STRATEGIES FOR THE IMPROVEMENT OF WATER-USE EFFCIENT IRRIGATED ALFALFA SYSTEMS

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ABSTRACT

Irrigated alfalfa is the largest water user in California and most other western states. Although there are several important advantages of alfalfa with regards to water, as well as widely-held misunderstandings, long-term strategies for improvement of water-efficient alfalfa production systems are necessary to meet the needs of a growing population, to mitigate drought events, and to lessen demands on water resources. One of the most important of these are strategies to enhance yield and stand persistence, which include genetic improvement and agronomic practices. Plant adaptation to deficit water situations and salinity must be considered. Technological solutions to irrigation improvement, e.g. switching from flood to sprinkler or drip hold promise, especially for certain soil types. Management strategies which improve the ability of growers to more closely match true crop demand are important regardless of which irrigation technology is utilized. There is no one-size-fits-all solution to improve water-use efficiency in alfalfa, but a range of practices which include plant genetic, crop management, irrigation technology, and water management elements. 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 California's highest acreage crop and is a major irrigated crop in virtually all western states. In California, for example, alfalfa is grown on nearly 1 million acres per year. It consumes the highest amount of water of any single crop (Table 1). In spite of this high seasonal water use, alfalfa has some very positive biological features with regards to water: it is one of the most water efficient crops due to its perennial nature, deep roots, high yields, and the fact that the entire above-ground portion is harvested as an economic product.

While there are a range of myths and misunderstandings surrounding water use in alfalfa—particularly the economic argument—there is little question that growers of this crop must improve water use efficiencies in the future, given water demands by an expanding population and intense competition for water resources. Several strategies for improvement of water use efficiency and productivity in irrigated alfalfa forage systems for the future are suggested here, considering both water quantity and water quality impacts.

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HOW MUCH WATER?

The California Department of Water Resources estimates the state-wide applied water use of alfalfa at over 5 million AF per year, or over 19% of the state's water used for agriculture in the early 2000s (Table 1). It should be pointed out that these percentages likely have changed significantly since this time, and are likely to change from year to year. Since that time, we've had large increases in some crops (tree crops and vines), decreases in some crops (cotton) and the alfalfa acreage itself has fluctuated at nearly +/- 200,000 acres since this period, with an average hovering right around 1.0 million acres. In 2012-13, for example, alfalfa acreage is likely to increase over 50,000 acres statewide, and was closer to 940,000 in 2011.

Table 1. Applied water of major California crops in a 3-year period (1998 (wet), 2000 (ave), 2001 (dry).

Crop	Applied Water (AF x 1,000)	Percent of Total Ag. Water Use
Potato	86	0.3%
Safflower	87	0.3%
Tomato (Fresh)	105	0.4%
Dry Bean	245	0.9%
Onion/Garlic	260	0.9%
Sugarbeet	284	1.0%
Curcurbits	292	1.1%
Other Field Crops (incl. sudan)	501	1.8%
Tomato (Processing)	748	2.7%
Grain	1,025	3.7%
Subtropical Tree (citrus)	1,295	4.7%
Other Truck	1,440	5.3%
Vine	1,569	5.7%
Corn (~80% silage)	*1,673*	*6.1%*
Other Decid. Tree	2,113	7.7%
Almond/Pistachio	2,113	7.7%
Cotton	2,277	8.3%
Rice	2,685	9.8%
Pasture (incl. grass hay)	*3,318*	*12.1%*
Alfalfa	*5,301*	*19.3%*
Total Crop Use	**27,417**	**100.0%**

In What Regions Does Alfalfa Have An Impact? The major production regions for alfalfa are the Intermountain, Sacramento Valley, San Joaquin Valley, and Low Desert Regions (Figure 1). Therefore, it is not surprising that alfalfa has the highest impact in these regions. Alfalfa is largely not important in coastal areas. The intermountain region is split between 3 hydrologic zones (N coast, Sacramento River, and N. Lahontan), thus it is difficult to estimate the water impacts in this region, but it is estimated that the % of agricultural water used by alfalfa in the

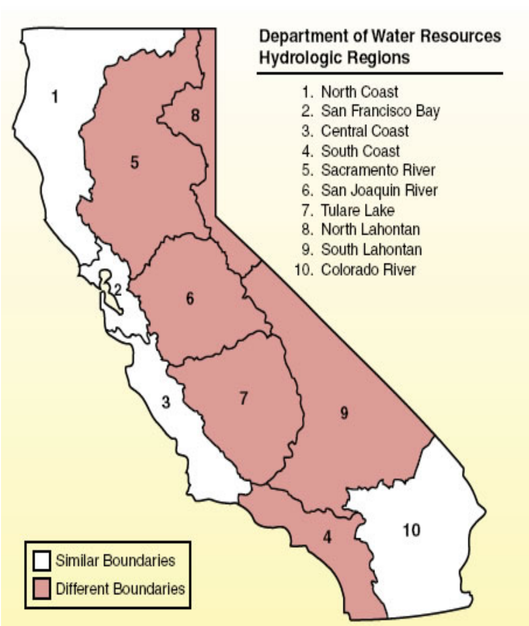
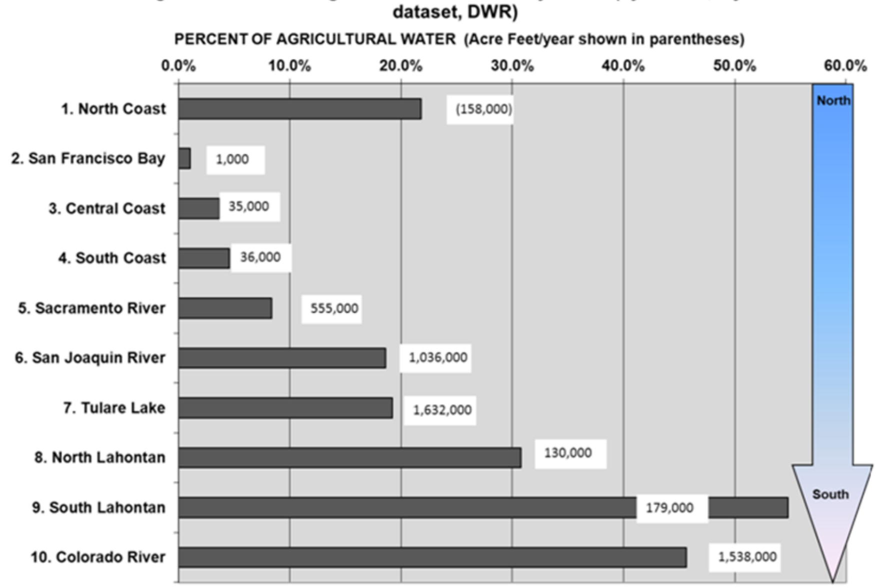


Figure 1. Percent of Agricultural Water used by Alfalfa (by district, 3 year dataset, DWR)



intermountain area is greater than 30% (S. Orloff, pers. Comm.).

Although critics often focus on the total annual water use of alfalfa, it has been adequately demonstrated that the seasonal water use itself is not the key issue, but the ability of water to produce a product (Water Use Efficiency or WUE), which can be either Dry Matter (DM), economic return, or nutritional value per unit water. Additionally, the ability of irrigated cropping systems to adjust to changing supplies (flexibility during drought years), or to accomplish voluntary water transfers when necessary, to mitigate water quality problems, and to adjust to poorer soils or saline conditions are often of equal or greater importance than simply the amount of water used by a crop.

WATER AND ALFALFA - KEY VALUES, MYTHS AND MISUNDERSTANDINGS

Advantages 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. The HI refers to 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. Herbaceous crops like lettuce and spinach have similarly high HI of nearly 100%, but relatively low DM yields. Crops such as corn and wheat have a HI of about 30-50% and many tree crops typically below 15%. Thus the WUE is very high with alfalfa, a characteristic it shares with other forages (e.g. corn and small grain silage), which produce high DM yields and the entire above-ground plant is harvested.
- **Deep-Rooted Perennial Characteristics Enable Alfalfa To Be An Efficient User Of Residual Rainfall And Subsurface Moisture.** Annual crops require water to germinate the seed and establish a canopy – a period of relatively low efficiency, since water is easily lost past the shallow root zone. After establishment, perennial crops generally do not require much irrigation to establish a plant canopy– this enables early season yields with little or no irrigation. Alfalfa roots are typically 3-6' in depth, and it is more difficult to irrigate past the root zone than with annual crops. Orchards and vineyards also benefit from deep-rooted perennial growth, but require years of irrigation before an economic crop can be harvested, unlike alfalfa which require only a few months.
- **Positive Impacts on Water Quality.** Alfalfa fields essentially act as a 'filter crop' in cleaning up particulates from agricultural fields. Thus, water from erodible row crops or orchard crops, containing suspended solids, can be improved by channeling tail water through alfalfa fields. In field measurements, tail water from alfalfa fields contained lower particulate levels compared with source water when initial levels are high (Long et al., 2002). In addition, the high nitrogen N uptake values of alfalfa (higher than corn) enable alfalfa fields to absorb nitrates from soil water, mitigating nitrate pollution of high

N-containing waters such as manures or municipal wastes (Nebeker, 2001). There are also some negative impacts of alfalfa on water quality, particularly off-site movement of pesticides (Prichard, 2010, Putnam, 2010). Both herbicides and insecticides applied to alfalfa fields have been found in surface waters, and growers and their consultants need to work cooperatively to minimize the risk of surface water pollution. However, these can be prevented. The deep roots, high N uptake, and particulate capture characteristics of alfalfa are innate qualities which enable it to contribute to cleaner water in agriculture.

- **Value of Alfalfa Water to Wildlife.** Alfalfa is one of the most important agricultural landscapes with regards to wildlife habitat, a fact that has been confirmed by wildlife biologists. This is to a considerable degree a function of surface water irrigation methods as well as high insect and vertebrate diversity, which form a food chain. 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.
- **Ability to be Deficit Irrigated**. Unlike many annual fruiting or seed-producing crops, where severe water stresses often result in dramatic decreases in (or zero) yield, it has been adequately demonstrated that alfalfa can be successfully deficit irrigated, for even long periods (2-3 months). 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). 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). This can be envisioned as a 'water bank', since even the avoidance of a month of irrigations in alfalfa statewide could be worth hundreds of thousands of acre feet per year. It is widely believed that voluntary water transfers between water users are an important strategy to deal with future droughts.

Myths-Economic Value vs. Water Use. Perhaps the most frequent criticism is the description of alfalfa is as a 'low value' crop in relationship to the water used (Putnam, 2010). These are often put forth rhetorically, essentially stating that 'some other use of water is superior' than merely irrigating alfalfa hay. This is probably more a reflection of the subjective and qualitative 'value' that is placed on the crop by those making this comment, not necessarily a careful analysis of the true economic value of the crop. Let's be frank – hay is not as widely appreciated by the public as, say, strawberries or wine! The economic value of alfalfa is frequently misunderstood, both its global value to a society, as well as the micro-economic value to farms.

OK – Admitted – Alfalfa Has Zero Economic Value. Alfalfa, pasture, and other forage crops have essentially zero economic value in and of themselves. Try calculating the economic value of a pasture or alfalfa field without cows, sheep or horses! Forages are innately and inextricably linked to animal enterprises. The #1 economic enterprise in California is dairy, and a large majority (>75%) of the state's alfalfa crop is consumed by dairy cows. Over a 30 year period, alfalfa itself has been worth an average of a little over $1 billion/year in 2009 dollars in California, not a small amount. But in 2011 milk and cream was worth >$7.2 billion, coupled with >$1.7 billion for hay, producing 21% of the milk in the US, clearly the most important economic component of California agriculture (Table 2). This doesn't include the value of beef or sheep or horses. Envisioned as a singular 'food-producing system', dairy-forage has a tremendous economic impact (note that these are just farm gate values, not other linked enterprises such as dairy processing and milk products, farm machinery, or multipliers like hay trucking and grocery clerks). Unlike other crops, such as lettuce and walnuts which do not depend upon other farm enterprises, forages by definition depend upon animal products (and vice versa) – and, other than indirect benefits such as rotation or wildlife, the direct economic value of alfalfa and forage crops should be considered along with the co-dependent animal enterprises.

Alfalfa Must Compete Economically For Water. The other important point with regards to economic value is that alfalfa receives no special allocation or subsidy, and must compete economically with all other crop options for each acre of land as well as for water on an individual ranch or in an irrigation district. Thus, growers make economic decisions to grow alfalfa (or not) based upon soil type, water supply, cost of water, tolerance for risk, economic value and other factors. In some years, alfalfa can make more money for growers than crops such as lettuce and tomato – and thus has managed to survive economically in a very competitive environment. Additionally, alfalfa hay provides farmers with a major 'cash flow' income advantage, which is important to sustain farm enterprises, with 5-10 harvests/year, unlike crops that are harvested once per year. A key point is that thousands of farms in many regions depend upon alfalfa as a mainstay of economic return. Underestimation of the economic value of alfalfa to farm enterprises and to a region is one of the most frequent misconceptions about this crop.

Table 2. Farm Gate Value of California Commodities (CDFA Statistical Overview)

	2009	2010	2011
Milk and Cream	4,537,171	5,928,150	7,680,566
Almonds (shelled)	2,293,500	2,903,380	3,866,880
Grapes	3,260,172	3,209,040	3,860,351
Cattle & Calves	1,676,375	2,068,412	2,825,125
Nursery	2,513,112	2,357,232	2,683,100
Berries, Incl. Strawberries	1,725,232	1,813,557	1,948,118
Hay (all)	926,660	1,033,152	1,734,660
Lettuce	1,743,573	1,605,283	1,513,023
Walnuts	747,270	1,028,160	1,323,070
Tomatoes	1,539,923	1,246,286	1,264,936
Flowers and Foliage	936,689	1,015,083	1,011,530
Cotton Lint, All	285,797	592,416	893,952
Pistachio	592,850	1,158,840	879,120
Rice	936,958	930,849	774,432
Chickens	691,518	721,723	702,051
Broccoli	750,600	684,659	684,033
Carrots	499,766	546,210	659,610
Oranges, All	595,909	720,899	659,338
Avacados	200,640	414,948	460,560
Eggs	319,805	367,788	391,578

Need for Change. Regardless of some of these biological advantages of alfalfa with regards to water use, and its economic value to farmers and society, there is little doubt that water supply and water quality impacts of this crop are major challenges. There is a strong need to envision much more efficient and water efficient forage systems for the future. Several approaches are suggested here, some of which are short term, and some long term.

PLANT STRATEGIES TO IMPROVE WATER USE EFFCIEINCY

One of the most important strategies for the improvement of water management in alfalfa is to increase yields. Remember WUE is dry matter production divided by the amount of water used. So increasing the numerator (alfalfa yield) improves WUE as does decreasing the numerator (water used). This is a concept which is frequently missed by water policy people and irrigation engineers. The genetic yield potential of alfalfa in some environments is likely currently at least in the 12-16 tons/acre range (we have routinely recorded these yields on UC Experiment Stations and in Arizona trials)—and maximum yields exceeding 20 tons/acre have been reported in Arizona. However, average on-farm yields are closer to ½ this amount or 5.0-8.5 tons/acre reported from farmer's fields from the highest yielding US states, Arizona and California. 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 more important (apologies to plant breeders, but they would likely acknowledge this). Better irrigation management is one of the key agronomic practices to increase yields.

Variety Improvement. 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). It is highly doubtful that irrigation practices would be significantly different for higher-yielding varieties compared with lower-yielding varieties – at least they were not in these controlled trials. Thus, even just using traditional variety selection, there is a potential of about 30% to improve WUE. 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 the dairies, with annual production losses of often 1-2 tons/acre. Genes such as the low-lignin genes 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 with little or no increase in water applications.
- **Stand Persistence-Resistance to 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 would 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 Tolerance And 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. Since alfalfa must be frequently harvested, periodic droughts are typically unavoidable, 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. These have been thoroughly covered in other papers (see Irrigated Alfalfa Management for Mediterranean and Desert Zones and this and other proceedings). These include good stand establishment procedures, 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. One of the important points is that applications of <u>more</u> water 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.

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.

CHANGE IN IRRIGATION TECHNOLOGY TO IMPROVE WUE

Improvement or wholesale change in 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 and sprinkler systems, some of which may have been in place for decades without improvement. However, it is important not to take a ‘knee jerk’ view that changes in irrigation technology itself are a fix-all solution to improving WUE in alfalfa. This has been frequently heard in criticisms of flood irrigation systems, by those who assume that wholesale moves to drip, for example, will always be beneficial. Surface flood systems can be made to be much more efficient and are quite appropriate for some soil types, while sprinkler or subsurface drip may be appropriate for other sites. Surface irrigation has other benefits too such as groundwater recharge, salt management, and wildlife benefit. There are advantages and disadvantages and economic realities with each system (Sanden et al., 2011, Table 3). Those who have studied this issue extensively have determined that virtually any one of the irrigation different irrigation systems may be best depending on the conditions of a particular field and environmental conditions, each has advantages and disadvantages. Each can be optimized, and thus there is no 'one size fits all' solution to developing the best irrigation system for a farm.

What's the Best Irrigation System? The best irrigation system for alfalfa is one that:

- Maximizes Distribution Uniformity (DU), approaching 100%
- Allows operators to very closely match applied water with the seasonal crop demand.
- 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)
- 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. Some are contradictory, for example, efforts to reduce surface runoff may reduce DU in flood systems, and more precise application methods may require more energy. Choice of the best irrigation system for a farm must be carefully analyzed using water supply, soil, 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 (see 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' wide levies (check flood) to guide the water, utilizing 'checks from 500 through ½ mile runs. 'Bedded' alfalfa involves furrow-irrigated beds which are sub-irrigated, similar to tomato or cotton beds. Dead level basins are smaller flooded basins (e.g. 200' x 500') that can be filled quickly.

Where it is most appropriate: These systems are appropriate where high flow rates are feasible (e.g. surface 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. Not as appropriate for lighter soils, highly variable soils, or very poorly drained soils.

Key Advantages: The major advantage of this system is the cost, which is usually lower than pressurized systems, since no pumps or pressurized systems are required. Less purchased hardware is required, but extensive 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. This water can then be used by the crop during harvest or short-term drought for deep-rooted alfalfa crops. Distribution uniformity for bedded alfalfa and dead-level basin can be excellent, depending upon soil type. Rodents (gophers) are usually kept under control through frequent flooding of burrows (an advantage of check flood vs. drip or sprinklers). Bedded alfalfa configurations have advantage isolating traffic only in the furrows, and allowing water drainage off of alfalfa crowns, both of which benefit plant growth. When used on the right soil type, dead level basins can have very high distribution uniformity and prevent off-site water movement.

Key Disadvantages: 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 –reducing WUE. 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 applied due 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 return systems, automation, improved flow rate, analysis of cutoff time, and improvement in field design could result in significantly greater WUE with surface systems (Bali et al., 2010). The goal is to reduce deep percolation (a major problem with light soils and even some heavy soils)-to reduce, eliminate, or recycle surface runoff, and to improve Distribution Uniformity (DU). Low DU is a major limitation of many check flood systems (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 (Bali, pers. Comm.), and would reduce labor costs. Damage to tail-ends of fields is a major challenge in check flood fields, reducing DU, yields, and WUE. 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. Capture of surface waters is the key to protecting water quality in these systems. Methods of remote signaling to signal when the water reaches the point of shutoff for a check irrigation system is important first step of automation. These are under development (Upadhyay, UCD, pers. Comm.). This combined with robust automated surface delivery systems would not only save labor, but also be more precise in delivering the right amount of water. 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.

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 hand-lines, to solid set (buried pipe with risers), to linear and pivot overhead systems.

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. 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 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 less so due to the 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 up 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 dealt with and shallow irrigation (1” to 6”) is feasible. No (or minor) land leveling is required with sprinklers, and pivots enable no-till 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. Requires filtration system in some cases. 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 on 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. 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 would be helpful.

Subsurface Drip Irrigation (SDI).

Description. Drip lines with a lifetime of 6 to 12 years are placed subsurface 8 to 18" below the soil surface on 30'-80" centers, depending upon soil type. 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 tomato over a 6-12 year period, leaving the system in place, so the return on investment would be optimized. Likely less than 1% of the western alfalfa crop is currently drip irrigated. This system is accurately described as still in development, but a number of growers have had success with this system.

Where it is most appropriate: Drip irrigation has likely the best fit in regions with highly limited water supply, sandy soils where subsurface losses are great, and in areas with low gopher pest pressure. Fit with heavier soils is still being evaluated. If yield advantages (evidenced by earlier research and grower experience) can be more broadly confirmed, it has wider applications on many soil types.

Advantages. The SDI system has near zero evaporative losses (unlike sprinkler and flood). 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. 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-this could be a major driver in some areas. Flexibility around harvest dry-down periods is greatest, since the surface is mostly dry, and moisture is provided 8-18” below the ground—a grower can conceivably irrigate even during harvest periods, or at least right up to harvest, and resume shortly after. The ability of SDI to save water is currently under debate, but significant water savings are likely on some 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.

Disadvantages. Initial Capital Cost and annual maintenance costs are likely the major disadvantages of this system. 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. 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, since the soil surface is dry.

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, especially on sandy sites, for water savings and higher yields compared with check flood irrigation with use of SDI. Higher yields may be key to adaption, since the cost of the system is not insignificant – and where water is cheap, higher yields are likely a requirement for adaptation. 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 (Michael, 2009), 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 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.

BETTER IRRIGATION SCHEDULING AND MANAGEMENT SYSTEMS

There is a strong need to improve application of superior irrigation management systems in alfalfa. It is striking that the CIMIS system (California's system of monitoring ET demand for different areas) is hardly used by alfalfa growers. There are good reasons for this. Growers using check flood systems have few options – they can only irrigate once, twice, or at most three times between harvests – thus harvest (not ET) is often the main driver for irrigation scheduling. Other logistical considerations come into play – the scheduling of water deliveries, machine or labor schedules, for example. These practical limitations are severe impediments to a more scientific approach to irrigation scheduling with alfalfa. 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. 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. This is a challenge for both growers and the scientific community.

CONCLUSIONS

While alfalfa holds some important advantages in terms of water use efficiency and water management, 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 technology where appropriate, and optimizing system performance in all systems, and 3) Improving water management monitoring systems to more closely estimate and match crop water demand with applied water.

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Table 3. 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. Controls gophers. Flood system flushes salts. Very low energy requirement.	Inability to finesse small amounts of water applications. Drought common during harvests. Often poor distribution uniformity. Tail water accumulation and damage to crop common. Labor requirement high. Diseases on very heavy soils. Scald risk during high temperatures. High losses on sandy soils.
Surface-'Bedded' Alfalfa	Distribution can be better than flood. Ability to move water effectively down the field – protection of alfalfa crowns from excess flood water. Keeping 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. High losses on sandy soils.
Surface-Dead Level Basin	Excellent Distribution Uniformity. Ability to push water down in profile. Flood system flushes salts. Control of rodents.	Need smaller basins and fields. Requires large head of water during irrigation. Scald risk during high temperatures. High losses on sandy soils.
Sprinkler-Center Pivot Irrigation Systems	Excellent Distribution Uniformity. 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.	Capital cost. Energy requirements due to pumping needs. Gopher management. Loss of productivity in corner areas.
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. Gopher management. Back-and-forth pattern creates challenges for distribution and timing.
Sprinkler-Wheel Lines	Inexpensive system. Wheels assist in movement of pipes. Good for smaller, square fields.	Distribution uniformity not always ideal, depending upon configuration. Labor requirement. Back-and-forth pattern creates challenges for distribution.
Sprinkler-Solid Set/	Robust system when installed as permanent system. Less labor than moveable pipe, but not as labor-saving as pivots.	Cost. Expensive to install buried pipe. Interference with harvesting operations. Distribution uniformity not always ideal, depending upon configuration. Labor costs.
Sprinkler-Moveable Pipe	Low capital cost, high flexibility system- can use pipes on other fields. 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 yield possibilities. Excellent Distribution Uniformity. Ability to fertigate. Ability to apply small amounts of water to meet crop needs and finesse irrigation schedule. Oxygen available in root zone. Low labor requirement for irrigation. Low weed pressure due to dry surface	High cost. Maintenance of this system, particularly gopher management, leaks. May require periodic alternative irrigation techniques (e.g. sprinklers or flood) to manage salts.