A goal programming approach for balancing diet costs and feed water use under different environmental conditions

J. Qu,¹ T. C. Hsiao,² E. J. DePeters,¹ D. Zaccaria,² R. L. Snyder,² and J. G. Fadel^{1*}

¹Department of Animal Science, University of California, Davis 95616

²Department of Land, Air and Water Resources, University of California, Davis 95616

ABSTRACT

Water is essential in livestock production systems. In typical dairy production systems, 90% of the total water used by a dairy farm is attributed to feed production. Theoretically, ration manipulation is a method to potentially reduce the irrigation water needed for feed crops without dramatically increasing diet costs. However, published quantitative studies on the relationship between feed production and water use that are integrated with linear programming models are scarce. The overall objective of this study was to develop an optimization framework that could achieve a balance between minimization of dietary costs and dietary irrigation water usage, and that could be used as a framework for future research and models for various livestock production systems. Weighted goal programming models were developed to minimize the dietary costs and irrigation water usage for a hypothetical cow under 8 different environmental scenarios. The environmental conditions used a $2 \times 2 \times 2$ factorial design, including 2 atmospheric CO₂ concentrations (400 and 550 ppm), 2 water years (dry and wet), and 2 irrigation methods (furrow and drip). A systematic weighting scheme was used to model the trade-off between minimizing diet cost and minimizing irrigation water use for feedstuffs. Each environmental condition generated a set of distinct diets, which each met the same nutrient requirements of the hypothetical cow but had a different water usage when the weighting scheme was changed from weighting minimum diet costs to minimum irrigation water usage. For water resource planning in areas of dairy production, this set of unique solutions provides the decision maker with different feeding options according to diet cost, water usage, and available feeds. As water was more constrained, dietary dry matter intake increased, concentrations of neutral detergent fiber, ether extract, and energy decreased, and the concentration of lignin

increased because less nutritive but more water-saving feedstuffs were included in the diet. Mitigation costs of water usage were calculated from goal programming results and indicated that the potential value of water under water-limited conditions (e.g., in a drought region) was higher than that under water-sufficient conditions. However, a smaller increase in feed costs can initially significantly reduce water usage compared with that of a least-cost diet, which implies that the reduction of water usage through ration manipulation might be possible. This model serves as a framework for the study of irrigation water usage in dairy production and other livestock production systems and for decision-making processes involved in water resources planning in the broader area of animal production.

Key words: goal programming, diet formulation, water usage, environment

INTRODUCTION

Water use in agriculture depends on the level of demand and the geographical region. For example, water demand in a dairy production system includes major components associated with animal consumption, animal cleaning, crop irrigation, milk cooling, and equipment cleaning. A comparative study of the water footprints in poultry, pork, and beef production (Gerbens-Leenes et al., 2013) concluded that, in general, beef production has a larger total water footprint than either poultry or pork production. Beckett and Oltjen (1993) estimated water requirements in a beef production system and reported that 97% of the total water was used for irrigation of feed crops and pasture. Similarly, more than 90% of the total water used on a dairy farm has been attributed to feed production (Innovation Center for US Dairy, 2013). Dairy producers focus on minimizing feed cost when formulating a diet for their animals, but they typically do not consider the water usage associated with feed production.

In past decades, several standards have established the nutrient requirements of animals and the chemical composition of selected feeds (e.g., INRA, 1989; NRC,

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*Corresponding author: jgfadel@ucdavis.edu

Table 1. Table of terminologies, definitions, and relationships of variables in the AquaCrop model (<http://www.fao.org/aquacrop/en/>)

Terminology	Definition	Relationship
Crop evapotranspiration (ET_c , mm)	The maximum evapotranspiration/water requirement of a specific crop.	
Effective rainfall (R_e , mm)	The depth of rainfall that contributes to ET_c ; it does not include the water that is lost to surface runoff or percolation below the rooting depth.	
Change in soil water content (ΔSW , mm)	Change in soil water content from the pre-season stored soil water content to the post-season soil water content.	
Evapotranspiration of the applied water (ET_{aw} , mm)	The depth of irrigation water that contributes to ET_c during a cropping season.	$ET_{aw} = ET_c - R_e - \Delta SW$
Net irrigation application (NA , mm)	The depth of irrigation water that contributes to ET_c in the i th irrigation event.	$ET_{aw} = \sum_{i=1}^n NA_i$
Gross irrigation (GA , mm)	The depth of irrigation application in one irrigation event.	
Application efficiency (AE)	The fraction of GA that either wets the plants or is stored in the root zone and contributes to ET_c .	$AE = NA/GA$
Water productivity (WP , kg/m ³ of water transpired)	The ratio of biomass production (B , kg/m ²) to transpiration (Tr , m ³ /m ²).	$WP = B/Tr$
Harvest index (HI , kg of yield/kg of biomass)	The ratio of economic yield (Y , kg/m ² ; e.g., grains proportion of crop) to total aboveground biomass on a DM basis (Hay, 1995).	$HI = Y/B$

1989, 2001). These standards led to more accurate estimates of dairy nutrient requirements and provided a base for least-cost diet formulation. To incorporate feed water use with diet costs, estimations of irrigation water used in feed production and the relationship between biomass production and water use for feed crops must be quantitatively integrated.

Many terms are used relative to irrigation requirements; their abbreviations, definitions, and relationships are described in Table 1 and used below. Estimation of crop irrigation requirements involves optimal resources planning, which requires the estimation of the total evapotranspiration of the applied water (ET_{aw}), which is the depth of gross irrigation (GA) that contributes to crop evapotranspiration (ET_c) during a cropping season. Water agencies use ET_{aw} divided by an estimated mean seasonal application efficiency (AE) to determine how much water to divert for the irrigation of various crops. Because of the close relationship between ET_{aw} and irrigation water requirements, several programs for estimating ET_{aw} (e.g., SIMETAW, CUP+, and Cal-SIMETAW) have been developed to inform irrigation planning for arid and semi-arid states such as California (Snyder et al., 2012; Orang et al., 2013). Transpiration (Tr) is often difficult to separate from ET_c ; therefore, water productivity (WP) is estimated as biomass production (B) divided by ET_c (instead of B/Tr with appropriate unit adjustments) and indicates the biomass production per unit of total water requirements of crops (Zwart and Bastiaanssen, 2004). Crops with the same production but requiring less water consumption or with higher production from same water consumed will have higher WP values (Zwart and Bastiaanssen, 2004). However,

the WP of a crop varies with climate and irrigation water management. For most crops, only a portion of biomass contributes to yield production. Hence, harvest index (**HI**) is used when a portion of entire plant is used as feedstuff. Based on these 2 complex research areas, a dynamic crop growth model, AquaCrop (<http://www.fao.org/aquacrop/en/>), was developed by the Food and Agriculture Organization of the United Nations (FAO, Rome, Italy) to simulate practical biomass yield with the water use of various herbaceous crops under different weather conditions and irrigation management schedules (Steduto et al., 2012). The model is parameterized and validated for several crops and is frequently used to assess the impact of climate change around the world.

To study the relationship between dietary costs and irrigation water used when formulating a diet, an optimization technique, such as linear programming (**LP**), can be used. Moraes et al. (2012) developed an LP model to balance the diet costs and the methane emissions for dairy cattle under different hypothetical greenhouse gas environmental policies. A goal programming (**GP**) approach was used by Moraes et al. (2015) to model trade-offs between minimizing diet costs and minimizing methane emissions. Theoretically, ration manipulation is a method to potentially reduce irrigation water for feed crops of dairy cows without dramatically increasing diet costs. Therefore, a GP model is considered applicable for exploring the trade-offs between minimizing diet cost and minimizing irrigation water usage for feed production.

Although several studies have been conducted to minimize feed costs on dairy farms, few published studies have integrated dietary water usage into a diet-

cost formulation model under different environmental conditions (White et al., 2014; White, 2016). The relationship between irrigation application and biomass production has been logically developed in the model through AquaCrop, which was not incorporated in the previous papers. The research presented in this paper is a first attempt to integrate these 2 areas under changing biological conditions. In this context, the overall purpose of this study was to develop a GP model to examine the trade-offs between minimizing diet costs and minimizing feed irrigation water under different environmental conditions. The specific objectives of this study were to (1) examine the changes in irrigation requirements of feed crops under different weather conditions; (2) explore the relationship between diet costs and irrigation water requirements; and (3) propose a model that can examine the trade-offs between minimizing dietary costs and minimizing irrigation water for feed crops, and that can be used as a catalyst for future studies and models in this area.

MATERIALS AND METHODS

Model Development

The model was structured in 3 sequential parts. In the first part, a least-cost LP model was developed to minimize the dietary costs. In the second part, a least-water LP model was developed and solved to minimize the irrigation water used for feed crops. Different environmental conditions were considered for this model, which resulted in different solutions. Finally, a weighted GP model integrating the results from the first 2 parts was developed and solved for the joint minimization of diet costs and irrigation water used for feed production under the various environmental conditions that were tested.

General Description of the Model

Models were constructed to deliver the nutrients required to sustain the average milk production characteristics of the 39 dairies described by Castillo et al. (2013). The average values describing these dairies were summarized by Moraes et al. (2015) as follows: the milk yield was 31.2 kg/cow per day, the concentration of milk fat was 3.58%, and the concentration of milk protein was 3.08%. In addition to these inputs, BW of the cow was assumed to be 650 kg, with no change in body reserves, and DIM was assumed to be 104 d. The timeframe of this model was 1 d. A diet was formulated to meet the minimal nutrient and energy requirements for this hypothetical cow. Nutrient requirements were mainly calculated according to NRC (1989). NRC

(1989) was used instead of NRC (2001) because the requirements of protein from NRC (2001) are expressed as the requirements of RUP and RDP, which vary according to actual DMI, concentrate proportion, NDF proportion, and TDN value of the diet. In addition, the requirements of some minerals from NRC (2001) vary depending on actual DMI. These criteria change after each LP solution, so that an iterative approach was required and convergence was not possible in most cases. However, feeds (Table 2) and feed composition used in the diet formulation were from NRC (2001) because of the more accurate and updated information available. The irrigation water required for specific feeds under different environmental conditions was calculated with the AquaCrop simulation model (Steduto et al., 2012). Additionally, both LP models were solved using the lpSolve package programmed in R (Buttrey, 2005).

Least-Cost Model

The first LP model was formulated to minimize diet costs while meeting the nutrient requirements for the hypothetical cow. The objective function (Eq. [1]) and

Table 2. Feed limits and feed costs

Feed	NRC Entry No. ¹	Limit ²	Cost ³
Almond hulls	2	No limit	0.18
Sugar beet pulp	11	No limit	0.23
Corn dried distillers grain	23	0.1	0.25
Corn gluten feed	24	0.15	0.23
Corn gluten meal	25	0.1	0.69
Cracked corn grain	26	No limit	0.23
Steam flaked corn grain	28	No limit	0.23
Corn silage	35	No limit	0.12
Whole cottonseed with lint	37	0.25	0.27
Legume hay	77	No limit	0.31
Legume silage	83	No limit	0.31
Beet sugar molasses	88	0.05	0.18
Sorghum hay	101	No limit	0.21
Sorghum silage	102	No limit	0.21
Wheat hay ⁴	117	No limit	0.21
Wheat middlings ⁴	118	0.15	0.18
Wheat silage ⁴	119	No limit	0.21
Sodium chloride	6-04-152	No limit	0.23
Mineral A ⁵	—	No limit	0.96
Mineral B ⁶	—	No limit	0.69

¹Entry numbers refer to Tables 15–1, 15–2a, and 15–3 in NRC (2001).

²In kg/kg of diet DM.

³In \$/kg of DM. Feed costs are mainly from the Penn State price list (V. Ishler, Pennsylvania State University Extension, University Park, personal communication, June 14, 2018). Almond hulls, cracked corn grain, and steam flaked corn grain prices were collected locally. Sodium chloride, mineral A and mineral B prices are from Moraes et al. (2012).

⁴Wheat products are limited to a total of 0.2 kg/kg of diet DM.

⁵Contained 15% Ca and 21% P.

⁶Contained 22.5% S, 18% K, and 11.5% Mg.

the constraints that determine the feasible region (Eq. [2–4]) are described below:

$$\min z_1 = \sum_{j=1}^n c_j x_j, \quad x_j \geq 0, \quad [1]$$

$$\sum_{j=1}^n a_{ij} x_j \geq b_i, \quad i = 1, \dots, m, \quad [2]$$

$$l_i \leq \frac{\sum_{j=1}^n x_j \varphi_{ij}}{\sum_{j=1}^n x_j} \leq u_i, \quad i = m+1, \dots, m+d, \quad [3]$$

$$\sum_{j=1}^n x_j \leq h, \quad [4]$$

where z_1 represents the total dietary costs (\$), c_j is the cost of feed j (\$/kg of DM), x_j is the amount of feed j (kg of DM), and n is the number of decision variables (i.e., feedstuffs) in the LP model. Equation [2] sets the minimal nutrient/energy requirements by using a_{ij} as the content of energy or nutrient i in feed j (Mcal, g, or kg/kg of DM), and b_i as the animal requirement of energy or nutrient i (Mcal, g or kg/cow per day); m is the number of energy and nutrient requirements in the LP model. Equation [3] sets the nutrient proportion constraints and several feed limits; d is the number of the corresponding nutrient proportion constraints and feed limits in the LP model; φ_{ij} is the proportion of nutrient i in feed j (kg/kg of DM), and l_i and u_i are the lower and upper limits, respectively, of the i th nutrient (in kg/kg of DM). Equation [4] is used to set the maximum DMI with h (kg of DMI/cow per day) denoting the calculated maximum DMI. The feed limits (Eq. [3]) and costs (Eq. [1]) for various feedstuffs are shown in Table 2. Most of the feed costs were taken from the Penn State price list (V. Ishler, Pennsylvania State University Extension, University Park, personal communication, June 14, 2018) because of its consistency and accessibility. However, because of the incompleteness of the Penn State price list, feed prices for almond hulls, cracked corn grain, and steam flaked corn grain were from an issue of *Progressive Dairyman* magazine (Tebbe, 2018).

Dry matter intake, calculated according to NRC (1989) as a function of BW and FCM, was set as the maximum DMI constraint (i.e., 21.8 kg/d), and the energy requirement for the lactating cow was calculated on a NE_L basis. Mineral requirements (i.e., Ca, P, K, S, Na, Mg, and Cl) were calculated according to

NRC (1989). The requirement of protein was calculated from NRC (1989) using the minimal requirement of CP. Other limits, including dietary proportions of NDF, forage, CP, and fat, were also specified. The minimum proportions of NDF and forage were limited to 0.25 and 0.40 kg/kg of DM, respectively, to avoid rumen dysfunction. The minimum and maximum proportions of CP in the diet were set as 0.16 and 0.2 kg/kg of DM, respectively. The maximum proportion of fat in the diet is set as 0.06 kg/kg of DM.

Least-Water Model

The second LP model was formulated to minimize water usage while delivering sufficient nutrients to meet the animal requirements. The model objective function (Eq. [5]) and its constraints (Eq. [6]) were described as follows:

$$\min z_2 = \sum_{j=1}^n \alpha_j x_j, \quad x_j \geq 0, \quad [5]$$

$$\mathbf{x} \in F, \quad [6]$$

where z_2 is the value representing water usage (L) for the second LP, α_j is the water required to grow the j th feed (L/kg of DM), and x_j is the amount of feed j (kg of DM). Equation [6] is used to state that the constraints of this LP model are the same ones used in the first LP model that specify a feasible region F constrained by Equations [2] to [4], and $\mathbf{x}$ represents the left-hand side of these equations.

Water Input. One of the important inputs for this model is α_j (expressed in L of gross irrigation application per kg of DM of feed j). Gross irrigation application over the cropping season is the water usage defined as ET_{aw} divided by the estimated mean seasonal AE, assuming that the irrigator avoids incurring any water deficit or stress in the crops. Recycled water can also be considered as a portion of the gross irrigation application, which was not considered in this study, but could be incorporated into this modeling framework.

The steps for computing α_j (L/kg of DM of feed j) using AquaCrop (version 6.1) are shown in Figure 1. The simulation was run in the “growing degree day” mode. With AquaCrop parameterized for a given crop species, the 4 major inputs were water-holding capacity of the soil, initial soil water content, weather data, and irrigation method and schedule. Specifically, the initial soil water content on the day of planting was specified as the level of water in the root zone of the crops. The required weather data input consisted of daily precipitation ($\mathbf{P}$,

mm), daily reference evapotranspiration (ET_o , mm), daily maximum air temperature (T_x , °C), and daily minimum air temperature (T_n , °C). Surface irrigation, sprinkler irrigation, and micro-irrigation (drip irrigation) were the options for irrigation methods in AquaCrop. With a selected atmospheric CO_2 level and crop, a standard AquaCrop simulation can be conducted based on the 4 inputs described above. The 5 simulation outputs of AquaCrop were WP, economic yield (Y , t/ha; as AquaCrop output), B (t/ha; as AquaCrop output), HI , and ET_{aw} (or net irrigation, ΣNA). Surface and

drip irrigation methods were examined because they are, respectively, the least and most efficient methods available in AquaCrop. However, because different irrigation systems have varying application efficiencies under reasonable irrigation management, as shown in Table 3, the model was designed such that other irrigation methods could be evaluated through their corresponding application efficiencies. Given the simulated values of economic yield and biomass production, liters of gross irrigation water per kilogram of feed crop can be computed. After appropriate water allocation to the

Figure 1. Procedure of α_j (L/kg of feed j) computation with the AquaCrop model (<http://www.fao.org/aquacrop/en/>). For the weather input, T_n (°C) is the minimum air temperature and T_x (°C) is the maximum air temperature; ET_o (mm) = reference evapotranspiration and P (mm) = precipitation. Outputs from AquaCrop are water productivity with respect to yield ($WP_{(y/et)}$, kg/m³), economic yield (Y , t/ha), biomass production (B , t/ha), harvest index (HI , kg of yield/kg of biomass) and net irrigation (NA , mm) through a cropping season. Application efficiency (AE , L of net irrigation/L of gross irrigation) is given in Table 3. Gross irrigation (GA , mm) through a cropping season can be calculated using the equation $\Sigma GA = (\Sigma NA)/AE$. GP = goal programming models used in this study.

Table 3. Estimated average application efficiencies (AE; L of net irrigation/L of gross irrigation) of several irrigation systems

System	AE ¹
Surface irrigation	0.70
Sprinkler irrigation	0.75
Micro-sprinkler	0.80
Drip	0.85

¹Application efficiency is the proportion of gross irrigation application that contributes to crop evapotranspiration.

byproduct feedstuffs, α_j was obtained and used as the input of the GP model (Table 4).

Allocation of Water. Dairy cattle can convert low-quality forage to human-edible products, such as milk, through rumen fermentation as long as their minimal nutrient requirements are met. Byproduct feedstuffs constitute a significant portion of the ingredients in diets fed to dairy cattle in California. The proportions of mass and economic value are considered when allocating irrigation water to byproducts and primary products (Ardente and Cellura, 2012). For any given crop with one or more byproducts, its water usage (L/kg of DM) can be divided among the products as follows:

For primary product:

$$Water_p = \frac{L \times [Wm \times PM_p + (1 - Wm) \times PC_p]}{PM_p}, \quad [7]$$

For byproduct i :

$$Water_{bi} = \frac{L \times [Wm \times PM_{bi} + (1 - Wm) \times PC_{bi}]}{PM_{bi}}, \quad [8]$$

where $Water_p$ and $Water_{bi}$ are the water usages of the primary product (L/kg of DM of primary product) and of the i th byproduct (L/kg of DM of byproduct i), respectively; L represents the usage of irrigation water (in liters) per kilogram of DM of the total crop (primary product plus byproducts); Wm represents the weight attributed to the mass proportion of feedstuffs (PM_p or PM_{bi}); and $1 - Wm$ is the weight attributed to the economic values (PC_p or PC_{bi}) ($0 \leq Wm \leq 1$) during water allocation. Essentially, Wm determines the proportion of water per kilogram associated with mass versus economic allocation; PM_p and PM_{bi} are the mass allocation factors for the primary product and byproduct i , respectively. Similarly, PC_p and PC_{bi} are the economic allocation factors for the primary product and byproduct i , respectively (Ardente and Cellura, 2012). These 4 factors are expressed as follows:

$$PM_p = \frac{m_p}{m_p + \sum m_{bi}}, \quad [9]$$

$$PM_{bi} = \frac{m_{bi}}{m_p + \sum m_{bi}}, \quad [10]$$

Table 4. Gross irrigation water usage per kilogram of feed (L/kg; values of α_j)

Feed	Environmental scenario ¹							
	FDC	DDC	FWC	DWC	FDP	DDP	FWP	DWP
Almond hulls	24	23	24	23	24	23	24	23
Sugar beet pulp	664	492	533	403	523	375	414	352
Corn dried distillers grain	431	287	283	186	428	280	277	197
Corn gluten feed	141	94	93	61	140	92	91	65
Corn gluten meal	814	542	534	350	807	528	523	371
Cracked corn grain	814	542	534	350	807	528	523	371
Steam flaked corn grain	814	542	534	350	807	528	523	371
Corn silage	392	261	257	169	388	254	252	179
Whole cottonseed with lint	861	629	603	435	755	593	550	444
Legume hay	744	607	744	607	744	607	744	607
Legume silage	744	607	744	607	744	607	744	607
Beet sugar molasses	477	354	383	290	376	270	297	253
Sorghum hay	389	279	308	206	425	310	239	165
Sorghum silage	389	279	308	206	425	310	239	165
Wheat hay	157	108	0	0	87	77	0	0
Wheat middlings	223	154	0	0	124	108	0	0
Wheat silage	157	108	0	0	87	77	0	0

¹Scenarios are described by 3-letter acronyms, where the first letter (F or D) represents furrow or drip irrigation, the second (D or W) represents a dry or wet year, and the third (C or P) represents current or predicted CO₂ levels. FDC = furrow, dry, and current CO₂ level; DDC = drip, dry, and current CO₂ level; FWC = furrow, wet, and current CO₂ level; DWC = drip, wet, and current CO₂ level; FDP = furrow, dry, and predicted CO₂ level combined with increased temperature; DDP = drip, dry, and predicted CO₂ level combined with increased temperature; FWP = furrow, wet, and predicted CO₂ level combined with increased temperature; DWP = drip, wet, and predicted CO₂ level combined with increased temperature.

$$PC_p = \frac{m_p c_p}{m_p c_p + \sum m_{bi} c_{bi}}, \quad [11]$$

$$PC_{bi} = \frac{m_{bi} c_{bi}}{m_p c_p + \sum m_{bi} c_{bi}}, \quad [12]$$

where m_p (kg) and m_{bi} (kg) are the masses of the primary product and byproduct i , respectively, under multifunctional process; and c_p (\$) and c_{bi} (\$) are the prices of the primary product and byproduct i , respectively. The mass proportions (m_p and m_{bi}) for different feedstuffs were from Fadel (1999). The economic values (c_p and c_{bi}) were from USDA (2017). The economic values selected for water allocation are prices before the additional steps of transport, conditioning, and packaging. The allocation ratios and types used in this study are shown in Table 5. Ratios in Table 5 can be adjusted if more accurate information is provided. Depending on the allocation method selected, the allocation of water per kilogram of DM can be computed for each feedstuff using Eq. [7] and [8] and the information in Table 5. In this experiment, the economic allocation method ($Wm = 0$) was primarily used to distribute irrigation water to byproduct feedstuffs. Irrigation usages of the feedstuffs without byproducts were calculated using the equation $\Sigma GA = (\Sigma NA)/AE$ directly, where ΣNA is one of the simulated outputs from AquaCrop and AE is provided in Table 3. Taking cottonseed as an example, irrigation usage per kilogram of whole cotton crop (2,506 L) was used as the irrigation requirement (L in Eq. [8]) to produce both cotton lint (primary product) and cottonseed (byproduct). Given $Wm = 0$, $PC_{bi} = 0.22$, and $PM_{bi} = 0.64$ from Table 5, the water usage per kilogram

of cottonseed was calculated to be 861 L through Eq. [8]. The model was developed so that the allocation methods could be altered or mixed per Eq. [7] and [8].

Experimental Design. Both ET_c and precipitation, and thus gross irrigation, vary under different environmental conditions. The experimental design for this LP model was a $2 \times 2 \times 2$ factorial. The 3 main effects were atmospheric CO_2 level and associated temperature, water year, and irrigation method. The CO_2 levels of 400 ppm (Snyder, 2017) and 550 ppm (Prentice et al., 2001) were used to represent the atmospheric CO_2 concentration observed in 2015 and that predicted for 2050, respectively (Prentice et al., 2001). In the following context, a CO_2 concentration of 400 ppm was denoted as current atmospheric CO_2 level and 550 ppm as the predicted atmospheric CO_2 level. For water year, the weather data for a dry year and a wet year in California were used. Because a typical hydrologic (water) year in California is usually considered as the period from October of one year to September of the following year, October 2014 to September 2015 was considered a dry year and October 2016 to September 2017 was considered a wet year. Specifically, the dry year had a precipitation (124 mm) that was 8% less than the 4-yr average and that of the wet year (153 mm) was 14% greater than the 4-yr average. These values were calculated from analysis of the weather data from Stratford weather station (<https://cimis.water.ca.gov/>) located in Kings County, California. Less than 0.4% of observations were missing in the weather data. Missing observations of daily precipitation and daily temperature were imputed as the mean of the values of the previous day and the following day. Furrow irrigation and drip irrigation were considered for the 2 irrigation methods. The average irrigation efficiency

Table 5. Summary of allocation factors and types used in this study

Co-product	Economic allocation (%) ¹	Mass allocation (%)
Almond ²		
Shelled almond nut : almond hulls	98:2	50:50
Sugar beet		
Sugar : beet pulp : molasses (dry)	77:16:8	61:23:16
Corn		
Ethanol : distillers grain (dry)	75:25	52.8:47.2
Starch : gluten feed : gluten meal : oil	86:4:5:5	67.5:23.5:4.5
Cotton		
Lint : cottonseed	78:22	36:64
Wheat		
Flour : wheat middling ³	83:17	75:25

¹Economic values used for allocation are from USDA (2017) in \$/kg of DM.

²Crops in bold represent the whole crops used in a multifunctional food process.

³Wheat grain price and wheat middling price are used, respectively, to calculate the economic allocation between flour and wheat middling.

for furrow irrigation was set as 70% and that for drip irrigation was set as 85% (Table 3). The ET_c was simulated by AquaCrop using ET_o data collected from the Stratford weather station. Under the current trend of climate change, the global daily maximum temperature (T_x) was predicted to increase by 0.1°C per decade and the daily minimal temperature (T_n) was predicted to increase by 0.2°C per decade (Roderick and Farquhar, 2005). The temperature increase could be greater for California, with a predicted increase of 3°C by the year of 2050 (Center and Cayan, 2006). However, because global warming is likely to increase the temperature, humidity, and canopy resistance of plants (Swelam et al., 2010), projected climate change is expected to have a relatively small impact on ET_o (Snyder, 2017). Therefore, for treatments under the predicted CO_2 concentration, T_n was assumed to increase by 2°C and T_x was assumed to increase by 1°C , whereas ET_o was assumed to remain the same. These increases in the temperatures were adjusted from Roderick and Farquhar (2005) for California.

California is a coastal state where much of the Central Valley has a Mediterranean climate, with warmer, drier weather in summer, and cooler, wetter weather in winter. Most of the precipitation in California occurs in the winter. For the water year factor, the general rainfall pattern was similar in both the wet and dry years, but the amount of rainfall varied between the years. The increasing winter precipitation was obvious in the wet year but a greater amount of precipitation was observed from March to April in the dry year (Figure 2). However, the total precipitation in the wet year was significantly greater than that in the dry year. In addition, the monthly average temperature and the monthly average ET_o were similar between the wet year and dry year (Figure 3).

Data Collection and Limitations. The simulation results of sugar beet, corn, cotton, sorghum, and wheat from AquaCrop were used to compute their corresponding α_j values (L/kg of DM). The weather data used for AquaCrop simulation were provided from the Stratford weather station located in Kings County, and were downloaded from the CIMIS website (<https://cimis.water.ca.gov/>). This weather station is located in the San Joaquin Valley, a region that is the home to the top 3 milk-producing counties in California: Tulare, Merced, and Kings (USDA, 2016). The irrigation schedule specified in AquaCrop generated an irrigation event when the readily available soil water in the root zone (RAW) was depleted by 30% in the first 60 d from planting. The planting dates for different crops are April 22 for summer crops (i.e., corn, sorghum, sugar beet, and cotton) and September 22 for winter crops

(i.e., wheat). After the first 60 d, an irrigation event was generated when the RAW was depleted by 80%. Irrigation events stopped 5 d after the start of canopy senescence. This irrigation schedule was determined to ensure adequate water supply for crop growth before harvest. In practice, farmers will stop irrigation when the foliage of the crop turns visibly yellow (senescence); therefore, irrigation events were stopped when canopy cover declined in the simulation. The soil type specified in the simulation was clay loam, which is the default soil type in AquaCrop. Although soil types vary at different locations, clay loam is a reasonable assumption for the soil type in Kings County, California. In the dry year, the initial soil water content on the day of planting was set as 50% of the available water content in the soil root zone, whereas that in the wet year was set as 100% of the available water content in the root zone. Default rooting depth in AquaCrop was used for the crop species.

Almond hulls and alfalfa are 2 major feedstuffs for dairy cows in California. Almonds, as a tree crop, are not included in the simulation of AquaCrop. Alfalfa is also not included in AquaCrop because it has several cuttings a year, which makes it difficult to parameterize

Figure 2. Monthly average precipitation (mm/d) of dry and wet years.

its periodic cuts and regrowth in AquaCrop. For these 2 feed crops, estimations of their irrigation requirements in California (USDA, 2014) were used in the model. The allocation of water to almond hulls is calculated through Eq. [7] and [8]. For simplicity, these values are

assumed to remain the same for different CO₂ levels and water years, although more realistically their α_j values (L/kg of DM) are likely to be lower under higher CO₂ levels. All crops included in the feed list were assumed grown locally, but this assumption is not necessarily true. The assumption of locally grown feeds affected the availability of feeds for ration formulation. However, crops grown in other locations can be included in the model as long as the weather data of the locations where the crops were grown are available for the future research.

GP Model

A GP model was developed to simultaneously minimize feed costs and irrigation water usage. This model incorporates a composite objective function in which goal satisfaction has been traded off according to the weights on the deviations from each target. The 2 targets being minimized were diet cost (z_1) and water usage (z_2) from Eq. [1] and [5]. The composite objective function (Eq. [13]) and the constraints (Eq. [14] to [16]) are described as follows:

$$\min z_3 = \sum_{q=1}^2 w_q \left(\frac{n_q + p_q}{z_q} \right), \quad [13]$$

$$\sum_{j=1}^n c_j x_j + n_1 - p_1 = t_1, \quad [14]$$

$$\sum_{j=1}^n \alpha_j x_j + n_2 - p_2 = t_2, \quad [15]$$

$$x \in F, \quad [16]$$

where z_3 is the goal programming objective function value for the third model, w_q is the weight of the q th goal ($q = 1$ to minimize diet cost; $q = 2$ to minimize water usage), and n_q and p_q are the negative and positive deviation variables, respectively, for the goal q . It is important to note that this model specification accommodates the goal programming restriction: $n_q p_q = 0$; n_q and $p_q \geq 0$. A weight grid is constructed for which $\sum_{q=1}^2 w_q = 1$, with w_1 and w_2 varying from (1,0) to (0,1) in increments of 0.001, as suggested by Jones and Tamiz (2010) and Moraes et al. (2015). The optimal values of each individual LP are used to set up the targets; that is, $t_1 = z_1$ (Eq. [1] and [14]) and $t_2 = z_2$ (Eq. [5] and [15]).

Figure 3. Monthly average reference evapotranspiration (ET_o) and monthly average temperature of dry and wet years.

A method to calculate the water reduction cost using solutions from the GP model was proposed by Moraes et al. (2015); the mitigation cost (**MC**) of water is defined by:

$$\text{MC } (\$/1,000 \text{ L}) = \frac{\Delta \text{Cost } (\$)}{\Delta \text{Water } (1,000 \text{ L})}, \quad [17]$$

where ΔCost is the change of diet cost between $\text{Cost}_{(i)}$ and $\text{Cost}_{(i-1)}$ for the i th distinct diet formulation ($i \geq 2$) generated by the GP model. Similarly, $\Delta \text{Water} = \text{Water}_{(i)} - \text{Water}_{(i-1)}$.

RESULTS AND DISCUSSION

General Solutions of Goal Programming

The weighted GP model generated 1,001 solutions for each environmental scenario, corresponding to the weight grid points from (1,0) to (0,1) in increments of 0.001. Thus, 8,008 GP solutions were generated for the 8 scenarios in total. However, only a few unique solutions were generated for each scenario and each solution represented a distinct diet with a specific associated diet cost and irrigation water usage (Table 6). The abbreviations for the 8 environmental conditions are indicated by 3-letter acronyms that describe the states of the factors. The first letter (F or D) represents the furrow or drip irrigation, the second letter (D or W) represents the dry or wet year, and the third letter (C or P) represents the current or predicted CO_2 levels, respectively. In general, the numbers of distinct solutions varied for each condition: 5 for the furrow, dry year, and current CO_2 condition (**FDC**); 5 for the drip, dry year, and current CO_2 condition (**DDC**); 5 for the furrow, wet year, and current CO_2 condition (**FWC**); 5 for the drip, wet year, and current CO_2 condition (**DWC**); 8 for the furrow, dry year, and predicted CO_2 condition (**FDP**); 7 for the drip, dry year, and predicted CO_2 condition (**DDP**); 5 for the furrow, wet year, and predicted CO_2 condition (**FWP**); and 5 for the drip, wet year, and predicted CO_2 condition (**DWP**).

The hypothetical cow required from 2,125 to 7,581 L of irrigation water for feed production per day under these different environmental conditions (Table 6). Other water usages on a dairy farm are important but not nearly as large as the irrigation requirement. For example, Appuhamy et al. (2016), using a meta-analysis, reported that a cow requires around 62 L of drinking water per day, although 120 L/d may be more reasonable for a high-producing dairy cow. A conservative estimate of the water requirement for cooling under the 2 water years examined was calculated and the

average requirement was about 130 L/d with a water nozzle system. Water retained in the feeds is negligible compared with other water usage on a dairy farm. For example, if a cow consumes 20 kg/d of corn silage, a feedstuff with 35% DM content, the water consumed from the silage is 13 L/day per cow and this value is relatively trivial. Assuming a total water use of 400 L/day per cow for drinking, cooling, and equipment cleaning, the irrigation water usage for feed crops in a semi-arid region ranges from about 84 to 95% of the total water requirement.

In scenarios where most of the weights were assigned to diet cost minimization, corn silage was the only forage selected in the diet. However, both corn silage and wheat silage were selected in the diet when more weights were assigned to water minimization because wheat, as a winter crop under a winter rainfall climate, requires less irrigation water than corn for growth. The proportional increase of water usage from the minimal-water diet to the minimal-cost diet varied under different environmental scenarios. The proportional increase in the 8 environmental scenarios ranged from 33 to 48% [e.g., for the DDC scenario, $\Delta \text{Water } (\%) = (5,208 - 3,820)/3,820 \times 100 = 36\%$], where 48% corresponds to the DWC scenario (Table 6). The reason that almost half of the water was reduced under the DWC condition when minimizing water usage is that the difference of water usage between summer and winter crops was larger in the wet year. For example, the winter crop in the feed list (i.e., wheat) did not require any irrigation water in the wet year and was therefore selected in the diet when minimizing water usage. In contrast, the proportional increase of diet cost when going from a minimal water diet to a minimal cost diet was 14.83% under all scenarios (Table 6).

Changes of Energy and Nutrient Content in the Diets

The range of weights that determines a unique solution can be used to assess the stability of a specific diet formulation. In LP terminology, the basis for that particular linear program solution does not change for a given range of weights used in the GP model. For instance, if the range of weights is large for a unique diet, it indicates that the diet is relatively insensitive to the small changes in the trade-offs between diet cost and irrigation water usage. Furthermore, the MC of water usage increased monotonically with decreasing water usage under 7 scenarios but decreased for the third and fourth unique diet solutions under the FDP scenario. Even though the MC did decrease slightly for the third and fourth distinct diets under the FDP scenario, the feed costs and water usage remained monotonic re-

Table 6. Result of goal programming models under 8 different environmental conditions¹

Scenarios and unique solution ²	w_1	Feed cost (\$/cow)	Water use (L/cow)	MC (\$/1,000 L)	DMI (kg/cow)	NDF (% of DM)	NE _L (Mcal/kg)	EE (% of DM)
FDC								
1	0.896–1	4.38	7,581	NA ³	20.4	40.2	1.57	5.97
2	0.686–0.895	4.45	6,806	0.09	20.8	38.5	1.54	3.95
3	0.624–0.685	4.71	6,081	0.36	21.2	37.5	1.51	3.92
4	0.405–0.623	4.81	5,852	0.44	21.4	38.3	1.49	3.92
5	0–0.404	5.03	5,665	1.18	21.8	38.8	1.47	3.85
DDC								
1	0.915–1	4.38	5,208	NA	20.4	40.2	1.57	5.97
2	0.675–0.914	4.45	4,553	0.11	20.8	38.5	1.54	3.95
3	0.614–0.674	4.71	4,088	0.56	21.2	37.5	1.51	3.92
4	0.393–0.613	4.81	3,940	0.68	21.4	38.3	1.49	3.92
5	0–0.392	5.03	3,820	1.84	21.8	38.8	1.47	3.85
FWC								
1	0.924–1	4.38	4,627	NA	20.4	40.2	1.57	5.97
2	0.779–0.923	4.45	4,015	0.11	20.8	38.5	1.54	3.95
3	0.713–0.778	4.54	3,775	0.37	21.0	39.4	1.52	3.95
4	0.358–0.712	4.81	3,285	0.55	21.4	38.3	1.49	3.92
5	0–0.357	5.03	3,199	2.54	21.8	38.8	1.47	3.85
DWC								
1	0.937–1	4.38	3,136	NA	20.4	40.2	1.57	5.97
2	0.777–0.936	4.45	2,636	0.14	20.8	38.5	1.54	3.95
3	0.698–0.776	4.54	2,478	0.57	21.0	39.4	1.52	3.95
4	0.329–0.697	4.81	2,176	0.89	21.4	38.3	1.49	3.92
5	0–0.328	5.03	2,125	4.35	21.8	38.8	1.47	3.85
FDP								
1	0.893–1	4.38	6,968	NA	20.4	40.2	1.57	5.97
2	0.871–0.892	4.39	6,915	0.19	20.2	39.0	1.58	5.89
3	0.863–0.87	4.41	6,755	0.13	20.2	37.6	1.58	5.36
4	0.705–0.862	4.46	6,354	0.12	20.5	36.3	1.56	3.80
5	0.702–0.704	4.55	6,089	0.34	20.7	37.2	1.54	3.81
6	0.643–0.701	4.71	5,638	0.35	20.9	36.5	1.53	3.78
7	0.394–0.642	4.81	5,417	0.45	21.4	38.3	1.49	3.92
8	0–0.393	5.03	5,252	1.33	21.8	38.8	1.47	3.85
DDP								
1	0.913–1	4.38	4,897	NA	20.4	40.2	1.57	5.97
2	0.834–0.912	4.45	4,306	0.12	20.8	38.5	1.54	3.95
3	0.685–0.833	4.46	4,270	0.28	20.5	36.3	1.56	3.80
4	0.67–0.684	4.61	4,006	0.57	20.7	35.7	1.54	3.78
5	0.657–0.669	4.71	3,835	0.59	20.9	36.5	1.53	3.78
6	0.383–0.656	4.81	3,676	0.63	21.4	38.3	1.49	3.92
7	0–0.382	5.03	3,568	2.05	21.8	38.8	1.47	3.85
FWP								
1	0.909–1	4.38	4,432	NA	20.4	40.2	1.57	5.97
2	0.779–0.908	4.45	3,935	0.14	20.8	38.5	1.54	3.95
3	0.712–0.778	4.54	3,700	0.38	21.0	39.4	1.53	3.95
4	0.357–0.711	4.81	3,221	0.56	21.4	38.3	1.49	3.92
5	0–0.356	5.03	3,137	2.61	21.8	38.8	1.47	3.85
DWP								
1	0.932–1	4.38	3,279	NA	20.4	40.2	1.57	5.97
2	0.777–0.931	4.45	2,792	0.14	20.8	38.5	1.54	3.95
3	0.7–0.776	4.54	2,624	0.54	22.0	39.4	1.52	3.95
4	0.334–0.699	4.81	2,301	0.83	21.4	38.3	1.49	3.92
5	0–0.333	5.03	2,246	4.03	21.8	38.8	1.47	3.85

¹ w_1 is the weight range on the deviation of diet cost from target 1 (minimal cost) that determines the same solution. Feed cost (\$/cow) is the cost of diet per cow per day; water use (L/cow) is the irrigation water usage per cow per day; MC (\$/1,000 L) is the mitigation cost per 1,000 L of irrigation water; DMI (kg/cow) is the daily actual DMI per cow; NE_L (Mcal/kg DM) is the diet concentration of NE_L in Mcal per kg of DM; NDF and ether extract (EE) are the diet proportions of each corresponding nutrient. The CP proportion remained at 16% for all of the solutions.

²Scenarios are described by 3-letter acronyms, where the first (F or D) represents furrow or drip irrigation, the second (D or W) represents a dry or wet year, and the third (C or P) represents current or predicted CO₂ levels. FDC = furrow, dry, and current CO₂ level; DDC = drip, dry, and current CO₂ level; FWC = furrow, wet, and current CO₂ level; DWC = drip, wet, and current CO₂ level; FDP = furrow, dry, and predicted CO₂ level combined with increased temperature; DDP = drip, dry, and predicted CO₂ level combined with increased temperature; FWP = furrow, wet, and predicted CO₂ level combined with increased temperature; DWP = drip, wet, and predicted CO₂ level combined with increased temperature. Unique solution is the identification number of unique solutions in the solution set under each scenario.

³Not applicable.

sponses for all of the 8 scenarios. The MC ranged from \$0.09/1,000 L to \$4.35/1,000 L over the 8 scenarios.

The DMI (kg/d per cow), dietary NDF (% of DM), energy content (Mcal/day per cow), and dietary ether extract (EE; % of DM) of each distinct diet are shown in Table 6. The diet costs were relatively low because the price of corn silage from the Penn State feed price list was low (\$0.12/kg of DM), and corn silage was a major source of forage in the diets. From the least-cost diet to the least-water diet, DMI increased, NDF proportion decreased, EE decreased, energy concentration decreased, and lignin increased (not shown), because the model tended to choose less nutritive but more water-saving feedstuffs in the diets to save water usage. For instance, non-mineral ingredients selected in the least-cost diet were 2.0 kg of corn dried distillers grain, 3.1 kg of corn gluten feed, 8.7 kg of corn silage, 2.5 kg of whole cottonseed, and 3.1 kg of wheat middlings, whereas 3.4 kg of almond hulls, 2.2 kg of corn dried distillers grain, 3.3 kg of corn gluten feed, 0.9 kg of corn gluten meal, 6.7 kg of corn silage, 2.4 kg of wheat middlings, and 2.0 kg of wheat silage were selected in the diet requiring the least amount of water. The formulations for the least-cost diet and the least-water diet were the same across all scenarios. In addition, dietary EE decreased as water demand decreased because the only major fat source in the feed list was cottonseed. Cotton is a high-water-demand crop, requiring 1,265 to 2,506 L of irrigation water per kilogram of whole cotton. To simplify the model framework, only plant-oriented crops were included in the feed list, because animal-oriented feeds (e.g., tallow) require more assumptions about water use. The constraint of dietary CP was binding in all of the diets under the different scenarios. In addition, methane emission, predicted using equation [34] from Niu et al. (2018), ranged from about 396 to 410 g/d over the range of solutions, which indicates that methane emission would not be expected to change much when water usage for rations decreased.

Limitations of Present Modeling Framework

Few unique solutions were generated under each of the 8 environmental conditions for 3 main reasons. First, AquaCrop has been parameterized for a limited number of herbaceous crops and is not designed for simulations of tree crops. Hence, the number of feeds available for the GP model is limited. If water information is available for more feeds, the number of distinct solutions will likely be greater because more feeds will be available for diet formulation. Second, the nutritive quality of each feed was assumed to remain constant under different scenarios. This assumption is

an approximation for most feeds because of the limited published data on the changing nutritive value under the scenarios evaluated in this study. For instance, although abiotic environmental stresses, such as drought and heat, cause significant agricultural yield losses, the protein concentration in the harvested portion of crops usually increases under these environmental stresses (Wang and Frei, 2011). In contrast, Liu et al. (2018) reported that fiber content increased and protein content decreased in alfalfa under drought conditions, which suggested that the nutritive value of alfalfa would decrease because of drought stresses. For other situations and crops, the opposite will occur (Wang and Frei, 2011). Studies on the change of nutritive composition for different plants under various environmental scenarios are important and critical for understanding the water usage of plants used for animal feeds. Third, in any linear program, the solutions typically stay the same under a range of changing constraints or inputs. For example, if the price of a given feed changes, the resulting ration can stay the same. This invariance of ration to changes in the price is also true for changes in nutrient requirements, where solutions stay the same over a range of a given requirement.

The assumption of equal nutritive quality also leads to the same diet cost and same nutrient composition of the 2 optimized diets (i.e., diet of minimal cost and diet of minimal water usage) under all 8 scenarios. These results will likely change if more detailed information about the changes in nutritive composition under different environmental scenarios becomes available. In reality, a consistent decrease in protein concentration and an increase in yield due to CO₂ enrichment have been shown for some crops (Taub et al., 2008), but the available data are not quantitatively sufficient for use in AquaCrop. Updated information could be incorporated into this modeling framework in future research.

The modeling approach used here provides a solid framework for future analyses and combines 2 important areas that are required to evaluate the use of water for feed crops in dairy production. The proposed model provides a novel approach for studying irrigation water demand for dairy production and other feeding systems in semi-arid regions. In the future, this model could be improved by including the impact of environmental conditions on the nutritive composition of feeds to better account for their impacts on diet costs and water use. Also, when information on water demand under different environments becomes available for more feeds, more feeds can be added to strengthen this model and expand the range of feedstuffs considered in the diet formulation.

Relationship Between Diet Cost and Water Usage Under Different Conditions

Changes in solutions with incremental changes of the weights from minimal water use to minimal diet cost are illustrated in Figure 4. The segments of the curves with slopes of 0 indicate the range of weights in which a new diet does not occur. Conversely, the vertical shifts in the curves represent situations where a new and distinct diet was formulated. The lengths of the segments, similar to the ranges of weights in Table 6, indicate the sensitivity of the diets to fluctuations caused by trade-offs between diet cost minimization and water usage minimization. For example, in Figure 4, 8 distinct solutions were found for the FDP scenario, and the lengths of the steps are very short, around $x = 0.85$ (see expanded portion in Figure 4). The changes of water usage with changes in weight under furrow irrigation were larger than those under drip irrigation, whereas the changes of dietary costs stayed the same under both furrow and drip irrigation systems. This implies that the MC of drip irrigation water was higher than that of furrow irrigation, as shown in Table 6. Generally, the MC of reducing water usage increases as application efficiency increases. With higher application efficiency, less irrigation water is required for feed production to meet the same nutrient requirement of a cow at a certain production level. Although the production level stays the same, the amount of water used to produce 1 kg of diet decreases, such that the potential value of the water increases and the MC of the water increases. The MC of water typically increases as the water required per unit of cost decreases. However, the energy cost related to drip irrigation (for water pressurization in the drip system pipelines) relative to the lower energy requirement for furrow irrigation was not considered in this study. Furrow and drip irrigation systems were assumed to not differ in irrigation cost because the economic benefits of drip irrigation (i.e., labor saving in operating the drip system and potential improvement in crop growth) may offset the increased investment cost in drip irrigation relative to furrow irrigation, especially for high- and intermediate-water-demanding crops (Amosson et al., 2011).

Figure 5A illustrates the relationship of water use and diet costs under the 8 different scenarios, with each data point in the figure representing a unique solution from Table 6. The 2 most water-consuming scenarios were FDC and FDP (i.e., furrow irrigation in the dry year under either current or predicted CO₂ levels). The maximum water usages under FDC and FDP were 7,581 and 6,968 L of water per cow, respectively. The 2

most water-saving scenarios were DWC and DWP (i.e., drip irrigation in the wet year under either current or predicted CO₂ levels), with minimal water usages of 2,246 and 2,125 L per cow, respectively. Two factors explain the large difference of water usage between “furrow, dry year” and “drip, wet year” scenarios. First, in wet years, soil water content was at field capacity on the day of planting due to sufficient winter rainfall, which contributes to the water required for crop evapotranspiration, whereas in dry years, the initial soil water content on the day of planting was set as 50% of the available water content in the soil root zone. Second, the drip irrigation system is more efficient, with 0.85 application efficiency, compared with that of the furrow (i.e., surface) irrigation system at 0.70 (Table 3). Water usage under the current CO₂ level was larger than that under the predicted CO₂ level in all scenarios except for the drip, wet year conditions. The water usage difference between the current and predicted CO₂ levels was largest under the furrow, dry year conditions, smallest under the furrow, wet year conditions, and intermediate under the drip, dry year conditions. The pattern is reversed under the drip, wet year conditions, possibly because the effect of temperature on total water usage increased.

Note that the similarity of water usage under the current and predicted CO₂ levels was a result of our initial assumptions. For higher CO₂ conditions, temperatures were assumed to increase accordingly so that the increase in water-use efficiency due to higher CO₂ levels could not overcome the negative effect from increasing temperature. All of these assumptions could be modified in future research efforts to further refine the modeling framework developed for this study.

Different Methods of Water Allocation

Although all previous results assumed the economic allocation of water when byproducts were fed, the model was constructed to allow consideration of different ways to allocate the water. The bar plot in Figure 6 shows 3 different water allocation methods (economic, $W_m = 0$; mass, $W_m = 1$; and equal weight on economic and mass, $W_m = 0.5$) and their corresponding water usages of the least-cost diet and the least-water diet under the 8 scenarios. The majority of this study assumed $W_m = 0$, but briefly examining other water allocation methods is useful. The total irrigation water usage per cow differed according to which W_m value was used to allocate water to byproduct feedstuffs. As shown in Figure 6, a cow used the least amount of water when the economic allocation method was applied and used the most water when only the mass allocation method

Figure 4. Feed costs and water usage of the weighted goal programming (GP) models versus weights on deviations from minimal water under the 8 environmental scenarios: FDC (furrow, dry year, and current CO₂ level), DDC (drip, dry, and current CO₂ level), FWC (furrow, wet year, and current CO₂ level), DWC (drip, wet, and current CO₂ level), FDP (furrow, dry, and predicted CO₂ level combined with increased temperature), DDP (drip, dry, and predicted CO₂ level combined with increased temperature), FWP (furrow, wet, and predicted CO₂ level combined with increased temperature), and DWP (drip, wet, and predicted CO₂ level combined with increased temperature). The x-axis shows the weight assigned to the cost minimization in the GP model (0 represents minimal water and 1 represents minimal cost); the solid line represents the water usage (L); and the dashed line represents the dietary costs of solutions of the GP models.

was considered. The reason for this difference is that the economic values (prices) of byproduct feedstuffs are relatively low compared with their primary products, thus their shares in the total proceeds are also low. Using almonds as an example, assume that it takes 100

L to produce 1 kg of DM of almonds, including shelled almond nut and almond hulls. Using Eq. [7] and [8] with the information given in Table 5, 196 L of water is required to produce 1 kg of shelled almond nut, and 4 L is required to produce 1 kg of almond hulls:

Figure 5. Water usage versus diet costs from the solutions of goal programming model under 2 different CP requirements. The dashed and solid lines represent furrow irrigation and drip irrigation, respectively; circle and triangle shapes represent current and predicted CO₂ level combined with predicted higher temperature, respectively; hollow and solid symbols represent dry and wet years, respectively. The 8 environmental scenarios are FDC (furrow, dry year, and current CO₂ level), DDC (drip, dry, and current CO₂ level), FWC (furrow, wet year, and current CO₂ level), DWC (drip, wet, and current CO₂ level), FDP (furrow, dry, and predicted CO₂ level combined with increased temperature), DDP (drip, dry, and predicted CO₂ level combined with increased temperature), FWP (furrow, wet, and predicted CO₂ level combined with increased temperature), and DWP (drip, wet, and predicted CO₂ level combined with increased temperature).

Figure 6. Water usage comparisons of 3 water allocation methods for the least cost diet and the least water diet under the 8 different scenarios. $Wm = 0$ represents economic allocation, $Wm = 1$ represents mass allocation, and $Wm = 0.5$ represents equal weight allocation on economic values and mass. The 8 different environmental scenarios are FDC (furrow, dry year, and current CO_2 level), DDC (drip, dry, and current CO_2 level), FWC (furrow, wet year, and current CO_2 level), DWC (drip, wet, and current CO_2 level), FDP (furrow, dry, and predicted CO_2 level combined with increased temperature), DDP (drip, dry, and predicted CO_2 level combined with increased temperature), FWP (furrow, wet, and predicted CO_2 level combined with increased temperature), and DWP (drip, wet, and predicted CO_2 level combined with increased temperature).

$$\text{Water}_{\text{shelled almond nut}} = 100 \times \frac{0.98}{0.5} = 196 \text{ L}$$

$$\text{Water}_{\text{almond hull}} = 100 \times \frac{0.02}{0.5} = 4 \text{ L},$$

based on the economic allocation method ($Wm = 0$). In contrast, when mass allocation is applied, almond production requires 100 L of water to produce 1 kg of shelled almond nut and 100 L to produce 1 kg of almond hulls. More valuable products are not necessary to account for the higher proportion with respect to mass. Conversely, the high-value products (primary products) may account for only a small proportion in the share of mass. The economic allocation method was chosen in this study because it is generally preferred when one or more co-products have markedly higher prices than the others (Ardente and Cellura, 2012), and

this principle applies to most of the byproduct feed-stuffs in our model.

However, in terms of the water productivity of plant biomass, the allocation of water to the primary product and individual byproducts produced by a crop can also depend on the amount of photosynthetic assimilates required to produce a unit of mass of each product. This is because all plant parts are derived from photosynthetically assimilated CO_2 , and the amount of water that is transpired in the assimilation of a unit of CO_2 is nearly constant for a given crop species when normalized for evaporative conditions of the weather and CO_2 concentrations (Steduto et al., 2007). However, different products (i.e., primary products and byproducts) of a crop can differ in chemical composition and energy content and hence, require different amounts of assimilates (Penning de Vries et al., 1975) and water to make a unit of mass. Typically, products high in oil

or protein contents require more assimilates to make a unit of dry mass. Although the present study did not incorporate this approach, the potential to consider it in the future clearly exists.

Effects of CP Requirements

An average CP concentration requirement of 16% DM is suggested for cows in early to mid lactation with average milk production of 30.9 kg/d (NRC 2001). However, because a requirement of 16% would always be binding in the model, the minimal CP requirement of 16% was removed from the model to investigate what changes might occur if the protein requirement were allowed to change. Instead, only the requirement of CP provided by NRC (1989), which specifies grams of CP depending on the production characteristics of the animals, was retained in the model to meet the minimal protein requirement of the hypothetical cow. Essentially, the lower requirement of CP did not change the pattern of the results. Similarly, MC and DMI increased, whereas NDF, EE, and energy content decreased as the weights assigned to water minimization increased. The concentration of CP remained around the lower boundary at 14%. However, the number of unique solutions and dietary nutrient compositions changed under different environmental conditions. Relationships between water usage and diet cost under different environmental conditions with a lower CP requirement are shown in Figure 5B. Comparing the effects of different CP requirements on the solutions of the present model indicates the robustness of this model framework for examining trade-offs between minimizing dietary cost and minimizing water usage.

Future Modeling Efforts

This study provides a modeling framework for integrating water usage for crop production and diet costs in an optimization model. In the process of developing this modeling framework, we identified several notable areas of research that are worthy of further investigation. Changes in crop nutrient composition with different environmental conditions, effects of drip versus furrow irrigation costs, importing crops not grown locally, and the use of lagoon water for irrigation purposes are areas for future research that ultimately should be incorporated into the proposed modeling framework. Eventually, the proposed modeling framework can be developed to provide a foundation for consequential analyses that incorporate the concept of life-cycle analysis with optimization programming.

As mentioned previously, the nutrient composition of a given crop changes under different environmental conditions. Unfortunately, studies in this area are sparse and a comprehensive understanding of how the environment affects different crops is minimal. This area of research requires the collaboration of plant, soil, and animal scientists to investigate these relationships over various environmental conditions. In the present study, the costs of irrigation were assumed the same between feed crops grown with furrow and drip irrigations. Although drip irrigation has a higher investment cost, it is able to (1) have lower operational costs per acre because less labor is required to manage the irrigation events relative to furrow irrigation; (2) realize some operational cost savings relative to furrow irrigation because of its higher water application efficiency; (3) realize some other operational cost savings resulting from fewer field operations (e.g., weed control, fertilizer application); and (4) achieve increased crop yield due to the higher frequency of water and nutrient applications (e.g., “spoon feeding” by adding nutrients to irrigation water) to the plants. Therefore, drip irrigation offers more than enough benefits to offset the additional investment costs (Amosson et al., 2011). Including all the costs and benefits associated with different irrigation strategies was outside the scope of this modeling objective. However, different costs for the irrigation systems could be added to this modeling framework if the data on the actual investments and operational costs of different irrigation systems were available and relevant to the modeling objectives.

Furthermore, incorporating imported feeds and their costs into the modeling framework is possible but beyond the scope of the current modeling framework. An additional decision variable that accounts for the proportion of irrigation water attributed to lagoon water could also be added to the model. Although the proposed model can serve as a foundation for consequential analyses, broader questions can be addressed by tapping into additional expertise in various areas.

Accurately accounting for climate change will require more efforts to understand and model how limited resources could be allocated to meet different production demands in the future. The modeling framework presented here provides a solid base for future development and expansion.

CONCLUSIONS

Eight weighted GP models were developed to jointly minimize dietary costs and irrigation water usage for a hypothetical cow under 8 environmental scenarios. Almost half of the water usage was eliminated under

the “drip, wet year, and current CO₂” condition when minimizing water usage. When going from the least-cost diet to the least-water diet, DMI increased, NDF proportion decreased, lignin proportion increased, energy concentration decreased, and ether extract decreased because the model, in general, tended to choose feedstuffs that have lower energy concentrations but save more water. Protein was shown to be a binding constraint in the diet formulation and was invariant to the GP weights used. A lower requirement of CP did not change the pattern of the results. The water mitigation cost of drip irrigation was higher than that of furrow irrigation because of the higher application efficiency of drip irrigation systems. Furthermore, the beneficial effect of a higher CO₂ level on increasing water-use efficiency of crops partially compensated for, but did not overcome, the negative effect of increasing temperature based on our assumption of an increasing temperature and a stable ET_o that accompany a higher CO₂ level. All of these assumptions can be modified in future models depending on different study purposes and as additional relevant research data become available. The results of this model are based on the feeds, production level of model animals, and prices adopted, and these inputs can be easily modified. The proposed model provides a conceptual framework for the study and evaluation of irrigation water usage in the field of dairy production and a technique for potential use with other livestock systems.

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ORCIDS

D. Zaccaria <https://orcid.org/0000-0002-0909-9663>

J. G. Fadel <https://orcid.org/0000-0002-3512-5036>