: Pivot and linear systems have some of the greatest opportunities for high distribution uniformity (Neibling et al., 2009) – hand lines and wheel lines are more limited in DU due to the design and amount of time needed for irrigation and moving sprinklers. One of the most important values of sprinklers is the ability to apply small amounts of water when needed uniformly, and ability to control subsurface losses, salts, and surface runoff. This enables irrigation close to the time of harvest, reducing the temporary deficits that are common in check flood systems.Sprinklers are likely the best system for stand establishment of small seedlings (even if other systems are used later), since crusts can be softened and shallow irrigation (1” to 6” or 2 to 15 cm) is feasible. Only minor land leveling is required with sprinklers, and pivots enable no-till establishment systems. No excess water at ends of fields in well-tuned systems.Many sprinkler systems (not all) have good capabilities of delivery of fertilizer elements (fertigation), improving fertilizer use efficiency.

*Disadvantages:*Significant capital costs. Sprinkler systems require pressure and energy (electric or fossil fuel) to run – therefore in addition to the substantial investment, ongoing energy costs.Loss of corner production (up to 21% of land area) with pivots is a disadvantage especially when land is expensive. Linear systems and wheel lines have the disadvantage of the need to move back to the beginning for a subsequent irrigation, or alternatively to schedule irrigations non-uniformly (pivots don’t have this problem). Runoff can be a problem on some soils with sprinklers if large amounts are applied, but amenable to management. Tracking of linear systems, and rutting on pivots is a management problem. Gophers and other vertebrate pests are a large issue with sprinkler systems, and an advantage for flood systems. Evaporative losses can be large with all sprinklers, depending upon nozzle design, wind and weather, but drop nozzles, LEPA technology can assist. Labor costs are significant for field-level sprinklers (wheel line, solid set, hand move), but generally lower for pivot and linear systems than for surface systems.

Key opportunities for Improvement: Nozzle technology continues to make progress, with low pressure type sprinkler heads and other delivery systems reducing evaporative losses and improving DU. Pump technology also is conducive to improvement in energy demand. Also, some of the best opportunities for automation is provided by sprinklers linked to monitoring systems (soil or crop or ET), or links with GPS site-specific applications. Since pivots are a well-developed system and generally work well, growers often ignore monitoring of distribution uniformity, nozzle problems, and soil moisture to assure that irrigation schedules are correct. Thus some of the major opportunities for improvements in sprinkler systems have to do with their management by growers and better management of irrigation schedules. Prevention of muddy wheel ruts is important. Wheel lines, movable pipe, and solid set systems have similarly been around a long time, and careful analysis of nozzle patterns, spacing, flow rates, leaks, and other maintenance would go a long way towards improving these systems.Strategies for edge-of field (corner) production using drip, sprinklers, or other methods are important.

Subsurface Drip Irrigation (SDI).

*Description.*Subsurface Drip Irrigation (SDI) is not widely used, but growers are showing interest in this technology due to the promise of higher yields. Drip lines with a lifetime of 6 to 12 years are placed subsurface 8 to 18" below the soil surface on 30'-40" centers, depending upon soil type (Figure 7). Requires pressurized system (pumps) as well as a filtering and filter maintenance system. Although highly familiar in orchard, vine, and specialty row crops (where SDI has major advantages), drip in alfalfa has not been as widely adapted as other systems. Alfalfa SDI fields would likely be rotated with another crop such as corn, wheat, cotton or tomatoover a 6-12 year period, leaving the system in place, so the return on investment would be optimized. Likelyless than 2% of the western alfalfa crop is currently drip irrigated. This system is still in development, but a number of growers have had success with this system.

Figure 7. Drip irrigated alfalfa field in Southern California. Water is delivered sub-surface to the roots directly, including fertilizers – yield increases of 20-30% have been observed vs. flood fields. Sometimes growth is different above the drip lines (corrugation, right). ***Key Opportunities for Improvement:*** Better rodent management, maintenance, filtering, optimization of drip spacing and scheduling for specific soils, crop rotation, reduced cost.

Where it is most appropriate: Drip irrigation has likely the best fit for farms with a high level of management, in regions with highly limited water supply, sandy soils where subsurface losses are great, and in areas with low gopher pest pressure. It has also been used successfully on clay loams and heavier soils.If yield advantages (evidenced by earlier research and grower experience) can be more broadly confirmed, it has wider applications on many soil types.

*Advantages.*Yield improvements are the major attraction (Putnam et al., 2014). The SDI system has near zero evaporative losses (unlike sprinkler and flood), and has some of the best Distribution Uniformity of any system. It offers the most flexibility of any system for application of water quantity to more precisely meet crop need, and excellent control of fertilizer applications. Water can be put onto field very quickly, irrigating the entire field, providing logistical advantages. Virtually any irrigation schedule can be accomplished (e.g. 4 hrs/day, 12 hrs/day, every other day, etc.), or 'spoon feeding' water and fertilizers to the crop to precisely meet demand. There is significant evidence for increased yields with SDI, which is likely due to the avoidance of periodic drought and ability to continually provide sufficient moisture for alfalfa. SDI completely solves off-site movement of pesticides with irrigation water, benefitting water quality. Growers have reported up to 50% water savings, but the ability of SDI to save water is currently under debate. Significant water savings are likely on lighter soil types, compared with less efficient systems. Fertigation or more precise fertilizer applications are feasible and easy to accomplish. In a well-tuned and designed system, irrigation costs of labor will be significantly less than other systems. Weed pressure is likely to be less due to dry surfaces which discourages weed germination. Alfalfa stands may last longer due to lack of standing water on the crop.

*Disadvantages.*Initial Capital Cost and annual maintenance costs are likely the major disadvantages of this system, and are not trivial. Rodent management (gophers primarily) has proved to be a very significant issue, since alfalfa provides a terrific habitat for gophers – they have source of food, a stable dry burrow system, and water from buried drip systems. Root intrusion may also occur, but hasn't been a big problem with alfalfa. Some of the labor savings for irrigation management may be taken up with gopher monitoring systems, and labor expenditure for maintenance of leaks. Similar to other pressurized systems, SDI requires energy to manage – unlike check flood systems. Filtration of water can be an issue when utilizing water with high suspended solids, pH problems, or other limitations. Conversion of check flood or sprinklers to SDI may result in less wildlife habitat.

Key Opportunities for improvement. Since this method has not been widely adapted, there are a range of opportunities for improvement of this system as applied to alfalfa. There are opportunities for water savings and higher yields compared with check flood irrigation with use of SDI, particularly in desert environments with sandy soils, high heat and wind. Higher yields may be key to adaption, since the cost of the system is not insignificant – higher yields are likely a requirement for adaptation. Substantial yield advantages have been widely seen with tomato (Hartz and Hanson, 2009) and in experimental and observational evidence with alfalfa (Hutmacher, 2001) and with growers (Putnam, 2014), across many types of soils.Innovative rodent management techniques using IPM and other approaches are absolutely required to make this system viable. This is probably one of the major challenges in addition to the cost. Techniques to

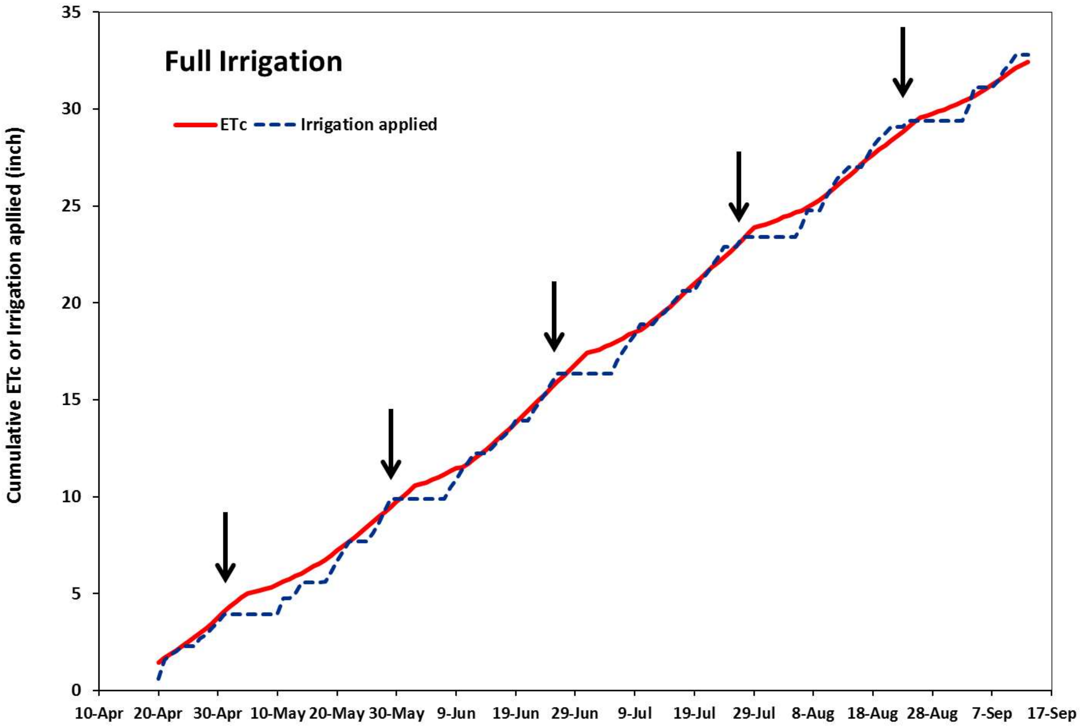

Figure 8. Irrigation monitoring to match ET in a drip-irrigated field in Davis, CA during the growing season (2015). Vertical arrows indicate harvests. Note limitation on irrigation surrounding harvests. Irrigation scheduling is designed to match very closely the ETc of the Crop (see Figure 1), since ET accumulates each day and over the season. (data from A. Montazar, J. Radovich, and D. Putnam, UC Davis). ***Key opportunities for improvement:*** Farmers can monitor water applications to match daily and seasonal ET values. Very few farmers currently do this.

reduce cost of installation may be necessary. Further work on optimizing irrigation scheduling, configuration of the drip lines is needed to understand the full potential of this system in alfalfa. Developing viable crop rotation strategies with buried drip are important for the long-term viability of this system.

III. **BETTER IRRIGATION SCHEDULING AND MANAGEMENT SYSTEMS**

One of the best ways to improve WUE in alfalfa is to improve the management of water (irrigation timings and amounts) utilizing current systems. There is little doubt that ALL irrigation systems can be improved by better water management. This primarily consists of 1) determining the best **timing** of irrigation, and 2) Correctly determining the **amount** to be applied. The principle of irrigation scheduling and better management is to match as closely as possible applications of irrigation water and rainfall with crop water need (see ETc Figure 1).

ET Monitoring. It is striking that the ET is not routinely followed by many farmers, and soils are rarely tested to see where the water ends up (e.g. how deep and how uniform). Many growers don't know if they are applying too little water, too much water, or whether their timing is correct. 'Real-time' ET values (Figure 1) are useful for determination of how much water a crop needs at that point in time. ET data is typically published by agencies – but even using long-term average ET values would be helpful as a start. Each day, the crop uses a given amount of water (for example, 0.25" or 6.35 mm per day water use). Over 28 days, then a farmer would need to apply 7" or 178 mm of water at a minimum (more to make up for field losses and evaporation from sprinklers). This is illustrated in Figure 8, which shows irrigation of a drip irrigated field to match the ET values. A grower can very quickly see whether enough water has been applied to meet the ET of the crop, or whether they are 'behind' in applying irrigation water. Note that in alfalfa, a 14-17 'drought' is induced every month or so, due to the requirement to dry the crop down for harvest, and this water must be made up by irrigating more just after a harvest.

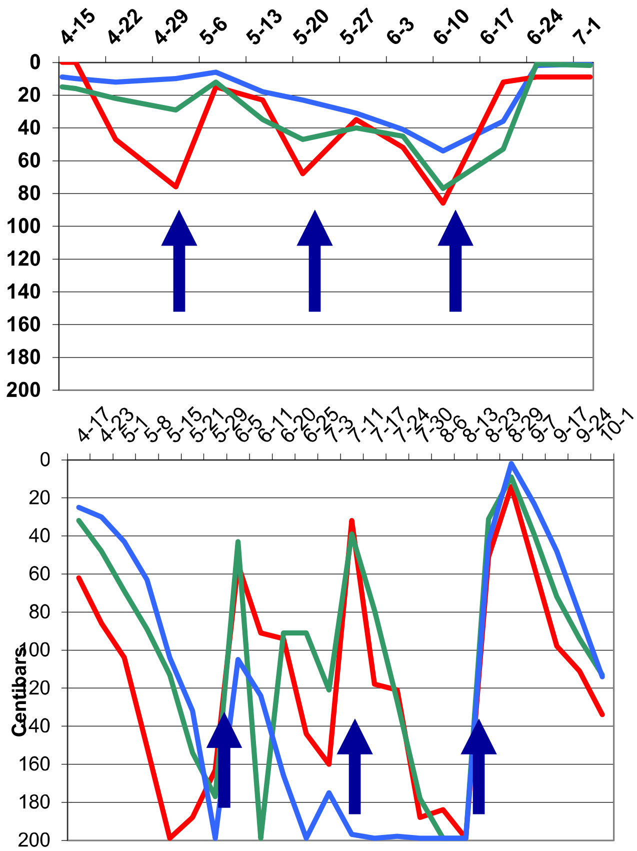

Figure 8. Soil Moisture monitoring can greatly assist in determining success of irrigation management. This data is from soil moisture monitors placed at 3 depths (30 cm red, 60 cm green, 120 cm blue). The higher number (centibars) indicates dryer soil. Vertical arrows indicate irrigations. The top graph represents a properly irrigated field, the bottom graph, the soil has dried out too much between irrigations. ***Key Opportunities for Improvement:*** Install moisture sensors at different depths to 'ground truth' water application levels.

Soil Moisture Monitoring. Additionally, monitoring of soil moisture status or plant stress is not often done, and would be highly beneficial (Sanden et al., 2003). Better irrigation management systems (scheduling, monitoring, remote sensing) would be very helpful in maximizing the water use efficiency of alfalfa. This is true using any of the irrigation technologies listed above, whether surface, sprinkler or drip. These technologies assist in improving delivery, but timing and amounts of water applied are under management controls.

On-line, easily accessible use-friendly irrigation and water management tools may be beneficial to improve management systems for alfalfa. There are known principles and technologies for better irrigation management – but the applications have not been widely accomplished for this crop. It may be truthfully said that the relatively low investment in research or implementation of water use improvements in alfalfa (either by USDA, water agencies, universities, companies or industry) has been a limiting factor in moving forward on improvements in water use efficiency with alfalfa.

IV. DEALING WITH DROUGHT AND DEFICIT IRRIGATION

As mentioned above, alfalfa has a unique ability to be 'deficit irrigated' – that is, in many situations when water supplies are short, alfalfa can be 'dried down' and still survive to come back and yield normally the following year. In most cases, alfalfa offers more flexibility when water is short than other crops. It is the combination of deep roots, ability to utilize rainfall early in the year, high water use efficiency, salinity tolerance, and ability to give partial yields with half or less of the irrigation water that makes alfalfa particularly valuable in a drought. UC work done over the past 20 years has confirmed the ability for growers to stop alfalfa irrigations in mid-summer, allow the crop to dry down, and re-water successfully later when irrigation water becomes available. This generally cannot be done with many other crop species. This flexibility is an important role of alfalfa in cropping systems during water-short periods.

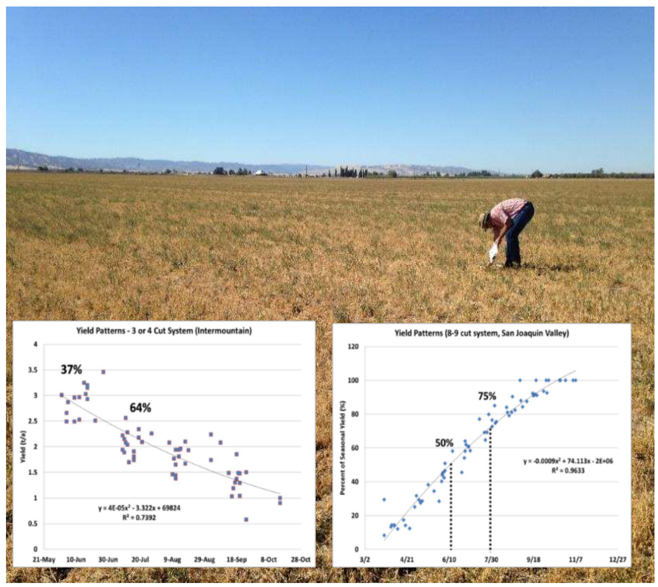

Figure 9. Solano County, California field which was completely dried up during the 2014 drought, becoming 'summer dormant'. This field was re-irrigated later, and yielded normally. Yield patterns show a high percentage of alfalfa yields can be attained by mid-summer (data from UC variety trials for 3-4 cut system or 8-9 cut system, multiple years). ***Key Opportunities for Improvement:*** When water is short, it's better to irrigate fully until mid-summer, then cut off water completely. Improved varieties may sustain lengthy droughts and have better root systems to attain subsoil moisture. Note: survival is highly dependent upon soil type and environment.

The best strategy for irrigating alfalfa when water supplies are insufficient is to fully irrigate the early-season cuttings and then cease irrigation partway through the season. This approach is often referred to as partial-season irrigation, early irrigation cutoff or summer dry-down. There are several advantages to this tactic. Spring and early summer cuttings are typically the highest yielding. Depending on the production area, approximately 2/3 to 3/4 of the total annual production occurs by mid-July (Figure 9). And, some alfalfa growth continues even after irrigation water is withdrawn, utilizing stored soil moisture. Because yields are typically higher in spring and the ET rate is less than the summer, the water use efficiency (yield per unit of water) is greater in spring than in mid-summer or fall (Figure 6). In addition, spring growth can utilize stored soil moisture from winter and spring rains further augmenting the amount of alfalfa yield per unit of applied irrigation water.

Conclusions

There is no question that the alfalfa industry needs to envision improvements in irrigation management and WUE for a water-scarce future. These long term strategies include 1) improving yields through genetic and crop management methodologies, 2) Changing irrigation delivery technology where appropriate, and 3) Improving water management monitoring systems to more closely estimate and match crop water demand with applied water.

Key opportunities to improve water use efficiency in alfalfa:

- **Improve Yields through Genetic Innovation**
- **Improve Yields through Agronomic Practices**
- **Improve Yields through Irrigation Management**
- **Shift irrigation techniques to more precise methods:**
  - **Well-designed surface systems**
  - **Precise pivot systems with good controls and nozzling systems**
  - **Subsurface Drip Irrigation**

Table 2. Advantages and disadvantages of different irrigation application systems as applied to alfalfa.

System	Advantages	Disadvantages
Surface- Check Flood Irrigation	Ability to deliver larger quantities in a short time. Low cost. Good fit with heavier soils with good internal drainage. Ability to irrigate deeply and fill soil profile. Controls gophers. Excellent ability to flush salts. Very low energy requirement. Wildlife benefit.	Must have large water supplies. Inability to finesse small amounts of water applications – since water is required to move down the field. Often poor distribution uniformity. Tail water accumulation and damage to crop is common. Labor requirement is high. Diseases on very heavy soils. Scald risk during high temperatures. High subsurface losses on sandy soils.

Surface-'Bedded' Alfalfa	Distribution can be better than check flood. Ability to move water effectively down the field – protection of alfalfa crowns from excess flood water by draining into ditches. Keeps wheel traffic completely off crowns. Avoidance of disease and scald.Low energy requirement.	Off-site tail water runoff. Erosion from ditches. Salt movements onto bed centers. Beds may interfere with harvests. Often requires modification of equipment to adjust to bed dimensions.High subsurface losses on sandy soils.
Surface-Dead Level Basin	Superior Distribution Uniformity. Ability to deliver water deep into soil profile. Flood system flushes salts. Control of rodents.	Requires smaller basins and fields. Requires very large head of water during irrigation to rapidly fill basins. Scald risk during high temperatures. High subsurface losses on sandy soils.
Sprinkler-Center Pivot Irrigation Systems	Excellent Distribution Uniformity with good nozzles. Low maintenance and labor. Ability to apply small amounts of water to meet crop needs. High flexibility of scheduling. Fertigation practical. Can manipulate salts. Ability to automate and operate remotely.	Capital cost. Energy requirements due to pumping needs. Evaporative losses can be substantial. Gopher management. Loss of productivity in corner areas (21.5% of square field). Wheels create ruts.
Sprinkler- Linear Overhead Systems	Good fit with high-value square fields (unlike pivots). Excellent Distribution Uniformity. Low labor requirement. Does not loose productivity in corners. Fertigation practical. Ability to automate.	Capital cost. Maintenance of system is more challenging than pivots – requires water delivery system (ditch or hoses). Energy requirements due to pumping needs. Evaporative losses can be substantial. Gopher management a problem. Back-and-forth pattern creates challenges for distribution and timing, unlike pivots.
Sprinkler-Wheel Lines	Inexpensive system. Wheels assist in movement of pipes. Can be used on smaller fields, unlike pivots. Good for smaller, square fields. Can be moved from field to field.	Distribution uniformity not always ideal, depending upon configuration and nozzling. Labor intensive. Back-and-forth pattern creates challenges for distribution and timing. Gopher management. Evaporative losses can be substantial.
Sprinkler-Solid Set/	Robust system when installed as permanent system. Less labor than moveable pipe or wheel lines, but not as labor-saving as pivots. 'In place' system.	Interference with harvesting and tillage operations. Cost. Expensive to install buried pipe Distribution uniformity not always ideal, depending upon configuration. Evaporative losses can be substantial. Labor costs.
Sprinkler-Moveable Pipe	Low capital cost, high flexibility system-can use pipes on other fields/crops. Excellent for stand establishment.	Very high labor requirement. Distribution uniformity not always ideal, depending upon configuration. Interference with harvest scheduling.
Drip-Subsurface Drip Irrigation (SDI)	Higher yields due to timing and Distribution Uniformity (DU) and lack of soil drying. Excellent DU. Ability to fertigate. Ability to apply small amounts of water to meet crop needs and finesse irrigation schedule. Oxygen availability in root zone. Low labor requirement for irrigation. Crop rotation with row crops such as tomato, sunflower, cotton feasible. Low weed pressure due to dry surface. Longer stand longevity.	High cost. Maintenance of system, particularly gopher management and leaks. May require periodic alternative irrigation techniques (e.g. sprinklers or flood) to manage salts and gophers. Requires continued water supply-may be a limitation when water is delivered only periodically. Water quality may be a limitation due to filtering requirements.