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Assessing the Viability of Sub-Surface Drip Irrigation for Resource-Efficient Alfalfa Production in Central and Southern California

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Abstract: In California, alfalfa is grown on a large area ranging between 325,000 and 410,000 hectares and ranks among the thirstiest crops. While the hay production industry is often scrutinized for the large usage of the state's agricultural water, alfalfa is a crucial feed-supplier for the livestock and dairy sectors, which rank among the most profitable commodity groups in the state. Sub-surface drip irrigation (SDI), although only practiced on approximately 2% of the alfalfa production area in California, is claimed to have the potential to significantly increase hay yield (HY) and water productivity (WP) compared with surface irrigation (SI). In 2014–2016 we interviewed a number of growers pioneering SDI for alfalfa production in Central and Southern California who reported that yield improvements in the order of 10–30% and water saving of about 20–30% are achievable in SDI-irrigated fields compared with SI, according to their records and perceptions collected over few years of experience. Results from our research on SDI at the University of California, Davis, revealed significantly smaller yield gain (~5%) and a slight increase of water use (~2–3%) that are similar to findings from earlier research studies. We found that most of the interviewed alfalfa producers are generally satisfied with their SDI systems, yet face some challenges that call for additional research and educational efforts. Key limitations of SDI include high investment costs, use of energy to pressurize water, the need for more advanced irrigation management skills, and better understanding of soil-water dynamics by farm personnel. SDI-irrigated fields also need accurate water monitoring and control, attentive prevention and repair of rodent damages, and careful salinity management in the root zone. In this paper we attempt to evaluate the viability of the SDI technology for alfalfa production on the basis of preliminary results of our research and extension activities, with focus on its water and energy footprints within the context of resource efficiency.

Keywords: *Medicago sativa* L.; flood irrigation; micro-irrigation; eco-efficiency; drought

1. Introduction

In California, alfalfa is currently the largest-acreage single crop after almonds, and among the most important forages for the dairy and livestock sectors, which comprise a \$12 billion industry [1]. Recent estimates by the California Department of Water Resources (DWR) reveal that, in normal years, alfalfa uses about 16% of the state's total available agricultural water supply [2]. Statewide, over 80%

of the alfalfa acreage is surface-irrigated, nearly 16% is irrigated with sprinkler systems, and about 2% with sub-surface drip irrigation (SDI) [3]. No surface drip irrigation is used on commercial alfalfa production fields.

Given the prospect of higher recurrence of droughts, water-efficient alfalfa production systems are crucial to reduce demand upon the state's resources (see also [4]), while meeting the needs of global markets and domestic agricultural industries to produce more safe food for a growing population and to cater to evolving dietary habits. The severe and prolonged drought facing California from 2013 to 2016 has impaired agricultural production across the state, with varying intensity. The farming community has been adversely affected by hard curtailments of surface water supplies, mitigated in some areas with increased groundwater extractions. Alongside that, the urban and environmental sectors have been demanding larger water shares, adding further to existing demand for fresh supplies, and calling for coordinated efforts by the farming community for more resource-efficient practices to sustain agricultural production, while reducing water usage and environmental burdens. In this context, attention has been traditionally given mainly to water savings pursuable through adoption of higher-efficiency irrigation technologies, such as pressurized irrigation systems, with the underlying assumption that they allow for substantial water conservation, making the saved water available to other sectors and uses (cfr. [5]).

In California, fostering the broader adoption of micro-irrigation practices has been the common reactive approach to physical and regulatory water limitations, and to environmental burdens (groundwater overdraft and aquifer decline, degradation of soil, water and air) related to the progressive intensification of irrigated agriculture. In the last 15 years, public agencies and regulators have provided financial incentives to encourage growers modernizing on-farm irrigation equipment and convert from surface and sprinkler irrigation to micro-irrigation. The rationale was that farmers would realize substantial reductions of water and energy consumption, and of greenhouse gas (GHG) emissions from higher irrigation efficiency. However, in many cases growers expanded crop acreages and converted from annual to perennial crops (with similar and higher water requirements) to maximize net farm profits (cfr. [6]), taking further advantage of financial subsidies. This has led either to no reduction or even to increases of overall on-farm water usage. As pointed out by Perry et al. [5], generally, when additional water becomes available through higher-efficiency irrigation, farmers tend to develop additional use of these resources and often end up increasing the water demand and consumption.

The irrigation modernization in California targeted mainly water conservation, but without considering at the same time resource-efficiency goals. Resource-efficiency, or eco-efficiency, is a business management concept that integrates the economic and ecological performance in the production of goods and services, and quantifies the relationship between the economic added value and environmental burdens generated by production activities [7,8]. In the case of irrigated agriculture, eco-efficiency gains can be pursued by increasing land and water productivity (WP), while minimizing the environmental externalities of crop production, both in terms of resource extraction, pollution emission and environmental degradation. While land productivity measures the crop yield per unit of land, and expresses the amount of farmland necessary to meet food needs [9], WP defines the above-ground dry matter produced per unit land area per unit of evapo-transpired water [10]. Evaluating the eco-efficiency of water use entails relating the economic performance of crop production systems with their water, energy and pollution footprints.

Irrigation system evaluations conducted in California by mobile irrigation laboratories operated either by irrigation districts, resource conservation districts (RCDs) or by the Natural Resources Conservation Service (NRCS) showed that well-designed and properly maintained modern micro-irrigation systems can achieve irrigation efficiencies of about 87–93%, yet longstanding environmental problems such as groundwater overdraft, soil and groundwater salinization, greenhouse gas emissions and air quality degradations, seem not to be relieved nor decreasing in many agricultural production areas throughout the state where farmers have largely adopted

micro-irrigation methods. It occurs that public agencies and regulators often overlooked relevant aspects of micro-irrigation, such as the need for on-demand water delivery to farms to enable high-frequency water applications; the reliance of farmers on groundwater as often-preferred source of irrigation water; the progressive degradation of aquifers due to unsustainable groundwater management practices in agricultural production areas; the need to apply additional water off-season for leaching micro-irrigated fields and prevent salinity build-up; and the energy usage to pressurize water. In other terms, the higher efficiency of modern micro-irrigation equipment and technologies has not necessarily been conducive to higher resource-efficiency of agricultural production, especially when the use of resources such as farmland, water, and energy, as well as the environmental externalities, were not regulated or limited in some way.

There are well-known limitations of surface irrigation (SI), including the inability to deliver small amounts of water and tailor irrigation applications to meet crop needs; the occurrence of in-season water losses by deep percolation and surface runoff; the generally lower distribution uniformity (DU); and the alternation of soil wetting and drying between irrigations with relatively long intervals that may cause water stress to crops. In the case of alfalfa, the efficiency of flood irrigation is further constrained by the cyclic dry-down periods necessary for harvesting the crop and curing the hay on the ground (see also [11]), which in Central and Southern California typically occur from 6 to 10 times per year.

The primary drivers for growers to adopt SDI are mostly economic, i.e., the prospects of higher yields and increased land and water productivity through better irrigation management. Several authors [12–16] documented yield and water-use efficiency gains with SDI relative to surface irrigation methods in shallow-rooted vegetables and some field crops, such as cotton and corn, as a result of improved water and fertilizer management made possible by SDI when combined with high-frequency irrigation. In the case of alfalfa, Ayars et al. [14] indicated that SDI outperforms SI as it allows greater control on water and nutrient applications, resulting in less water losses through deep percolation; whereas other authors documented that SDI can improve hay yield because it eliminates leaf scalding, which may occur with sprinkler irrigation [17] and with surface-ponded water (flood irrigation) in hot weather [18].

Rogers et al. [19] provided a detailed description of the main SDI system components and some guidelines for their minimum requirements and proper selection; whereas key aspects of design (dripline spacing, depth of installation, emitter spacing), management and maintenance of SDI systems, and their economic implications on various field crops are described by [18,20–26]. Alam et al. [18] also indicated that root intrusion into the dripline emitters could be an aspect of concern because alfalfa is a perennial crop, but this problem was not observed in a three-year trial in Kansas, and can be effectively discouraged with periodic injections of chemicals (chlorine, acids, trifluralin and copper sulfate) through the driplines. They also noted that fully irrigated alfalfa is less likely to be affected by root intrusion than deficit-irrigated alfalfa.

In this paper we focus on addressing three main questions: (1) whether SDI allows water-efficient alfalfa production in the Central and Southern California; (2) if SDI has the claimed potential for increasing yield and water productivity relative to SI; and (3) what skillset, technologies and practices growers need to achieve crop yield and irrigation performance gains. In this regard, our considerations are based on the preliminary key findings from research and extension activities that our team from the University of California Cooperative Extension (UCCE) has been conducting during the last few years. We also describe the likely mechanisms that could potentially generate better crop and irrigation performance with properly designed and managed SDI systems, highlighting some existing challenges of this technology, and making preliminary considerations to assess SDI within the context of resource-efficiency. Finally, we indicate some future research and extension work needed for the broader and successful adoption of SDI for alfalfa production.

2. Applied Research and Extension Activities

2.1. Field Research Experiments at UC Facilities

In 2016, our team established an applied research trial at the Russell Ranch facility (coordinates 34.545959 N, −121.876284 W) of the University of California, Davis (UCD), with the aim of documenting comparative differences in actual crop evapotranspiration (ETa), hay yield (HY), and water productivity (WP) between alfalfa plots with SDI and SI. We selected this site to represent the typical growing conditions (soils, weather and farming practices) of the Sacramento Valley. The experiment was established on a 3.2-ha silty-clay loam field with three different treatments, namely (1) SI; (2) SDI with driplines spaced 0.75 m apart; (3) SDI with driplines spaced 1.0 m apart, all installed 0.30 m deep, and replicated three times with randomized block design. The dripline was Toro Neptune (The Toro Company, El Cajon, CA, USA) with 22-mm internal diameter and 0.33-mm wall thickness.

We installed driplines with characteristics tailored to site-specific soil textures, accounting for their typical lateral and vertical soil-water dynamics. Prior to establishing the alfalfa stand and installing driplines, we appraised the in-field variability of soil properties through the soil apparent electrical conductivity (ECa) using the electro-magnetic induction (EMI) technology. According to [27,28], ECa mapping is one of the most valuable methods in agriculture for measuring the spatial variability of soil properties at field and landscape scales. We also conducted field measurements of the unsaturated soil hydraulic conductivity within each mapped soil zone using a retention disk infiltrometer (Soil Measurement Systems, LLC, Tucson, AZ, USA), and then estimated the maximum vertical and horizontal dimensions of wetted area for different drip emitter flow rates with irrigation durations from 1 h to 24 h according to the method proposed by Schwartzman and Zur [29] for determining the geometry of a wetted soil zone under point-source water application. Based on these measurements and calculations, for treatment number 2 we selected an optimal soil-specific SDI setup, among those commercially available, consisting of driplines spaced 0.75 m apart with two alternative emitters' spacings and flow rates (0.36 m and 0.61 L·h^{−1} vs. 0.60 m and 0.95 L·h^{−1}) that apply very similar water amounts per unit of dripline length. In treatment number 3, we installed sub-optimal SDI consisting of driplines spaced 1.0 m apart with the same alternative emitters' spacings and flow rates as in treatment number 2. In the majority of micro-irrigated commercial alfalfa fields the most common SDI systems consist of driplines spaced 1.0 m apart, installed 0.30 m to 0.35 m deep, with emitter spacing of 0.35 m to 0.40 m and emitter flow rates ranging from 0.70 L·h^{−1} to 0.95 L·h^{−1}.

We instrumented the experimental plots with various equipment to measure and monitor: (a) the actual crop evapotranspiration (ETa), using the residual of energy balance (REB) method by means of commercial surface renewal (SR) equipment (cfr. [30–34]); (b) the applied water (AW) through calibrated flowmeters and data-loggers; (c) the soil-moisture (SM) using sensors, data loggers and telemetry for monitoring, storing and retrieving soil-water information.

Following the REB method, ETa (mm·d^{−1}) was calculated on a daily time-step from the latent heat flux (LE) according to the Equations (1) and (2) below:

$$LE = Rn - G - H \quad (1)$$

$$ETa = \frac{LE}{\lambda} \quad (2)$$

where: LE = latent heat flux; Rn = net radiation; G = soil heat flux; H = sensible heat flux; λ = latent heat of vaporization.

Daily values of Rn were estimated with remote sensing techniques from reflectance data acquired by the Geostationary Operational Environmental Satellite (GOES), whereas H was calculated on a daily time-step from high frequency (10 Hz) temperature measurements (averaged to half-hourly time-step) collected by commercial surface renewal stations by means of a fine-wire thermocouple above the canopy, and stored in a dedicated data-logger. We assumed the term G to be zero on a daily time-step,

given the balance between the positive ground heat flux (from the atmosphere to the ground, i.e., the ground storing energy) during daytime, and the negative ground heat flux (from the ground to the atmosphere, i.e., the ground releasing the same amount of energy) during nighttime. ET_a was then calculated (Equation (2)) by dividing the LE ($MJ \cdot m^{-2} \cdot d^{-1}$) by $\lambda = 2.45 MJ \cdot kg^{-1}$ (which is the specific heat to vaporize 1 kg of water from the liquid state) to obtain the actual crop evapotranspiration rates in $kg \cdot m^{-2} \cdot d^{-1}$, which is equivalent to $mm \cdot d^{-1}$.

We installed 1 commercial surface renewal ET station (Tule Technologies, Inc., San Francisco, CA, USA) per treatment for ET_a ; one propeller Woltman-type mechanical flowmeter (McCrometer, Inc., Hemet, CA, USA) per replicate for AW; and 2 SM measuring units per replicate, each consisting of 3 granular matrix soil moisture tension sensors (Watermark, Irrrometer Company, Inc., Riverside, CA, USA) at the depths of 0.30 m (12 inches), 0.60 m (24 inches), and 1.20 m (48 inches), respectively, and 1 data-logger (900 M, Irrrometer Company, Inc., Riverside, CA, USA) connected with nodes of a telemetry network.

The SDI and SI plots received similar water amounts, as we conducted ET-based irrigation scheduling followed by feedback control from the SM- and AW-monitoring devices.

2.2. The UC Survey on Forage Growers Utilizing Sub-Surface Drip Irrigation (SDI)

Between 2014 and 2016, our team surveyed 18 commercial alfalfa growers pioneering SDI in the Central Valley and Low Desert of California, through farm visits and structured interviews. We selected progressive alfalfa producers following indications provided by UCCE farm advisors, from the counties of Colusa (1 farm), Yolo (5 farms), Solano (1 farm), Fresno (3 farms), Kings (2 farms), Kerns (3 farms) and Imperial (3 farms), respectively (Figure 1). With the selected case studies, we surveyed approximately 50% of the total alfalfa production area under SDI in California.

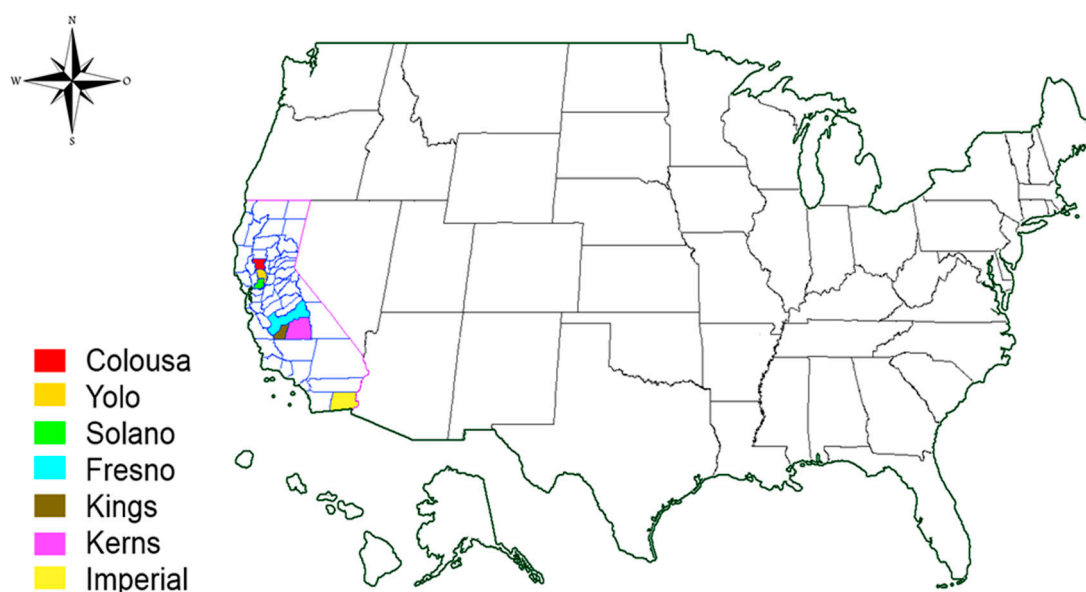


Figure 1. Locations of the case studies selected in California for the survey on sub-surface drip irrigation (SDI) conducted by researchers from University of California Cooperative Extension (UCCE).

During the survey, we gathered information at the visited farms using an ad-hoc questionnaire developed through the Agricultural and Natural Resources Survey Tool of the University of California and centered on aspects of SDI systems' design and installation (dripline spacing, emitter spacing and flow rate, installation depth), operation and maintenance, as well as on advantages and constraints that growers experienced with SDI in alfalfa. The questionnaire included 43 questions with a combined format requiring growers to answer using either multiple choices or their own words. The questionnaire

was sent to the selected growers a few days in advance of the scheduled field interviews. During field interviews, we discussed the different questions and answers, paying specific attention to various challenges facing growers and to solutions they tested and implemented. We also collected the main growers' concerns and reported them in an online "case history" of SDI for alfalfa production, which is currently under development to enable producers learning from each other's experience (<http://ucanr.edu/sites/adi/>). The survey did not gather specific information on flood irrigation systems and practices at the selected farms. However, typical widths and lengths of flood irrigation basins (checks) ranged from 10 m to 30 m, and from 180 m to 400 m, respectively, with individual basins separated by small levies (border checks) about 0.15–0.30 m high. Typical slopes ranged from 0.1% to 0.2%, and no tail water recovery/recirculation or storage/reuse systems were available at the surveyed farms.

A few clear aspects stemmed from the survey, with interviewed growers reporting that:

- ✓ Yield gains are possible with SDI compared to surface-irrigated fields.
- ✓ SDI may allow a reduction of labor requirements and costs for irrigation, as these systems can be semi or fully automated, whereas SI typically requires full-time irrigators to oversee irrigations and adjust flows and shut-off times. However, some extra farm labor is generally necessary with SDI after each cutting for scouting rodent infestations and damages, spotting and fixing dripline leaks, re-testing system functionality after repairs, and trouble-shooting the field monitoring and control devices (soil moisture, ET, flow and pressure control and regulation, etc.). These operations in general require average extra costs ranging between \$20 and \$80 per acre per year, depending on the level of infestation, damages, and other specific issues being addressed.
- ✓ Rodent infestations and damages are experienced during summer in 60% of cases, and year-round in 40% of cases. Growers prevented and/or controlled rodent infestation using different methods such as raptor nest boxes (for hawks and owls), trapping (pincher and box traps), baiting with rodenticides and toxicants (strychnine, zinc phosphide and anticoagulants) using hand probes or mechanical bait applicators, and fumigation of mounds and burrows. Several growers consider rodent damages among the major challenges of SDI in alfalfa.
- ✓ The most common dripline installation depth and lateral spacing in commercial farms are 0.30 m and 1.0 m, respectively.
- ✓ A frequent problem occurring in commercial farms with light soils (sandy and loamy sand) is the limited lateral subbing of water between the driplines. This often lead farmers to irrigate with longer set-times in the attempt to compensate for poor water distribution between the driplines, which cause alternation of wet and dry stripes. When SDI systems are designed and installed, not much attention is given to dripline spacing and to spacing and flow rates of emitters along the driplines to tailor the system capacity and application rates to soil hydraulic features, crop water uptake, and evapotranspiration rates. Although possible solutions to these problems could be deeper SDI installations (>0.30 m) or closer dripline and emitter spacing (see also [35,36]), growers are normally quite sensitive and concerned about the additional costs of closer dripline installations and leak repairs.
- ✓ The high frequency of SDI requires some type of on-farm water storage to buffer for infrequent surface water delivery (7–10 days) by irrigation agencies or water districts; this aspect, along with the need for energy to pressurize and filter water, and the additional cost of storage reservoirs, often leads growers to rely mainly on groundwater pumping for SDI rather than on surface-water supplies, thus further increasing the energy usage of SDI and the potential environmental burdens.
- ✓ In nearly 85% of cases, growers are highly satisfied with SDI in alfalfa, especially during the first two years of operation, and the remainder are medium to less satisfied with the technology. We also found that some growers experienced serious problems with SDI due to uncontrollable

rodent infestations and damages, and lack of skilled on-farm personnel, and finally decided to abandon the SDI technology on alfalfa and revert to flood irrigation.

2.3. Economics of SDI in Alfalfa

Our team developed a preliminary data-driven model to help growers assess the economic viability of SDI for the main alfalfa production areas of California prior to its adoption and installation. The model is based on a relationship between seasonal HY and crop ET from previous studies on SDI-irrigated alfalfa, validated with information from the undergoing studies and the surveyed alfalfa producers using SDI in California [37]. This model provides preliminary economic information to alfalfa growers interested in SDI and enable a general understanding of costs that may be incurred during both the crop establishment and production phases. The model also allow growers calculating the hay yield increments necessary to offset the additional costs of SDI relative to SI, with those increments being closely dependent on the total investment and operational costs of SDI, the hay market price, and the longevity of SDI equipment. This latter aspect is critical to the economic sustainability of the SDI systems and closely related to proper maintenance of the different systems' components (driplines, laterals, mainlines, filters, pump, valves, etc.) in order to increase their life duration (cfr. [25]) and economically justify SDI with prolonged low hay market prices.

The economic analyses suggest that greater HY and WP could be potentially achieved in SDI-irrigated alfalfa relative to flood irrigation as a result of higher DU and irrigation efficiency from better water and nutrient management [37], but the study also recommends more in-depth investigation of aspects related to design, installation, operation and maintenance of SDI systems in alfalfa, and of the main constraints to achieving the potential crop and irrigation performance gains.

3. Key Findings

3.1. Potential for Yield Increase

From the UC survey we found that many alfalfa growers think or experienced that SDI can significantly improve alfalfa yield. Growers interviewed during the survey reported various yield increases that averaged 2.7 tons per acre (~20–30%) with SDI relative to SI under the same farming and climatic conditions. Such increases are within the broad range of yield gains (10–30%) with SDI relative to other irrigation methods documented from previous studies conducted during the 1990s in California, Nevada, the Central Plains and Hawaii [17,37–39]. Studies conducted in California found slightly higher yields with SDI, which increased WP more than using less water [14,40].

Since the 1990s, significant technological improvements have been made in the irrigation industry on SDI equipment and materials (e.g., [41,42]), projecting higher yield gain expectations, but those have mainly targeted applications of SDI to high-value row crops such as processing tomatoes, melons and vegetables. Less attention has been given to adapting SDI systems to agronomic crops such as alfalfa, wheat, or corn, given their relatively lower market values. When growers and the irrigation industry started applying SDI to agronomic and field crops, expectations were mostly driven by the encouraging results documented for processing tomatoes and other vegetable and fruit crops (e.g., [43,44]).

Alfalfa differs from other agronomic crops as it consists of deep-rooted closely-spaced plants, typically utilizing moisture from a deeper soil-root zone to achieve high-yield performance. Irrigation practices in alfalfa are constrained by the harvesting schedule, which often creates built-in drought periods of 12–20 days during which water is not applied to fields, likely resulting in water stress around harvests, from 6 to 10 times per year in the Central Valley and Low Desert of California. Irrigation is usually withheld before, during, and after cuttings to allow multiple passages by field equipment for cutting, curing hay on the ground, raking, baling, and finally for the removal of bales out of the fields. These specific crop and farming aspects of alfalfa require attentive SDI design, monitoring

and management, given the localized water application, non-uniform wetting pattern, and extended duration of SDI events, which typically have lower application rates.

Table 1 reports preliminary values of ETa, HY and WP of alfalfa production under SI and SDI, collected at the UCD Russell Ranch experiment during 2016, averaged over the three replicates, with indications of significant differences between SDI and SI based on statistical tests (analysis of variance (ANOVA) and Tukey's Range Test). From the 2016 field data, we also estimated the energy usage (EN, kWh) and greenhouse gas emissions (GHG, ton-eq. of CO₂) resulting from pumping (groundwater lifting and pressurization) the total water amounts necessary to match the ETa values measured at the SDI and SI plots. The energy usage was estimated using the Nebraska Pumping Plant Performance Criteria (NPPPC) (cfr. [45,46]), developed during the 1960s and recognized as the standards throughout the US. The GHG emissions were estimated using the COMET-Farm online system developed within a partnership between the United States Department of Agriculture (USDA) and Colorado State University (<http://cometfarm.nrel.colostate.edu/Home>). Based on these parameters, we then calculated the energy productivity (EN P, ton·kWh⁻¹) and GHG productivity (GHG P, ton·ton-eq. of CO₂⁻¹) by relating the HY obtained (ton) to the energy used (kWh) and the GHG emissions (ton-eq. of CO₂).

Table 1. Preliminary results on yield, water, energy and greenhouse gas emission footprints and productivities from the UCD–Russell Ranch study.

Parameter	SI	SDI	Difference SDI vs. SI (%)
ETa (mm)	833.1 (ns)	853.4	+2.5
HY (ton·ha ⁻¹)	19.7 (ns)	20.7	+5.0
WP (ton·mm ⁻¹)	0.023 (ns)	0.024	+2.5
EN (kWh)	58.3 (b)	120.8 (a)	+107.2
EN P (ton·kWh ⁻¹)	0.34 (a)	0.17 (b)	−50.0
GHG (ton-eq. CO ₂)	0.022 (b)	0.045 (a)	+104.5
GHG P (ton·ton-eq. CO ₂ ⁻¹)	895 (a)	460 (b)	−48.6

Abbreviations—SI: surface irrigation; SDI: sub-surface drip irrigation; ETa: actual crop evapotranspiration; HY: hay yield; WP: water productivity; EN: energy usage; EN P: energy productivity; GHG: greenhouse gas emissions; GHG P: greenhouse gas emission productivity. Note: Significant differences (Tukey's Range Tests, $p \leq 0.05$) among the treatments are denoted by different bracketed letters (a, b); ns = non-significant.

As far as ETa, HY, and WP are concerned, our data and analyses show very limited gains (2.5–5%) in SDI-irrigated plots, resulting in non-significant differences relative to SI. Significant differences between SI and SDI resulted instead from the statistical tests on the parameters of EN, EN P, GHG and GHG P. In other words, the statistical analysis showed that SDI uses more energy and releases more greenhouse gas emissions (from energy usage for pumping) than SI per unit of alfalfa hay produced.

Results from our experimental trial showed smaller yield gains (~5%) than those reported by the surveyed alfalfa producers, which we think can be related to better performance of SI at the study site compared to that typically achieved in commercial farms. The main reasons for better SI performance are the relatively shorter length of flood irrigation checks at the UCD experiment (100–145 m vs. 350–400 m at commercial production fields); the different scale between commercial fields and the experimental field (30–65 ha vs. 3–4 ha); and the more advanced control of flood irrigation at the experimental field (ability to accurately adjust the flow rates and cut-off times through variable frequency drives, SCADA system and remote control) than typically occurring in commercial conditions.

3.2. Water and Energy Use and Productivity

Three water-related questions often arise when dealing with alfalfa production under SDI:

- (1) Can SDI lead to less water consumption (ETa)?
- (2) Is irrigation water more productive with SDI relative to SI?

- (3) What additional equipment, skillsets and practices are necessary in commercial production farms to pursue higher WP with SDI?

The surveyed growers reported water savings that averaged 20–30% with SDI relative to surface-irrigated fields, while previous studies in California [14,40] documented modest reductions of water use around 6–8%, but also noted that SDI irrigation may increase water use as a result of increased yields, i.e., higher ET may occur with SDI as a result of a denser or taller canopy under well-watered conditions. The preliminary results from our UCD field trial show that ETa values are on average slightly higher in SDI than SI (Figure 2).

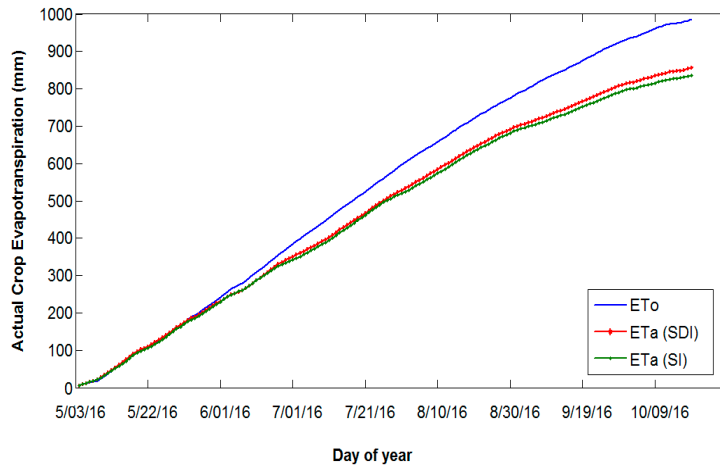


Figure 2. Cumulative actual alfalfa evapotranspiration (ETa) obtained with the residual of energy balance (REB) method through commercial surface renewal (SR) equipment for surface irrigation (SI) and sub-surface drip irrigation (SDI) during 2016 at the UC Davis experiment.

Our data also show that, during individual cutting cycles, the cumulative ETa of SDI and SI may also differ, with similar or slightly higher ETa of SI during the first part of the cycle, and SDI picking up the difference and then slightly exceeding that of SI during the second half of the cycle (Figure 3).

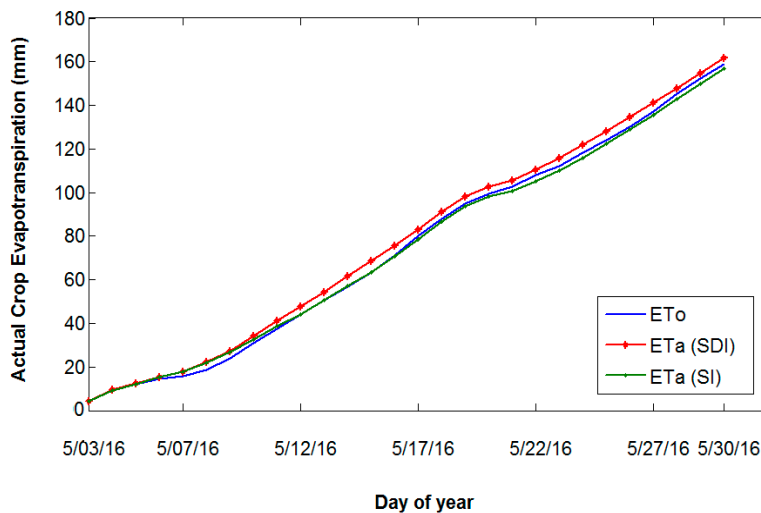


Figure 3. Actual alfalfa evapotranspiration (ETa) during an individual cutting cycle for surface irrigation (SI) and sub-surface drip irrigation (SDI) obtained with the residual of energy balance (REB) method through commercial surface renewal (SR) equipment in 2016 at the UC Davis experiment.

We observed that SI and SDI have similar ETa during the initial part of the cycle. However, since SI wets the entire soil surface when the alfalfa canopy is not yet fully developed (after harvest), we think that higher soil evaporation (E) may occur because the wet soil is exposed to solar radiation for a few days. We also consistently observed faster canopy re-growth by visual inspection in SI than SDI for 6–7 days after flood irrigations over multiple cutting cycles, as plants probably benefit from more complete and abundant soil wetting to a deeper soil layer with SI relative to SDI. Although the dry-down period around cuttings can be shortened with SDI, at the UCD experiment water applications in SDI plots were suspended 8–10 days before cuttings to allow access to the field by harvest machinery. Irrigation resumed after the bales were completely removed from the field (6–8 days after cuttings) to avoid hay molding, due to ground moisture, and the need for longer hay drying on the ground.

In the second part of the cutting cycle, SDI likely allows more canopy growth due to frequent and small water applications (1–2 day irrigation intervals) that enable better matching of crop water needs and avoiding stress periods due either to insufficient soil moisture, too much water or too little oxygen in the root zone. This probably results in producing denser and taller canopy and thus higher crop transpiration (T) in SDI than SI. However, these initial preliminary considerations need some further validation at our field trial across multiple cutting cycles and crop seasons.

Although our field data showed non-significant differences of cumulative ETa in SDI and SI, we think that the higher control on the applied (and soil-infiltrated) water with SDI systems, along with the higher operational flexibility, can reduce on-farm water usage by minimizing in-season losses due to soil evaporation, deep percolation and surface runoff (tail-end drainage) that are frequently occurring with SI. In other terms, reductions in water usage with SDI would mainly result from its superior water application efficiency and DU relative to SI.

Our preliminary results from the UCD experiment also show that higher energy requirements and GHG emissions of SDI (Table 1) than SI result from the need to pressurize water, and should be carefully considered for a thorough resource-efficiency assessment of SDI.

Table 2 reports the calculated units of different energy sources necessary to lift 1000 m³ of water per meter of head, as well as the CO₂ emission factors for the different energy sources obtained from the US Environmental Protection Agency [47].

Table 2. Units of the different energy sources required to lift water and CO₂ emission factors

Source of Energy	Energy Units to Lift Water (Units per 1000 m ³ of Water per Meter of Lift)	CO ₂ Emission Factors (Ton-Eq CO ₂ per Energy Unit)
Electricity	4.12 kWh	0.000379 ton-eq. CO ₂ per kWh
Natural gas (925 BTU)	1.61 m ³	0.0000793 ton-eq. CO ₂ per m ³
Natural gas (1000 BTU)	1.50 m ³	0.0000793 ton-eq. CO ₂ per m ³
Diesel	1.0 liter	0.013717 ton-eq. CO ₂ per liter
Propane	2.0 liters	0.00572 ton-eq. CO ₂ per liter

Note: BTU: British Thermal Units.

These figures provide basic information for growers to calculate the energy cost they will incur using SDI and the amount of CO₂ that will be released to the atmosphere from the different energy sources to pump water. For instance, in case of electric-powered pumps, assuming the cost of electricity in California of \$0.227 per kWh averaged between summer and winter, alfalfa growers will spend \$0.93 and generate 0.000379 ton-eq of CO₂ to lift and apply 1000 m³ of water per each meter of lift. This unit energy cost must be considered in addition to the unit cost of water.

Following the context of resource-efficiency, we calculated the hay production per unit of water consumed. This figure, especially for field crops (forages, grains, fibers, sugarcane), is widely reported in the literature to be “conservative”—in other words for a given crop and agro-climatic conditions, the relationship between water consumption and crop production is linear, as documented for alfalfa by Sammis [48], Shewmaker et al. [49], and Lindenmayer et al. [50]. The important implication of this relationship is that if yield per unit area increases, it is likely that water consumption also increases [5].

The preliminary observations from our UCD experiment showed a 2.5% higher WP of SDI relative to SI during the first crop season (2016). We think that higher WP could potentially be generated with SDI as a result of the key mechanisms described below:

- i The possibility with SDI to increase the crop transpiration fraction (T) of applied water. SDI systems typically deliver small water amounts in the vicinity of plants' roots without wetting the soil surface, thus reducing the potential for soil evaporation (E). The higher level of control of SDI on water applications can also minimize non-consumptive water losses that may occur by deep percolation and surface runoff. Moreover, SDI systems have the ability and flexibility to tailor water applications and better match alfalfa ET during different growth stages within individual cutting cycles and along the entire crop season. With SDI, growers can also apply small amounts of water closer to and soon after the cuttings, thus maximizing the crop transpiration while reducing the risk of crop exposure to insufficient and excessive soil moisture before, during and after harvesting, which may adversely impact re-growth. The combination of SDI with adequate irrigation scheduling (ET-based, SM-based, or a combination of the two methods) can potentially increase alfalfa water uptake and beneficial use (T), while minimizing water stress to plants, and thus possibly increase the forage production, which is linearly related to actual crop ET (e.g., References [38,42,48–50]).
- ii The ability of SDI to establish and maintain better soil-water and aeration conditions. Well-designed and properly operated SDI systems have significant advantages in maintaining more uniform soil water distribution (see [24,51,52]) over time that is beneficial for the plants' roots, and avoid long wetting-drying cycles and resulting large soil moisture fluctuations in the root zone during growth periods (particularly before and after cuttings) that are typical of SI methods. All this likely contributes to enhancing the presence and circulation of oxygen in the root zone, which is beneficial to root growth and activity. Also, the SDI's operational flexibility allows the establishment and maintenance of unsaturated soil water conditions and possibly net upward hydraulic gradients, and targeting adequate soil moisture for optimal plant growth and farming practices (pest and weed control, cuttings, hay-curing, racking, baling, bales removal, etc.). As a result, with SDI the majority of water-uptake roots commonly develop and thrive within a shallower soil depth (Figure 4) where good moisture and aeration conditions are maintained, reducing the risk of soil saturation and root asphyxia. However, it must be noted that shallower root systems may also incur some risk of water stress in case of insufficient water applications, irrigation scheduling mistakes, SDI system failures, or when the SDI system is down for either functionality problems or maintenance, or during heat spells when the SDI system capacity cannot keep up with high ET rates.

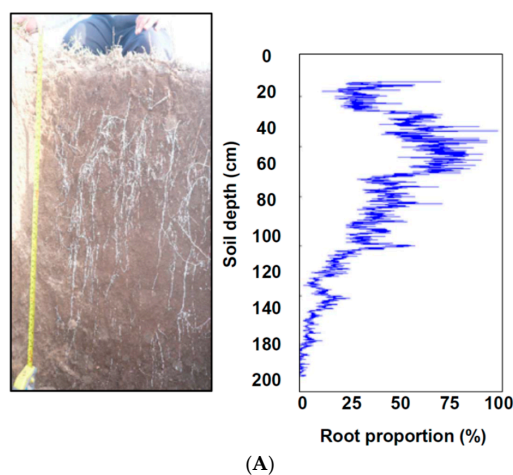


Figure 4. Cont.

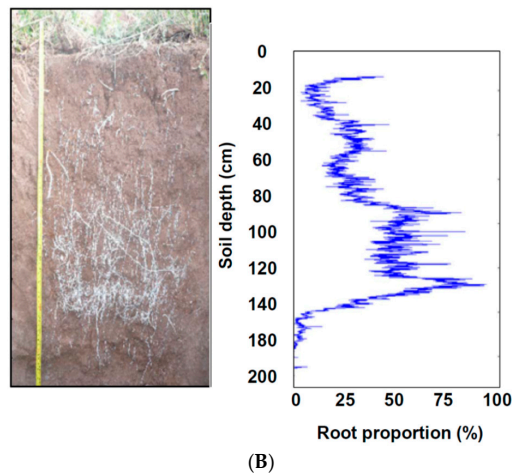


Figure 4. Different rooting patterns of alfalfa under: (A) sub-surface drip irrigation; and (B) surface irrigation. (Source: Courtesy of UC Desert Research and Extension Center, Holtville, CA, 2015).

The full deployment of potential improvement of soil-water-air conditions entails the use of soil moisture monitoring devices, which, together with SDI’s operational flexibility and better control on water applications, can contribute to more water-efficient irrigation regimes than with SI. Soil moisture monitoring is in fact key to providing relevant information for effective irrigation scheduling with SDI, as shown in Figure 5 where soil moisture tension values and trends are displayed for SI and SDI during an individual cutting cycle at the UCD field experiment.

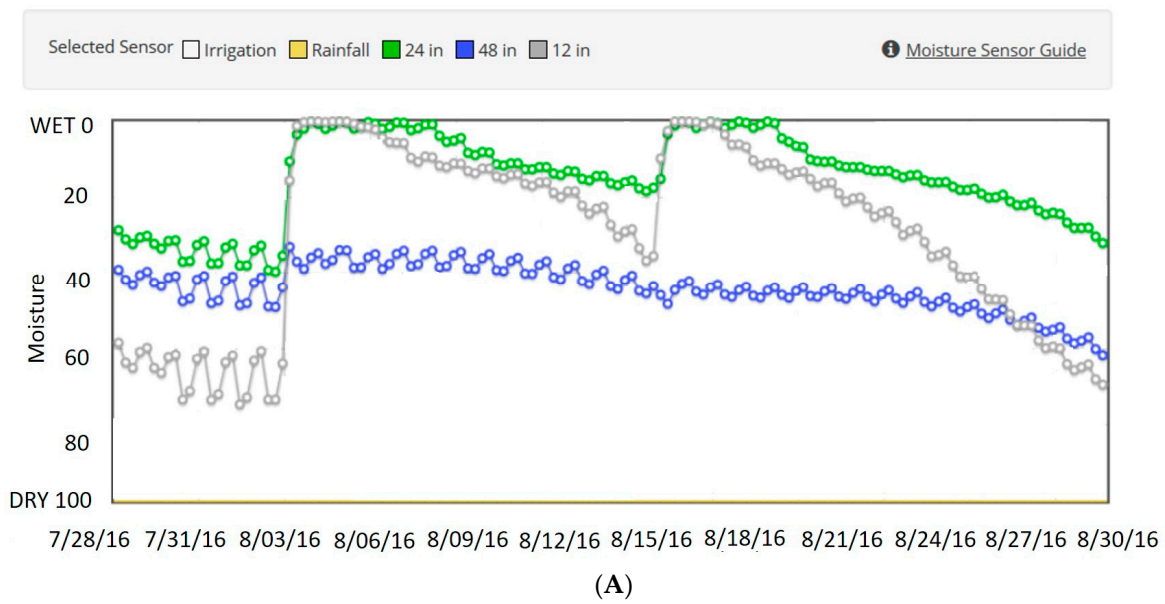


Figure 5. Cont.

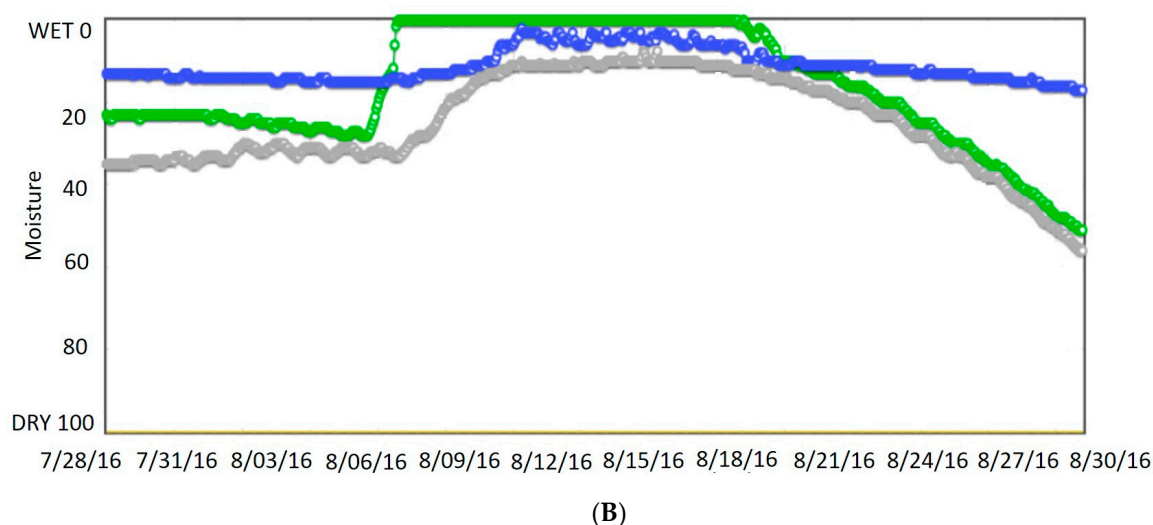


Figure 5. Soil moisture tension (Centibars) at 0.30, 0.60 and 1.20 m deep (12, 24 and 48 inches) in (A) surface irrigation (SI); and (B) sub-surface drip irrigation (SDI), at the UC Davis experiment for an individual cutting cycle in 2016.

- iii The ability of SDI to tailor applications of water to plants with higher control, better DU, in a timely and time-uniform mode across the entire field. From our experience, a unique advantage of SDI results from higher uniformity of water application over space and time. With SI, as well as with periodic and continuous-move sprinkler irrigation (center pivots, linear moves, wheel lines, reel lines, etc.), some sections of the field (usually the distal ends from where irrigation starts) receive water later than others (and sometimes in different amounts), as it normally takes hours or even days to get water across the entire field. On the contrary, properly designed and operated SDI systems can achieve far superior DU over the entire field (Putnam et al. [3]), and apply similar water amounts to the different field sections with similar timing, reducing the risk of tail-end areas being exposed to water limitations due to delayed or non-uniform irrigation applications.

The information our team collected from the UCD field trial and surveyed growers is in line with findings from earlier studies [3,14,36,40,53,54], indicating that greater WP could potentially be achieved with SDI relative to SI as a result of better irrigation management. However, the following considerations can help explain the differences between our field observations and growers' claims on water savings, HY and WP gains of SDI with respect to SI:

- ✓ At the UCD Russell Ranch experiment, alfalfa was established in January 2016 and thus our preliminary data and observations refer to the first crop season, whereas claims by most of the surveyed growers refer to 2–3-year old stands. From our viewpoint, more comprehensive evaluation of SDI must be conducted to encompass the entire crop duration, i.e., 3–5 years, typical of Central and Southern California.
- ✓ During the survey and while collecting field data at the UCD experiment, we reached the conclusion that SI in commercial alfalfa fields may normally achieve lower irrigation efficiency than in our research experiment. At the UCD experiment, surface runoff and tail end drainage are minimized during flood irrigations thanks to shorter checks than those of commercial production fields and as a result of better monitoring of the water advance front; the ability to maintain and/or adjust flow rates with pumps equipped with variable frequency drives (VFD); and thanks to more precise control on water applications and cut-off times. This advanced management capacity is often not available at commercial production fields.
- ✓ Water savings claimed by the surveyed growers may not account for occasional flood irrigations that are necessary in SDI fields to refill the soil profile (after dry winters or during and after

heat spells), control rodent infestations, and leach salts accumulated in the soil root zone (the questionnaire did not consider leaching practices), which cannot be easily achieved with SDI. Growers' claims may also only refer to individual crop seasons, while salt build-up and rodent infestations often occur with increased frequency and intensity over the course of multiple crop seasons. In addition, some significant difference in water use may arise from the different scale of commercial fields (30–65 ha) vs. that of our experimental field (3–4 ha).

- ✓ The surveyed growers and irrigation industry may also often report their perceptions rather than facts, which are not necessarily based on consistent measurements of ET, applied water and yield performance parameters.

More skilled irrigation management by farm personnel in combination with advanced monitoring (ETa, soil moisture sensors, flow meters) and control technologies (driplines with pressure-adjustable emitter flow, pressure control and regulation devices, volume- or time-control automated flow valves, VFD-pumps, telemetry systems) are typically needed to deploy the full advantages of SDI and gains in crop and irrigation performance. These devices can help growers avoid long wetting–drying cycles, and prevent water stress to plants due to deficit and excessive water applications during growth stages through more attentive monitoring of crop water-uptake rates (ETa) and soil moisture variations.

Contrasted with SI systems, where only one or two irrigations between alfalfa harvests are feasible (see [11]), timelier, more precise and adjustable, water applications are key aspects for yield gains utilizing SDI. ET-based irrigation scheduling coupled with feedback collection from flow meters and SM monitoring equipment are key to the success of SDI. This normally entails significant investment costs, but also requires farm managers and irrigators to have an understanding of soil- and plant-water dynamics, of irrigation system features and operations, and the ability to trouble-shoot field monitoring and control equipment quickly.

3.3. Irrigation Management

Our team observed that with SDI water can be applied following at least three alternative irrigation management strategies within individual cutting cycles, as described hereafter with indications of relative advantages and drawbacks:

- (1) Apply water evenly along the cutting cycle. In this case, the amount of water necessary to meet the actual crop evapotranspiration of each individual cutting cycle is evenly distributed over the useful days for irrigation, thus applying fixed irrigation depths at regular intervals. As an example, in our UCD field trial each individual cutting cycle normally lasts 28–30 days, with about 14–16 days available for irrigation and the need to withhold water at least 8 days prior to cutting and for at least 6 additional days after cutting for drying hay on the ground, raking, baling, final removal of hay bales, rodent control and leak repairs prior to start irrigation for the new cutting cycle. On 28- to 30-day cycles, we normally measured cumulative ETa of about 205–215 mm, corresponding to daily irrigations of about 15 mm over 14 useful days for irrigation. Although this irrigation schedule is quite straightforward and easy to implement by farm personnel, plants might incur some water stress during the dry-down periods, and re-growth might be somehow slowed down due to small water applications at the start of the new cutting cycles that may not be sufficient to refill the root zone to optimal soil moisture for rapid growth.
- (2) Apply water according to ETa rates. In this case, an ET-based irrigation schedule is followed, applying water amounts to meet the measured ETa, or estimated crop ET (ETc) using the reference ET for grass (ETo) and crop coefficient (Kc) method ($ETc = ETo \times Kc$). The irrigation schedule consists of small irrigations after harvest and at re-growth, progressively larger irrigations as the cycle progresses and canopy grows, and more consistent water applications when the crop approaches full canopy and towards cutting. This irrigation schedule requires accurate monitoring of ETa and frequent checking of application rates and applied water, and can create

some risks related to higher water applications during the second part of the cycle. This may delay cutting due to relatively higher soil moisture, or eventually extend the hay curing period on the ground for a few extra days. Some water deficit at re-growth might result from the delayed harvest.

- (3) Relatively larger water applications at the start of the cutting cycle. Since water is withheld for a period of 10–15 days around cuttings and harvest time, with this irrigation management practice water is applied in larger amounts during the first 4–5 days of the new cycle to quickly refill the soil, minimize stress at re-growth, and build up some soil water storage for later use by plants. The rest of the water is then applied with small depths during the remaining useful days for irrigation. As an example, out of an average ETa of 205–215 mm during the individual cutting cycle, 90–100 mm can be applied within the first 4 days and the remaining water can be applied evenly over the remaining 10–12 useful days. The advantage of this irrigation practice is to stimulate fast canopy re-growth, build some deep soil water storage that plants can use later in the cycle, and minimize the risk of both water stress and excessive soil moisture towards the cutting and harvest, thanks to small and frequent water applications in amounts lower than the peak daily ETa occurring during the last part of the cutting cycle. We observed that in silty clay-loam soils this latter irrigation schedule with decreasing water applications, relative to increasing crop water needs along the individual cutting cycles, may work best and minimize risks of water deficit and excessive soil moisture.

However, the proper implementation of any of the three above-indicated irrigation management strategies entails monitoring crop ET and soil moisture by means of reliable field devices, and high-level control of water applications through pressure and flow regulation, periodic checking of actual flows and application rates, and adequate volume- or time-based irrigation sets.

Regardless of the irrigation scheduling method and strategy used, we think that farmers growing alfalfa with SDI should maintain in place the infrastructure and operational capacity to conduct flood irrigations at some point during the crop season to: (a) recharge quickly the soil profile after dry winters and prior to stand re-growth in spring; (b) prevent and control rodent infestations; (c) buffer the limited capacity of SDI to cope up with high ET before and during heat spells; (d) offset irrigation scheduling mistakes and potential problems with SDI, such as consistent rodent damages that cannot be fixed during the short time window (5–6 days) between hay harvest and plant re-growth; and (e) leach out the eventual salts accumulated in the root zone.

4. Need for Further Research on SDI

Although recent applications by alfalfa growers pioneering SDI appear promising in terms of potential yield and WP increases, our team perceived some design, operation, and management challenges that call for further research and outreach efforts.

4.1. Design Aspects

More in-depth investigations are required about the impacts of soil hydraulic properties (hydraulic conductivity, soil texture and structure, water-holding capacity, redistribution and retention of soil water) on design and operational parameters, with specific attention to the selection of adequate dripline spacing, depth of installation, emitter spacing and flow rate, and irrigation set-times.

Soil hydraulic properties must be considered for selecting dripline and emitter spacings, emitter flow rates, adequate application rates, irrigation timing, frequency and duration, as well as other factors such as the system's operational pressure, and the need to refill the soil root-zone with water and leach salts. In this regard, soil-specific SDI design and operational recommendations should be developed to enable growers schedule irrigations; establish and maintain unsaturated soil moisture conditions; balance upward/downward and horizontal hydraulic gradients from driplines; and allow uniform redistribution of water while preventing surface wetting, poor soil aeration and unnecessary deep percolation that may result from application rates exceeding the saturated hydraulic conductivity.

Soil compaction, excessive application rates and over-irrigation may cause hydrostatic pressure in some soils that impede free flow from emitters and adequate soil moisture redistribution, lowering the actual application rate and DU. Moreover, understanding how the SDI system's sensitivity to hydraulics translates into soil-water dynamics, water redistribution in the soil root-zone and resulting crop performance represents another important knowledge gap that is necessary to address. In general, inadequate SDI design commonly lowers investment costs, but often leads to higher operational costs and lower WP due to longer irrigation set-times that growers conduct in the attempt to compensate for inadequate wetting, poor water distribution, and sub-optimal yields. In other words, SDI performance depends upon the system's hydraulic and operational parameters (flow rate, pressure, and their variations), which in turn affect the soil-water-plant interactions, given that point-source water discharges get redistributed in the soil following hydraulic and osmotic gradients.

Some of the interviewed growers reported unsatisfactory performance of SDI due to inaccurate system designs, while other regretted not paying enough attention to the careful selection of soil-specific design parameters, such as dripline spacing, emitter spacing and flow rates, application rates, operational pressure, and system capacity. Further research efforts focusing on soil-specific design solutions of SDI systems are necessary to avoid costly mistakes that may result in unsuccessful stories with SDI in the alfalfa production community.

4.2. Costs

Some research questions concern the relative sensitivity of SDI's investment and operational costs to design parameters related to crop, soil and climate. Most SDI systems entail a 6–15-year system life span across multiple crops within typical rotations, with the delivery infrastructure (pumps, main lines, manifolds, submains, filters, etc.) having a longer economic life (12–15 years or longer) than the driplines (6–10 years). As an example, increased or adjustable flow discharge capacity of SDI systems may be necessary to quickly recharge soil moisture with shorter sets during dry periods and heat spells, or to minimize energy costs under tiered energy tariffs from the power grid (on-peak vs. off-peak hours). Another example concerns the role of proper maintenance of the different SDI components to increase their longevity and allow longer cost recovery periods, thus decreasing the annual cost recovery rates. Investigating how system capacity affects investment and operational costs would enable better informed design decisions towards the achievement of yield and cost targets.

4.3. Salinity Management

Control of salt build-up in the root zone may be challenging under SDI, as salts brought to soil with irrigation water, nutrients and fertilizers usually concentrate along the wetting fronts between and above the driplines, affecting plants' water uptake and growth. Limited rainfall may not be sufficient to dilute and leach out the accumulated salts. Further research is necessary to understand the dynamics of soil moisture and salt movement under saline soils and with water applications through various dripline spacings and emitter characteristics in different soil types, and to appraise alternative options for salt leaching. Maintaining the capacity on the field to conduct either surface or sprinkler irrigation for leaching management is also crucial when adopting SDI systems.

Leaching requirements and frequencies depend on several factors, including rainfall and its distribution, irrigation water and soil salinity, dripline depth, and soil texture, and should be calculated for each field also on the basis of actual crop evapotranspiration. For instance, with water salinity exceeding $1.0 \text{ dS}\cdot\text{m}^{-1}$, an additional 10–15% of water is approximately needed for salt leaching. For water salinities exceeding $1.0 \text{ dS}\cdot\text{m}^{-1}$ and crop evapotranspiration above 500–600 mm per year, approximately two surface irrigations during the year will be sufficient to leach salts out of the root zone. For water salinities between 0.5 and $1.0 \text{ dS}\cdot\text{m}^{-1}$ and evapotranspiration rates around 600 mm per year, leaching every other year is sufficient to maintain the salinity level below the yield reduction threshold.

Although alfalfa is considered moderately sensitive to salts, maintaining soil salinity below 4–5 dS·m⁻¹ is recommended. Applying the extra water with SDI is not advised as it is ineffective in removing salts above and between driplines, whereas both surface and sprinkler irrigation systems are much more efficient in leaching salts. The use of surface or sprinkler irrigation in addition to SDI would also be beneficial for establishing and irrigating crops such as wheat, Sudan grass, or other cover crops within typical crop rotations to alfalfa.

4.4. Plant-Based Irrigation Management

Valuable information could result from experiments aiming to quantify the reduced evaporative cooling of alfalfa canopy under SDI as opposed to sprinkler and surface irrigation methods, and of its effects on canopy health, growth rate, and on the quality of hay production (fiber and protein contents) on different soils. Recent studies conducted on corn and cotton [55–57] raise research questions about the relationships between canopy temperature, hay yield and quality, and WP, which could be addressed through specific applied research efforts, and can lead to development of plant-based irrigation scheduling for resource-efficient alfalfa production with SDI.

4.5. System Monitoring

A strong limiting factor with SDI is the lack of visual indications of system's operation and performance (e.g., [58]), given that water is discharged through buried driplines. Growers and irrigators must rely on sensors and telemetry to monitor and report on irrigation operational and performance parameters. In this respect, research could target the development of reliable and affordable closed-loop irrigation and feedback control systems that integrate information from relevant field-monitored parameters, such as ETa, SM, flow and pressure, relating those to crop- and soil-specific thresholds, and alerting growers about successful irrigation events or potential problems. Such monitoring systems could eventually operate based on machine-learning techniques to provide growers with increasingly accurate feedback, and enable semi- or fully-automated irrigation scheduling with SDI.

4.6. Dripline Materials

Several growers reported that rodent infestations and damages to driplines are among the major challenges of SDI in alfalfa. When rodent infestations occur and cannot be properly controlled by growers, repairs of rodent damages can become quite onerous and troublesome given the limited time window available and the peak-demand for field labor. As a matter of fact, field crews can repair leaks only within the 5–6 days between harvest and plant re-growth, and any delay in irrigation due to leak repairs may result in water deficits at the sensitive alfalfa re-growth stage. In addition, repair of multiple leaks along dripline sections can also cause stand loss due to excessive wetting/ponding, soil compaction and spoiling of plant crowns. These issues call for research efforts aimed at developing and testing new materials and solutions for cost-effective driplines that could repel rodents and eventually resist damages.

4.7. Deficit Irrigation

Summer deficit irrigation practices on alfalfa using surface irrigation in Central and Southern California often yields partial or even complete loss of alfalfa stand at the end of the deficit irrigation cycle (July through September) due to the lack of sufficient moisture to sustain alfalfa roots toward the end of cycle. Deficit-irrigated fields often require re-seeding and stand re-establishment prior to returning to full production. SDI could be used to minimize the impact of summer deficit irrigation on stand loss and minimize the need for re-seeding/re-establishment after deficit-irrigation practices. SDI could be used to keep roots hydrated during the end of the deficit period by applying small water amounts to maintain sufficient moisture level in the root zone, and sustain healthy alfalfa roots.

Further research is necessary to evaluate the use of SDI for implementing different deficit irrigation strategies (sustained deficit, irrigation cut-backs, combinations of full and partial irrigation, etc.) as well as their impact on hay yield and quality.

4.8. Other Research Needs

Knowledge gaps exist on qualitative aspects of hay production attainable under SDI with respect to other irrigation systems. In this regard, research studies should target the effect of different irrigation methods (surface, sprinkler and SDI) and practices (full irrigation and different levels of deficit irrigation) on quality-related aspects, such as the fiber and protein contents of hay. Our UCD study did not include comparative evaluations of hay quality from SDI and SI, but the forage production community would benefit from research efforts on those aspects.

Further research should focus on the application of fertilizers and chemicals through SDI driplines. Alfalfa does not require nitrogen (N) applications, given the ability of *Rhizobium* bacteria on its roots to fix the atmospheric N in sufficient amounts in the soil, but phosphorus (P) and potassium (K) are essential nutrients that must be applied in adequate amounts to sustain alfalfa production. In fact, alfalfa yield significantly decreases and productive stand life shortens if these nutrients are inadequate in the soil root zone. Both P and K can be efficiently supplied to plants' roots by fertigation through the driplines. Specific research is needed to understand the effects of SDI fertigation regimes on alfalfa yield and quality.

Finally, research could appraise the effectiveness of chemical applications through the SDI driplines to maintain the soil pH near neutrality (pH ~ 7) to allow *Rhizobium* bacteria-fixing nitrogen for use by the alfalfa plants, as well as of fumigants and rodenticides to repel and control rodents.

5. Concluding Remarks

Due to severe and prolonged water shortages and supply restrictions in California, the alfalfa production community is becoming increasingly interested in the SDI technology to improve HY and WP. Although substantial improvements in the SDI technology and components have been made in the last 15 years, key limitations still exist in the application of this irrigation technology to alfalfa production that call for additional research and educational efforts. Those should focus on design, operation and management aspects to address major knowledge gaps and growers' concerns, and develop reliable and affordable monitoring and automation solutions.

Although one must be cautious about its shortcomings, the potential ability of SDI to achieve higher yields through more accurate irrigation management should be further explored as a viable strategy for water-efficient alfalfa production systems to cope with increasingly limited water supplies that are likely to be a key feature of California's future. SDI systems require frequent delivery of water supply by irrigation districts or collective distribution networks, have higher energy requirements, and generate higher GHG emissions than surface irrigation systems due to water pressurization. However, we think that some HY and WP gains could also be attained from improved surface irrigation practices aimed at increasing irrigation efficiency by reducing deep percolation below the root zone and surface runoff. All these aspects should be carefully evaluated in regard to the economic added value of crop production vs. the total costs and environmental externalities of SDI technology.

In our opinion, the agricultural and regulatory communities should give adequate attention to the economic and environmental performance of different irrigation methods and practices with the aim of pursuing more eco-efficient food production in California.

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