

Irrigation water requirements for seed corn and coffee under potential climate change scenarios

Ali Fares, Ripendra Awal, Samira Fares, Alton B. Johnson and Hector Valenzuela

ABSTRACT

The impact of potential future climate change scenarios on the irrigation water requirements (IRRs) of two major agricultural crops (coffee and seed corn) in Hawai'i was studied using the Irrigation Management System (IManSys) model. In addition to IRRs calculations, IManSys calculates runoff, deep percolation, canopy interception, and effective rainfall based on plant growth parameters, site specific soil hydrological properties, irrigation system efficiency, and long-term daily weather data. Irrigation water requirements of two crops were simulated using historical climate data and different levels of atmospheric CO₂ (330, 550, 710 and 970 ppm), temperature (+1.1 and +6.4 °C) and precipitation (±5, ±10 and ±20%) chosen based on the Intergovernmental Panel on Climate Change (IPCC) AR4 projections under reference, B1, A1B1 and A1F1 emission scenarios. IRRs decreased as CO₂ emission increased. The average percentage decrease in IRRs for seed corn is higher than that of coffee. However, runoff, rain canopy interception, and deep percolation below the root zone increased as precipitation increased. Canopy interception and drainage increased with increased CO₂ emission. Evapotranspiration responded positively to air temperature rise, and as a result, IRRs increased as well. Further studies using crop models will predict crop yield responses to these different irrigation scenarios.

Key words | climate change, coffee, IManSys, irrigation water requirements, seed corn

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INTRODUCTION

Population growth, climate change, and anthropogenic land-use changes trigger severe negative effects on the global water resources. The impacts of these changes have more pronounced effects on small elevation-variant islands, e.g., Hawaiian Islands. These islands have been experiencing prevailing spatio-temporal variability of the major water cycle components, e.g., rainfall, evapotranspiration, and to a less extent temperature. Human activities are altering the global climate (Hansen *et al.* 2006) by raising the

concentration of the greenhouse gases especially methane, nitrous oxide and carbon dioxide (CO₂). Atmospheric CO₂ is expected to increase from its reference (330 ppm) concentration used in this study to between 550 and 970 ppm by 2,100 (IPCC 2007). Increased greenhouse gas concentrations are likely to raise the earth's mean temperature and influence precipitation, storm patterns and sea level (IPCC 2007). However, in general, the magnitude of these changes will depend on future anthropogenic activities as well as on technological and economic development. Over the past years of the 21st century, the global average surface temperature has increased by approximately 0.6 °C and is projected to rise by an additional 1.1–6.4 °C (IPCC 2007).

Timm & Diaz (2008) analyzed the precipitation variations over the Hawaiian Islands during most of the first

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decade of the 21st century using the AR4 A1B emission scenario. They predicted a 5–10% reduction of wet season precipitation and 5% increase during the dry season. [Karl *et al.* \(1996\)](#) reported an increase of the mean air temperature by 2.5 °C and 20% decrease in precipitation between 1,900 and 1,990 based on analysis of observed air temperature and precipitation at Honolulu International Airport, Hawai'i. [Giambelluca & Luke \(2007\)](#) reported an increasing trend in the mean annual temperature between 0.12 and 0.23 °C per decade across the Hawaiian Islands between 1905 and 2006. Although the magnitude of change in temperature and precipitation varied temporally and spatially, the anticipated impact on the hydrology and thus, irrigation water requirements for the crops in the mountainous Hawaiian watersheds is a serious matter for sustainable future water yields.

Anticipating changes in the hydrologic cycle is particularly important for regions with limited water supplies ([Ficklin *et al.* 2009](#)) such as the Hawaiian Islands. The Hawaiian Islands are the most isolated oceanic island group on earth and rely solely on precipitation and subsequent groundwater recharge for their fresh water needs ([Mair & Fares 2010](#)). Streams in Hawai'i supply more than 50% of irrigation water and a fair amount of drinking water in some places ([Oki 2003](#)). Examining the sensitivity of hydrologic responses to climate across different geomorphic regions is important to formulate appropriate water management policies and irrigation water allocations for local responses ([Qi *et al.* 2009](#)).

An increase in average daily temperature due to climate change will increase reference evapotranspiration (ET_o) resulting in an increased use of irrigation water whereas increase in atmospheric CO_2 will increase crop water use efficiency (WUE, which is the ratio of CO_2 uptake to evapotranspiration) resulting in less water needed for irrigation ([Ficklin *et al.* 2010](#)). The likely net effect of increased temperature and CO_2 will be insignificant changes in ET_o within the next 30 years ([Hatfield *et al.* 2008](#)).

Elevated atmospheric CO_2 often reduces plant stomatal conductance ([Nederhoff *et al.* 1992](#); [Rodaglou *et al.* 1992](#)) and plant transpiration per unit leaf area ([Goudriaan & Unsworth 1990](#); [Dugas *et al.* 1997](#)). Reduced transpiration increases the leaf temperature which can further increase

photosynthesis ([Acock 1990](#)). The effect of higher levels of CO_2 on stomatal conductance and transpiration is observed in both C3 and C4 species ([Dugas *et al.* 1997](#)). [Morison & Gifford \(1984\)](#) found that stomatal conductance was reduced by 36% while transpiration was reduced by 21% for several plant types, the difference being attributed to the higher leaf temperatures. Similar average values of 34% for stomatal conductance and 23% for transpiration were found in a literature survey by [Cure & Acock \(1986\)](#). An increase in photosynthesis and a decrease in transpiration result in an increase in the plant's water use efficiency.

Many studies estimated future changes in irrigation water requirements without considering a decrease in stomatal conductance due to elevated CO_2 in calculating ET_o . These studies calculated ET_o using temperature-based equations, e.g. Modified Hamon equation ([Lee & Huang 2014](#)), Priestley-Taylor method ([Doll 2002](#)). Several investigators, e.g., [Strzepek *et al.* \(1999\)](#), [Hatch *et al.* \(1999\)](#), and [Rosenzweig & Iglesias \(1998\)](#), used the Priestley-Taylor method to calculate ET_o ; in addition, they incorporated the effect of elevated CO_2 on stomatal closure and leaf area index and consequently, their impact on potential transpiration using the ratio ([Peart *et al.* 1989](#)) of transpiration under elevated CO_2 conditions to that under ambient conditions. However, very few researchers have attempted to estimate future changes in irrigation water requirements based on projected climate changes from GCMs, and estimates of decreased stomatal conductance due to elevated CO_2 in ET_o (e.g., [Allen *et al.* 1991](#); [Izaurrealde *et al.* 2003](#)). Thus, in this study we used a modified version of the FAO Penman-Monteith ET_o equation to account for the effects of elevated atmospheric CO_2 concentration and increase in temperature on ET_o .

In this study, the connections between anticipated climate change and hydrologic processes were studied to better understand the climate change impact on irrigation water requirements for two major crops in the islands of Hawai'i. The specific objectives of this research are to evaluate the potential impact of climate change on: (i) irrigation water requirements for a short cropping season annual crop, seed corn, and a perennial crop, coffee; and (ii) the major water cycle components, e.g., evapotranspiration, canopy interception, runoff, and excess water losses/groundwater recharge below the rootzone under Hawaiian conditions.

MATERIALS AND METHODS

Study area

Climate change sensitivity assessment was performed based on long-term historical weather data collected at Honolulu International Airport (Station ID–GHCND: USW00022521) on the Island of Oahu, Hawai'i, USA. The latitude and longitude of this station are 21.323° and –157.929°, respectively. The station is located at an elevation of 2.1 m AMSL. Daily climate data (precipitation, wind speed, maximum and minimum temperature) from 1984/01/01 to 2010/10/31 (27 years) were downloaded from the Global Historical Climatology Network (GHCN) of the National Climatic Data Center on the National Oceanic and Atmospheric Administration's (NOAA) website (<http://www.ncdc.noaa.gov/cdo-web/>).

Irrigation Management System (IManSys) model

The IManSys is a numerical simulation model; it calculates irrigation water requirements (IRRs) for different crops based on the water balance approach and using site-specific data and historical weather data. Water budget models have been used for irrigation scheduling and crop water requirement estimation (Smajstrla & Zazueta 1988; Obreza & Pitts 2002; Fares et al. 2008). Smajstrla & Zazueta (1988) reported on the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model that uses a water balance approach with a layered soil column to simulate soil water infiltration, redistribution, and extraction by evapotranspiration as steady state processes on a daily basis. The AFSIRS model simulates the irrigation requirements for a crop based on plant physiology, soil, irrigation system, growing season, climate and basic irrigation management practice. The AFSIRS does not account for runoff neither for canopy interception nor does it multiple crops. In addition, it cannot calculate ET based on other weather data, nor does it have databases for soils other than those found in Florida. Another major deficiency is that AFSIRS does not account for climate change effects on IRRs calculation. Based on the deficiencies of the current water

balance models, e.g. AFSIRS, it was necessary to develop a new model that builds on the water balance approach used by AFSIRS and offers new functions needed to calculate IRRs across different climates and environmental conditions where runoff, canopy interception, and climate change are important. Such a new model should also be able to calculate ET data.

Thus, IManSys was developed based on AFSIRS' approach (Smajstrla & Zazueta 1988); in addition to IRRs calculations, IManSys calculates runoff, canopy interception, effective rainfall, ET and IRRs for multiple crops based on crop growth parameters, soil properties, irrigation system efficiency, and long-term weather data (precipitation and evapotranspiration). IManSys accounts for climate change effects and water management practices on IRRs. If ET data is not available, IManSys calculates evapotranspiration using limited weather data, e.g. temperature-based model ETM (Fares & Mansell 1996) or using complete weather data, e.g. FAO Penman-Monteith method (Allen et al. 1998). IManSys uses multiple databases, e.g., soil and plant growth parameters, irrigation system efficiencies, and canopy interception. IManSys was implemented in JAVA object oriented language. IManSys output includes detailed net and gross IRRs, and all water budget components at different time scales (daily, weekly, biweekly, monthly, and annually) based on non-exceedance drought probability which is calculated from a conditional probability model that uses the type I extreme value distribution for positive non-zero irrigation values (Fares & Fares 2012).

IManSys' simulated soil profile depth is assumed to be equal to the crop root zone depth. The plant root zone is divided into irrigated (upper 50%) and non-irrigated (lower 50%) zones based on the common practice of irrigating only the upper portions of the crop root zone where most of the roots are located (Smajstrla 1990; Smajstrla & Zazueta 1988). It is assumed that 70% and 30% of crop ET are extracted from the irrigated and non-irrigated zones, respectively, when water is available (SCS 1970). This pattern of water extraction is typically assumed for well-irrigated plants on non-restrictive soil profiles (Smajstrla & Zazueta 1988).

The plant specific irrigation water requirements are calculated based on plant physiology, soil hydrological properties, irrigation system efficiency, growing season,

climate and basic irrigation management practices. The daily water balance equation for the soil column defined by the crop root zone expressed in terms of equivalent water depth per unit area (cm) is:

$$\Delta S = P + G_w + IRR_{net} - (Q_D + Q_R + ET_c + I) \quad (1)$$

where ΔS is the change in soil water storage expressed as equivalent water depth (cm), P is the gross rainfall (cm), G_w is the groundwater contribution (cm) from shallow water table, IRR_{net} is the net irrigation water requirement (cm), $(Q_D + Q_R)$ is summation of groundwater drainage and surface water runoff (cm), ET_c is the plant evapotranspiration (cm) and I is canopy rainfall interception (cm).

The water storage capacity is the amount of water that is available for plant uptake. It is calculated as the equivalent water between field capacity and permanent wilting point for a given soil multiplied by the depth of the root zone. Irrigation is scheduled based on an allowable level of soil water depletion from the root zone. Irrigation amounts are calculated to restore the soil water content to field capacity.

Assuming a negligible groundwater contribution to the rootzone ($G_w = 0$) and since gross $IRRs$ is $IRRs = IRR_{net}/f_i$ and the detailed equation is as follows:

$$IRRs = \frac{ET_c + \Delta S - (P - Q_R - Q_D - I)}{f_i} \quad (2)$$

where f_i is the efficiency of the irrigation system used.

The irrigation requirement is calculated as the depth of water required to replenish the soil water content to field capacity in the irrigated crop root zone. Irrigation events were assumed to start when the available water for plant uptake decreases to a predetermined minimum allowable level, termed allowable soil water depletion (AWD) percentage. Allowable soil water depletion values were determined from the literature and are fractions of the available soil water storage capacity that can be allowed to be depleted without significant reduction in crop yield. Allowable soil water depletion values for the annual and perennial crops are user specific and can be provided with crop information. The model uses AWD equals to 0.50 as the default value for all perennial crops. A value of 0.50 means that 50% of the available water in the

irrigated crop root zone is allowed to be depleted between two consecutive irrigation events.

More details about the IManSys model can be found in Fares (2008), Fares (2009), and Fares & Fares (2012). The theoretical and computational methods used in IManSys are the same as those used in IWREDSS (Fares 2008). Details about the IWREDSS model and its validation are given in Fares (2008).

Modification of FAO Penman-Monteith equation

Different methods to calculate potential evapotranspiration were implemented in IManSys. The FAO Penman-Monteith equation was modified to incorporate climate change scenarios of different CO₂ emissions and temperature rises in future ET calculations.

Reference evapotranspiration (ET_o) based on the FAO Penman-Monteith method (Allen et al. 1998), is calculated using the following equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (3)$$

where ET_o is the reference evapotranspiration (mm day⁻¹), R_n is the net radiation at the crop surface (MJ m⁻² day⁻¹), G is the soil heat flux density (MJ m⁻² day⁻¹), T is the air temperature at 2 m height (°C), r_s is the bulk surface resistance (s m⁻¹), r_a is the aerodynamic resistance (s m⁻¹), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa °C⁻¹), γ is the psychrometric constant (kPa °C⁻¹), and u_2 is the wind speed at height 2 m (m s⁻¹).

The ratio r_s/r_a in the FAO Penman-Monteith equation is a function of wind speed at 2 m height (0.34 u_2). We modified the value of ratio r_s/r_a according to variations in CO₂ concentration. An increase in CO₂ concentration not only causes increases in air temperature but also will result in a reduction of the leaf stomatal conductance (Saxe et al. 1998; Medlyn et al. 2001; Wullschlegel et al. 2002) and an increase in LAI because of enhanced photosynthesis (Pritchard et al. 1999; Wand et al. 1999). The stomatal conductance

of reference grass surface is adjusted using a similar approach to that used in the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998). Similar to Eckhardt & Ulbrich (2003), we used a smaller increase (7%) in LAI with a doubling of CO₂ concentration.

Bulk surface resistance (r_s) is defined by using the following equation:

$$r_s = \frac{r_l}{LAI_{active}} \quad (4)$$

where r_l is the bulk stomatal resistance of the well-illuminated leaf ($s\ m^{-1}$), LAI_{active} is the active (sunlit) leaf area index (m^2 (leaf area) m^{-2} (soil surface)).

Stomatal resistance and LAI for different CO₂ emission scenarios can be calculated using the following equations:

$$r_l = \frac{1}{g_{CO_2}} = \frac{1}{g \left[1.4 - 0.4 \left(\frac{CO_2}{330} \right) \right]} \quad (5)$$

where g_{CO_2} is the modified leaf conductance (Neitsch et al. 2011) and g is the conductance without the effect of CO₂ for the reference crop, grass, $0.01\ m\ s^{-1}$.

LAI for different CO₂ emission scenarios (LAI_{CO_2}) based on assumption of 7% increase in LAI with a doubling of CO₂ emission is given by the following equation,

$$LAI_{CO_2} = LAI \left[1 + \frac{7}{100} \left(\frac{CO_2 - 330}{330} \right) \right] \quad (6)$$

For clipped grass, a general equation for leaf area index (LAI) is:

$$LAI = 24h \quad (7)$$

where h is the height of reference crop, grass (0.12 m),

$$LAI_{CO_2} = 24h \left[1 + \frac{7}{100} \left(\frac{CO_2 - 330}{330} \right) \right] \quad (8)$$

For reference crop, grass,

$$LAI_{active} = 0.5LAI_{CO_2} \quad (9)$$

The expression for bulk surface resistance (r_s) can be modified to Equation (10) using Equations (4)–(9),

$$r_s = \frac{1}{g \left[1.4 - 0.4 \left(\frac{CO_2}{330} \right) \right]} \times \frac{1}{12h \left[1 + \frac{7}{100} \left(\frac{CO_2 - 330}{330} \right) \right]} \quad (10)$$

The ratio r_s/r_a can be calculated for different CO₂ emission scenarios (Table 1) using Equation (10) and r_a ($=208/u_2$) for a grass reference surface (Allen et al. 1998).

ET_o is calculated for different scenarios of temperature rise and CO₂ emission using the modified FAO Penman-Monteith equation (Figure 1). The details of climate change scenarios are given in the subsequent section. ET_o increased with increase in temperature and decreased with increase in CO₂ emission (Figure 1).

The remaining terms are estimated; following Allen et al. 1998 using observed or increased daily maximum and minimum temperature in different scenarios.

Table 1 | r_s/r_a for different CO₂ emissions

CO ₂ emission (ppm)	r_s/r_a
550	0.435 u_2
710	0.573 u_2
970	1.311 u_2
330	0.340 u_2

Note: u_2 is the wind speed at height 2 m ($m\ s^{-1}$).

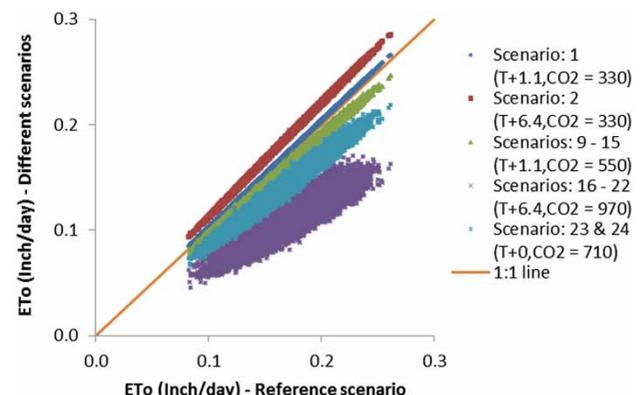


Figure 1 | ET_o for different scenarios of temperature increase and CO₂ emission.

Climate change scenarios

In this study, a total of 24 climate change scenarios (Table 2) were generated on the basis of the IPCC Special Reports on

Table 2 | Climate change sensitivity scenarios based on different potential emission scenarios

Scenarios	CO ₂ emission (ppm)	Temperature (°C)	Precipitation variation (%)	Emission scenario
Reference	330	0	0	Reference emission scenario
1	330	1.1	0	
2	330	6.4	0	
3	330	0	-5	
4	330	0	-10	
5	330	0	-20	
6	330	0	5	
7	330	0	10	
8	330	0	20	
9	550	1.1	0	B1 emission scenario
10	550	1.1	-5	
11	550	1.1	-10	
12	550	1.1	-20	
13	550	1.1	5	
14	550	1.1	10	
15	550	1.1	20	
16	970	6.4	0	A1F1 emission scenario
17	970	6.4	-5	
18	970	6.4	-10	
19	970	6.4	-20	
20	970	6.4	5	
21	970	6.4	10	
22	970	6.4	20	
23	710	0	-5% in wet and +5% in dry season	A1B emission scenario
24	710	0	-10% in wet and +5% in dry season	

Emission Scenarios (IPCC 2001), local trend analysis and GCM downscaling (Timm & Diaz 2008) similar to the climate change scenarios used by Ficklin *et al.* (2009) and Safeeq & Fares (2012). On the basis of the IPCCs projections of greenhouse gas emissions for the 21st century, atmospheric concentration of CO₂ is expected to increase between 550 (B1 emission scenario) and 970 ppm (A1F1 emission scenario) from its reference emission scenario of 330 ppm. The two extreme scenarios represent a future world of a very rapid economic growth (A1F1 emission scenario-970 ppm) or a future world with low economic growth and fossil fuel independency (B1 emission scenario-550 ppm).

To bracket the range of changes in precipitation over the Hawaiian Islands, four arbitrary precipitation scenarios with respect to the reference level (i.e., 0, ±5, ±10 and ±20%) were selected. Two additional precipitation-based scenarios were generated on the basis of six GCM predictions for Hawai'i under AR4 A1B emission scenario. Temperature-based scenarios were generated by increasing the temperature by 1.1 and 6.4 °C. All the climate change scenarios were generated using the 'delta method' (Hamlet & Lettenmaier 1999) on observed precipitation and air temperature data from the Honolulu Airport Weather Station for the period between 1984 and 2010. Daily precipitations were increased or decreased relative to the original observed data; thus, the latter data were multiplied by a scaling factor. A scaling factor with a value of 1.05 means a 5% increase in precipitation compared with historical data. One of the reasons for choosing two cropping seasons for the annual seed corn crop is to cover the potential impact climate change might have on rainfall distribution across the year. Changes in air temperature were made by adding the required 1.1 or 6.4 °C to observed temperature, half of each of these values is added to the maximum daily temperature and the other half to the minimum daily temperature.

RESULTS AND DISCUSSION

Different scenarios were simulated using IManSys for 27 years after adjusting precipitation, temperature, leaf conductance, and LAI. Other climate variables (i.e., solar radiation, wind speed, and relative humidity) were kept constant for all

scenarios. Seed corn growing seasons and their corresponding lengths are given in Table 3. The growing seasons used for all simulated scenarios are the same for both crops. The dry and wet seasons for corn start in June and December, respectively. The irrigation system used in all simulations is the drip irrigation system which has an irrigation efficiency of 0.85. Simulation results are presented on a monthly and an annual basis; they were then compared with those of the reference scenarios.

Gross irrigation water requirements and crop evapotranspiration

Irrigation water requirements decreased with increased CO₂ emission (Figure 2) for both crops. The decrease level for coffee was 6.4% and 42.2% for CO₂ emission levels of 550 ppm and 970 ppm, respectively. The corresponding average decrease in IRRs for seed corn was 8% and 50.1%, respectively. Similarly, gross irrigation water requirement has an inverse relationship with precipitation, i.e., it decreased with rise in precipitation but increased with fall of precipitation. The average annual gross rainfall for the reference scenario is 430 mm for this study area.

Table 3 | Growing seasons selected for simulating irrigation water requirements

Crop	Season	Sowing	Harvesting	Length of season
Coffee		January 1	December 31	365
Seed corn	Dry	June 1	September 6	98
Seed corn	Wet	December 1	March 8	98

Evapotranspiration increased with increase in temperature for the reference scenario of CO₂ emission (CO₂ = 330 ppm and $\Delta P = 0$); thus, gross irrigation water requirement also increased (Figure 3). However, the combined effect of temperature and CO₂ emission as illustrated in scenarios B1 and A1F1, resulted in a decrease of all monthly ET and gross IRRs (Figure 4).

Based on an extensive review of the literature, the authors did not find any previous studies on the potential impact of climate change on IRRs of crops in Hawai'i; however, there were other studies under non-tropical environments. Projections of future irrigation requirement for field corn in Georgia, USA calculated using a climate change scenario derived from the HadCM2 (Johns et al. 1997) global circulation model showed a decrease in IRRs by 20% by 2030 and 50% by 2090 due to the combined effect of precipitation increase and shortening of the growing seasons (Hatch et al. 1999). Hatch et al. (1999) used the Priestley-Taylor equation to calculate reference evapotranspiration; they also incorporated the effect of elevated CO₂ on stomatal closure on potential transpiration using the ratio (Peart et al. 1989) of transpiration under elevated CO₂ conditions to that under ambient conditions. In general, results of the current study concur with their prediction of an IRR decrease. However, results of IRRs across the US corn-belt, under three climate change scenarios showed mixed result (Strzepek et al. 1999). In their study they also used a similar approach to calculate ET_c; the calculated potential transpiration reflects the effects of elevated CO₂. Allen et al. (1991) studied the effects of

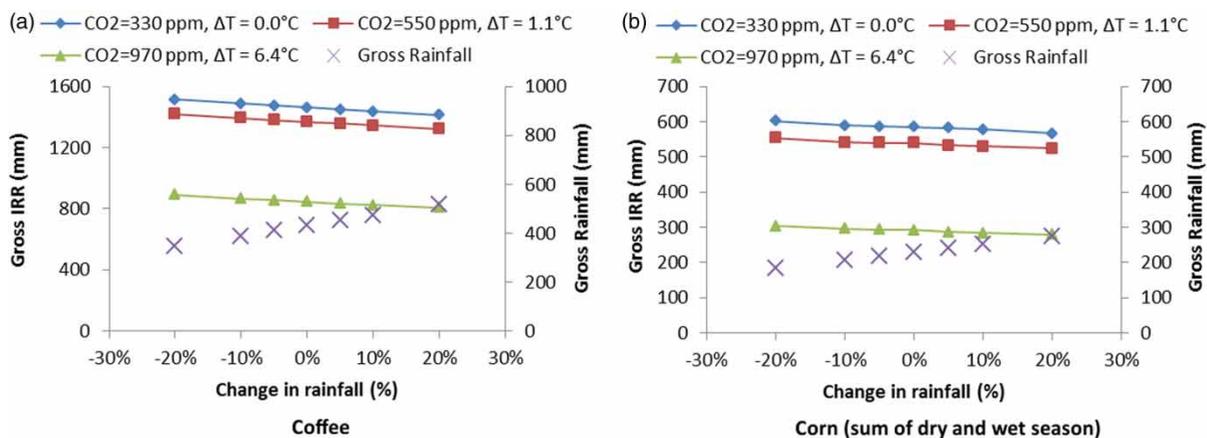


Figure 2 | Gross irrigation water requirement for different scenarios of temperature increase and CO₂ emission.

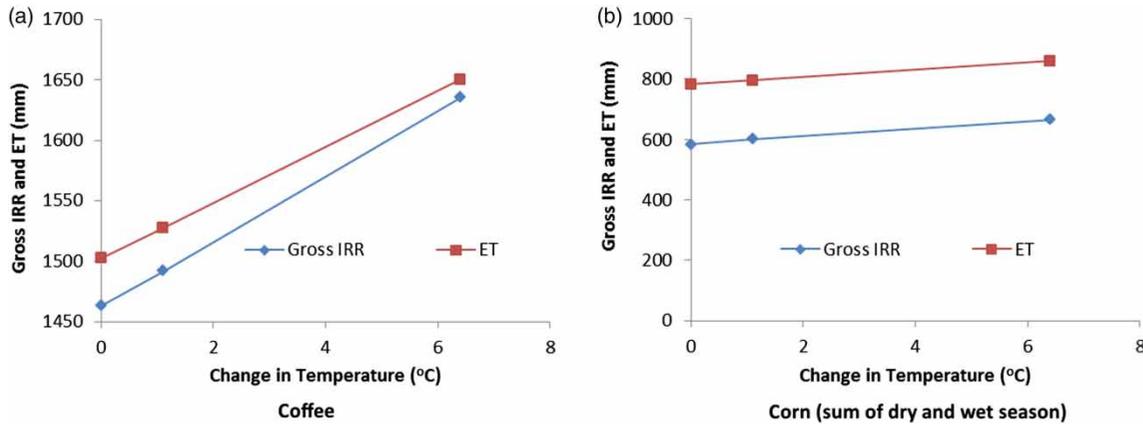


Figure 3 | Effect of changes in temperature on gross IRR and ET ($CO_2 = 330$ ppm and $\Delta P = 0$).

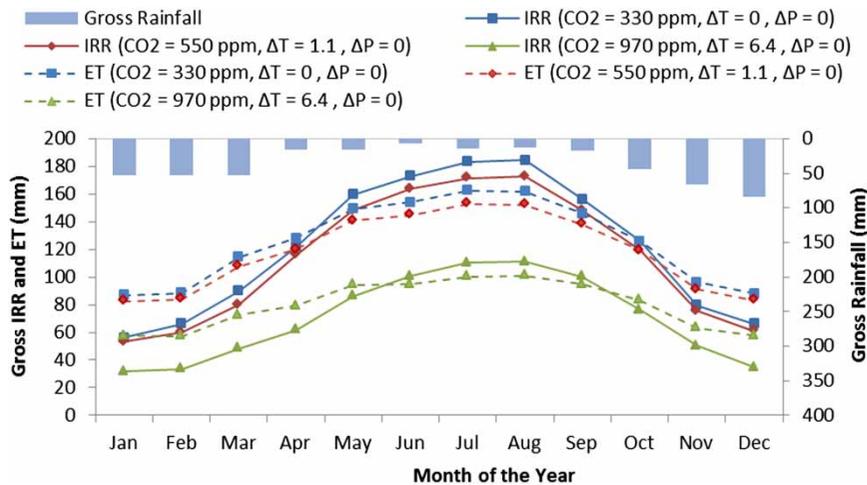


Figure 4 | Monthly variation of gross IRRs and ET for different CO_2 emission scenarios (coffee).

CO_2 -induced climatic changes on IRR in the Great Plains region (Nebraska, Kansas, Oklahoma and Texas) using GCMs data and a water balance model. They also used the Penman-Monteith equation to calculate ET_o ; they simulated the effect of elevated CO_2 level transpiration by increasing the value of reference crop bulk stomatal resistance (+20, +40, +60 and +80%). They reported a decrease in IRR for corn at all locations for increased bulk stomatal resistance of 40–80% under the GISS (Goddard Institute for Space Studies) scenario; however, IRR increased at all locations for increased bulk stomatal resistance of 20–60% except for Texas under the GFDL (Geophysical Fluid Dynamics Laboratory of Princeton University)

scenario. The IRRs may increase or decrease depending on the spatial location of the study area and climate change scenarios used.

The negative correlation between precipitation and gross IRRs for these scenarios was consistent during all months (Figure 5); thus, gross IRRs increased by 7.7–17.2% for a temperature rise of 6.4 °C at the reference CO_2 level (330 ppm). The variation in gross IRRs during the wet season (November–April) is higher than during the dry season (May–October). Gross IRRs almost were consistently lower than those of the reference case for all scenarios of B1 emission ($CO_2 = 550$ ppm) except during 4 months of scenario 12 (which has only 80% of the

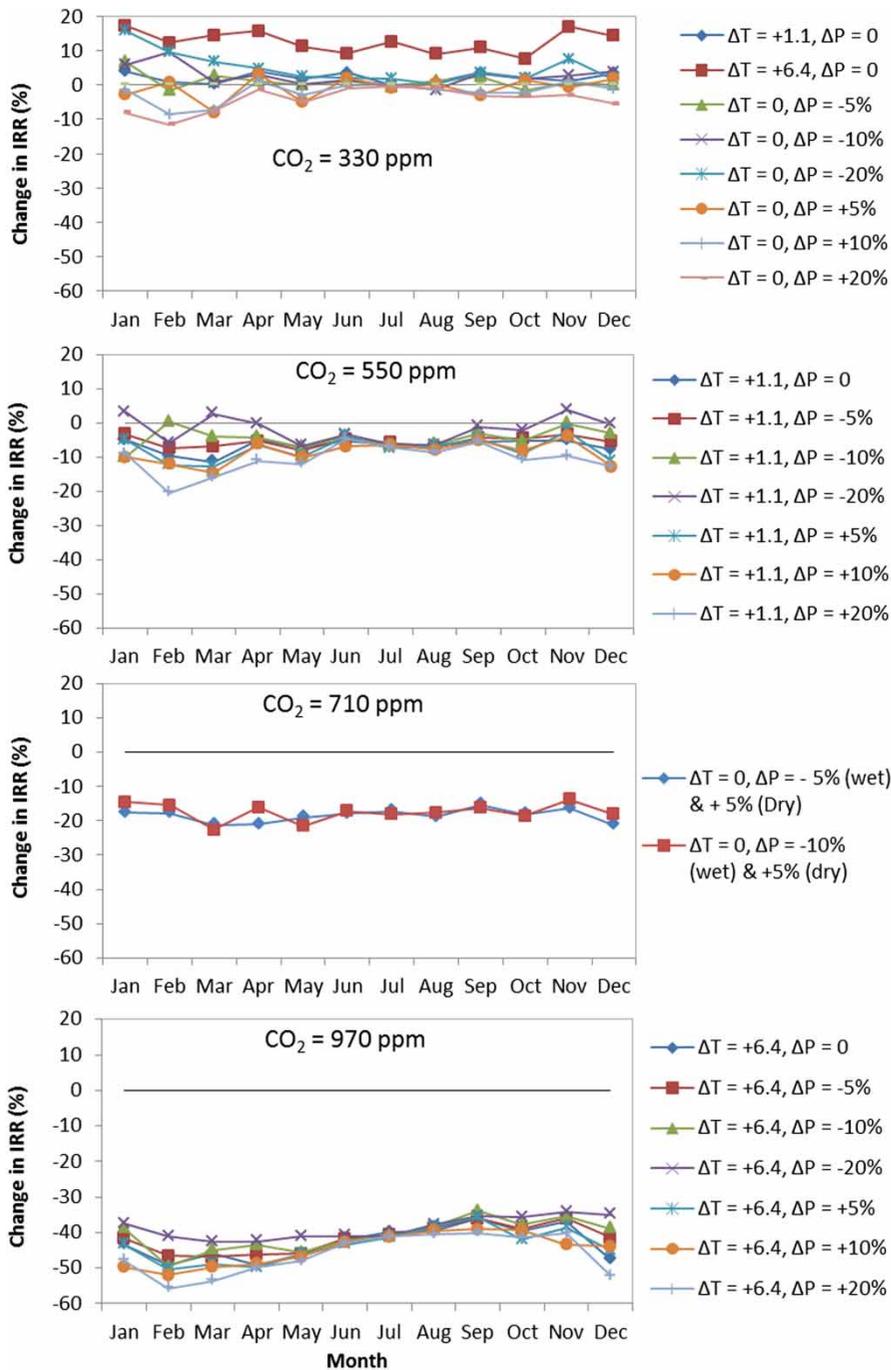


Figure 5 | Change in average monthly gross IRRs relative to the reference scenario (coffee).

reference precipitation) (Figure 5). The highest monthly decrease in the gross IRRs of 20.4% is during February for scenario 15 which has the highest precipitation increase (20%). Decrease in gross IRRs varies between 13.7 and 22.6% for the two scenarios of A1B emission (CO₂ =

710 ppm). Decrease in the gross irrigation water requirements is more pronounced for the A1F1 emission scenario where the minimum decrease was 33.9% (Scenario 18) and the maximum decrease reached 55.7% (Scenario 22).

Rainfall, runoff and canopy interception

In IManSys, surface runoff is calculated using the SCS curve number method (Fares & Fares 2012). Thus, runoff is a function of precipitation, soil hydrologic group, land use, and management practices. Runoff is not influenced by the CO₂ emission level; thus, for this case it only responds to precipitation levels (Figure 6). For each crop and at a given precipitation level, runoff is the same for all CO₂ emissions. Runoff represents about 18.3% of the gross rainfall for the perennial coffee crop and about 7% for the dry and 18.9% for the wet seasonal seed corn crop.

IManSys calculates precipitation canopy interception as a function of the maximum leaf area index (LAI_{max}) of the crop; it assumes that LAI_{max} will increase by 7% with doubling of CO₂ emission for all crops. Thus, interception is higher for higher CO₂ emission scenarios. Canopy

precipitation interception increases with increases in gross rainfall (Figure 7). About 19 to 22% of the gross rainfall was lost as precipitation canopy interception under the coffee crop. However, precipitation canopy interception represents 10–12% of the gross precipitation under seed corn.

Drainage

Drainage and precipitation are positively correlated (Figure 8) for both crops; thus, drainage increased with increase in precipitation and decreased with a decrease in precipitation. However, the magnitude and the rate of drainage increase are higher for seed corn than for coffee. This drainage increase represents 8% of the gross rainfall for coffee and 20% for seed corn. Similarly, the rate of drainage rise as a result of precipitation increase is equal to 0.82 cm cm⁻¹ of precipitation for seed corn and 0.18 cm cm⁻¹ for

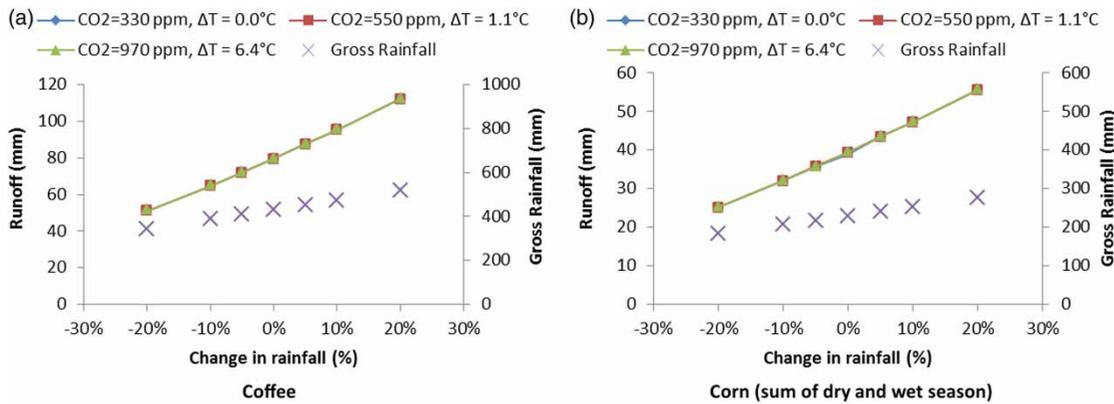


Figure 6 | Runoff for different scenarios of temperature increase and CO₂ emission.

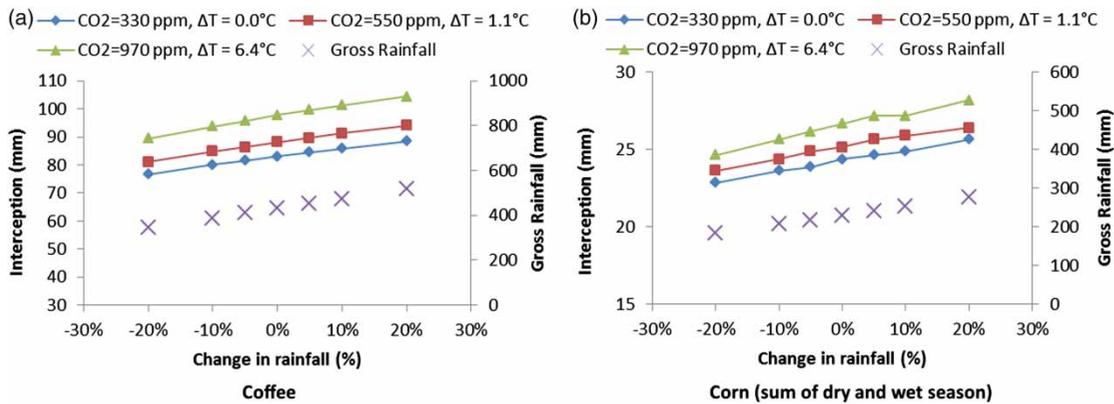


Figure 7 | Interception for different scenarios of temperature increase and CO₂ emission.

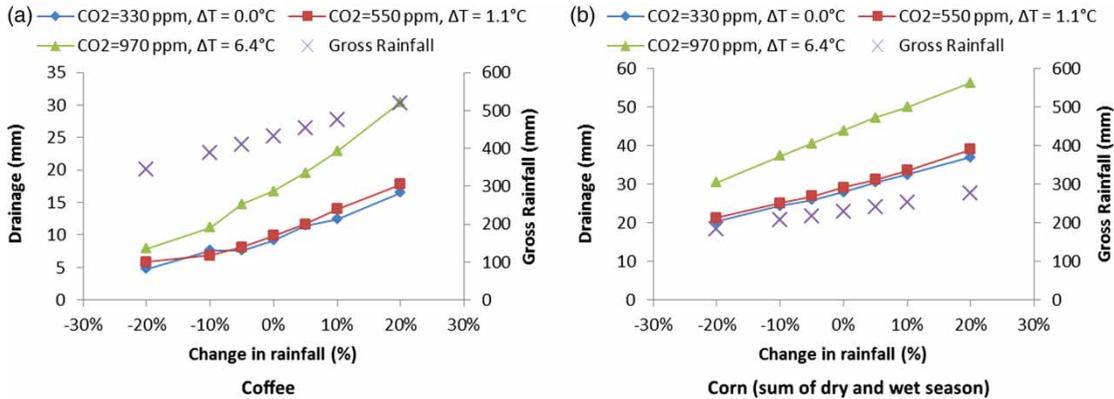


Figure 8 | Drainage for different scenarios of temperature increase and CO₂ emission.

the coffee crop. The lower predicted drainage rates under the coffee crop is due to a combination of several factors including LAI, and difference in the cropping season as coffee is a perennial crop and seed corn is a short growing season annual crop.

CONCLUSIONS AND RECOMMENDATIONS

This work investigated the impact of potential future climate change scenarios on the gross IRRs of two major agricultural crops (corn and coffee) in Hawai'i and the subsequent water budget components (runoff, drainage, and canopy interception) using IManSys.

It was found that an increase in temperature resulted in an increase in ET demand and consequently in an increase of IRR for both crops; however, IRR is higher for coffee (>10%) than for that of seed corn. As expected, gross IRR is negatively correlated with precipitation; however, there is a direct correlation between drainage and precipitation. Irrigation water requirement decreased with increased CO₂ emission. Results of the study indicated that the impact of climate change on two major crops grown in a major Hawaii Island (seed corn and coffee) is very sensitive to future climate scenarios generated as predicted by different GCMs. The average percentage decrease in IRRs for coffee is 6.4% and 42.2% for CO₂ emission levels of 550 ppm and 970 ppm, respectively. Whereas the corresponding average decrease in IRRs for seed corn are 8% and 50.1%, respectively. The average percentage decrease

in IRR for seed corn is comparatively higher than that of coffee. Runoff increased with a precipitation rise, but it did not show any change in response to CO₂ level variations. Canopy interception and drainage increased with increased CO₂ emission. However, the magnitude and the rate of drainage increase are higher for seed corn than for coffee. Evapotranspiration increased for rising temperatures, and as a result the gross irrigation water requirement was also increased. Changes in rainfall variability and increased evaporation will directly impact rain-fed agriculture and reduce water availability for irrigation.

Results of this study as well as those obtained from other studies suggest that as the CO₂ content in the atmosphere continues to rise, terrestrial plants will likely display reductions in transpirational water loss. As a result, most plants might be able to better deal with periodic water shortages and warmer temperatures, possibly even could expand their ranges into areas where it was too dry for them to successfully live and reproduce in the recent past.

This study only focused on IRR calculations for two main crops grown on Hawai'i. Further studies on predicting crop yield responses to these different irrigation scenarios using crop modeling are essential to quantify the impact of climate change on the yield of these two crops in Hawai'i.

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