CO₂ AND TEMPERATURE EFFECTS ON EVAPOTRANSPIRATION AND IRRIGATED AGRICULTURE

By Jorge A. Ramírez,¹ and Bryce Finnerty²

ABSTRACT: A sensitivity analysis of potential evapotranspiration (PET) rates under both CO₂ and air temperature changes was conducted. PET was modeled with the Penman-Monteith equation so that the effects of atmospheric CO₂ concentrations on plant stomatal resistance, and the effects of temperature on land-surface–atmosphere water vapor exchanges were explicitly taken into account. A root-zone soil-water balance was performed using a physically based soil-crop-climate model to analyze the sensitivity of soil moisture to changes in atmospheric temperature and CO₂ concentrations, and the effects of CO₂ fertilization on plant photosynthesis and crop yield. A wide spectrum of directional climate change scenarios were analyzed, including both a 3°C increase and a 3°C decrease in air temperature, and both a 50 and a 100% increase in atmospheric CO₂ concentrations. An additive crop yield model and an optimal irrigation scheduling model were used to maximize agricultural benefits by maximizing crop yield and minimizing irrigation costs. The model was applied to an irrigated potato crop in the San Luis Valley of Colorado.

INTRODUCTION

The natural dynamics in the Earth’s oceanic, atmospheric, and land-surface components of the global climate system cause the weather and climate to change in time and space. Human impacts on the land-surface features through urbanization, deforestation, reforestation, and agriculture have a significant impact on water mass and energy budgets, thus affecting hydrologic system response, weather, and climate (Cotton and Pielke 1992). Anthropogenic emissions into the atmosphere of radiatively active greenhouse gases such as carbon dioxide, methane, sulfur dioxide, chlorofluorocarbons, and water vapor, will affect atmospheric energy balances.

Increased concerns for the potential impacts of climate change on regional hydrology and water resources have prompted this and other impact assessment studies [e.g., Lettenmaier and Ghan (1990), Nash and Gleick (1991), Allen et al. (1991), Fennessey and Kirshen (1994), Epstein and Ramírez (1994)]. Climate change concerns of the agricultural industry include changes in temperature, precipitation, and atmospheric carbon dioxide concentrations that may lead to changes in potential evapotranspiration (PET) rates, root-zone soil moisture storage, crop yield, and net agricultural benefits in dollars/acre ($/acre). General circulation model (GCM) simulations generally indicate that global climate will be warmer under doubled carbon dioxide concentrations (2 × CO₂), with both positive and negative departures in precipitation and temperature at regional scales (Cotton and Pielke 1992). However, GCM model output at large spatial scales cannot be used directly in regional impact assessment studies because of their incongruent characteristic space and time scales. Climate inversion schemes or disaggregation procedures must be used to obtain regional-scale climate information from GCM global climate simulations. Epstein and Ramírez (1994) have developed one such scheme and applied it successfully to assess climate change impacts on the annual, seasonal, and daily water balances for the Upper Rio Grande basin in Colorado. In this study, the emphasis is on a sensitivity analysis. Thus, a range of plausible climate change scenarios is analyzed.

CARBON DIOXIDE, GREENHOUSE GAS HYPOTHESIS, AND CLIMATE CHANGE

The greenhouse gas hypothesis predicts global warming trends as a result of the trapping of outgoing longwave radiation from the Earth’s surface by increasing concentrations of greenhouse gases. Trapping longwave radiation in the atmosphere theoretically alters the earth’s radiative energy balance and, therefore, the temperature. Greenhouse gases include carbon dioxide, water vapor, methane, nitrous oxide, chlorofluorocarbons, and others. Carbon dioxide is of great concern because of its rate of increase in the atmosphere since the industrial revolution. The preindustrial revolution global atmospheric CO₂ concentration is estimated to be in the range of 265–290 ppm, as estimated from ice core samples (Neftel et al. 1985). Since record keeping began at Mauna Loa Observatory, Hawaii, observed CO₂ concentrations have increased from 315 ppm in 1958 to 350 ppm in 1989 (Schera gia and Mintzer 1990). This increase is attributed to deforestation and the burning of fossil fuels such as fuel oil, natural gas, and coal. Atmospheric carbon dioxide concentrations are expected to double preindustrial revolution concentrations at some point in the 21st century.

Water vapor is the most important greenhouse gas. Its temporal and spatial distributions are controlled by hydrologic cycle processes. Greenhouse warming is expected to increase evaporation from the oceans and evapotranspiration from the land. As a result, a global increase in cloudiness is expected to occur from an increase in atmospheric moisture. Depending on the altitude and location, a cloud’s ability to reflect and scatter incoming shortwave solar radiation may outweigh the cloud’s ability to trap longwave radiation. Therefore, increasing cloudiness may reduce the net solar radiation absorbed at the Earth’s surface, and reduce global warming (Cotton and Pielke 1992).

The global greenhouse warming hypothesis is difficult to confirm by climate records of the past century. Data obtained by remote sensing of the Earth’s atmospheric temperature over the years from 1979 to 1988 showed no obvious trend in atmospheric temperature over the 10-yr period (Spencer and Christy 1990). Statistical evidence supports a 0.4°C decrease in temperature for the northern hemisphere from the years 1940–80 (Idso 1983). MacDonald et al. (1979) found global temperature to rise less than 0.4°C from 1880 to 1970, according to the statistical analysis of climate records. A more recent analysis of global climate records from land and the
oceans around the world, which excluded records expected to be tainted by land-use changes, shows a temperature increase over the past 90 years to be in the range of 0.4°–0.6°C (Kellogg 1991).

GCM simulations under 2 × CO₂ concentrations result in global temperature increases of 2.5°C, with regional temperature changes from –3°C to +10°C. Precipitation fluctuates in the range of +20% to –20% from current regional averages (Peterson and Keller 1990). GCMs simplify the spatial and temporal scales of global fluid dynamics as well as the complex physics that drive the exchanges of water, heat, and energy between the Earth’s atmosphere, oceans, and continental land masses. In addition, GCMs’ spatial scales are too large to account for the effects of mountainous terrain and other heterogeneities on the local and regional climate. Different GCMs use different modeling strategies, and often produce different model climates. Therefore, there is a large degree of uncertainty associated with potential climate changes. These uncertainties require research to investigate a wide spectrum of plausible climate change scenarios, consistent with those reported in the literature.

**Carbon Dioxide Effects on Plant Stomatal Resistance and Evapotranspiration**

Carbon dioxide causes a physiological reaction, affecting plant stomata. Varying the stomatal resistance allows the plant to regulate the respiratory rate and the rate of absorption of CO₂ for photosynthesis. Increases in atmospheric CO₂ increase the leaf’s internal CO₂ absorption rate. The plant reacts by increasing stomatal resistance, which reduces the CO₂ absorption rate. Increasing the stomatal resistance reduces transpiration from the leaf into the atmosphere (Morrison 1987). This reduces the plants’ water use requirements and increases the plants’ water-use efficiency. Stomata respond to increased CO₂ to regulate photosynthesis in more than 50 species analyzed by Kimball and Idso (1983). Plants are categorized by their photosynthetic mechanisms controlling the chemical processes that manufacture glucose from CO₂ and water. Most agricultural and forest vegetation species are categorized as C₃ and C₄ species because of their photosynthetic pathways. Plant species which have been found to have stomata that respond to atmospheric CO₂ concentrations include angiosperms (monocots and dicots), and gymnosperms. These plants have one of three photosynthetic pathways: C₃, C₄, or CAM (Morrison and Gifford 1983; Morrison 1987).

**Carbon Dioxide Fertilizing Effects on Plant Biomass Production and Water-Use Efficiency**

Increasing atmospheric CO₂ concentrations generally increases photosynthetic rates and the plants’ biomass production. A doubling of atmospheric CO₂ concentrations increased biomass production by an average of 33% in the vegetal species studied by Kimball (1983). This increase in biomass production coupled with a reduction in evapotranspiration results in a significant increase in plant water use efficiency, which is defined as the ratio of plant biomass produced to the volume of water used for biomass production. Both forest and agricultural species have been shown to double water use efficiency under a doubling of atmospheric CO₂ concentrations (Rogers et al. 1983).

More than 500 studies analyzing the effects of increased atmospheric CO₂ concentrations have reported an increase in crop yield, biomass production, leaf area, and photosynthetic rates, as well as a decrease in plant water use requirements (Idso 1983; Kimball 1983; Allen et al. 1991). An increase in biomass and leaf area implies that plants can transpire more water. However, the reduction in transpiration caused by an increase in stomatal resistance results in a cumulative decrease in evapotranspiration (Morrison and Gifford 1984; Idso et al. 1986). This research addresses the effects of increased CO₂ on agricultural crops, which are categorized as C₃ and C₄ plant species. Photosynthetic reactions of C₃ plants are more sensitive than C₄ plants to increased CO₂ concentrations, resulting in a larger increase in biomass production in C₃ plants. Increases in leaf area from 20 to 75% have been observed in C₃ species (Rosenberg 1981; Rosenberg et al. 1988).

Negative feedback processes exist that may reduce the effects of increased CO₂ on stomatal resistance and evapotranspiration. Reducing transpiration by increasing the stomatal resistance acts to reduce the loss of heat from the leaf that occurs during transpiration and may increase the leaf temperature. Humidity, vapor pressure deficits, and temperature gradients between the vegetation and the near-surface atmospheric boundary layer may be affected (Morrison and Gifford 1984). Output from two GCMs show almost a linear relation between stomatal resistance and leaf surface temperature (Allen et al. 1991). These possible feedbacks are not included in some models. The inclusion of a negative feedback effect is beyond the scope of this sensitivity analysis.

**OBJECTIVES**

The general objective of this work is to assess impacts of long-term climate variability on irrigated agriculture. Irrigated agricultural systems are constrained and driven by climate-soil-plant processes, as well as by engineering decisions. In this study, optimization of irrigation scheduling decisions is performed using physically based models of the soil-crop-climate system coupled with stochastic dynamic programming procedures. These models allow for analysis of the effects of various climate change scenarios on optimal irrigation decisions, and on the expected agricultural benefits obtained from the optimal decisions. Using physically based models, the long-term impacts of climate variability, water-table variations, and agroeconomic sensitivity on irrigated agriculture are evaluated in this two-part paper (see also Ramirez and Finnerty [1996]). Specific objectives of this paper are to: (1) Evaluate the sensitivity of PET rates to both a 3°C increase and a 3°C decrease in air temperature, 50 and 100% increases in atmospheric CO₂ concentrations, and combinations of the two climate change scenarios; (2) use climate change PET rates to evaluate the sensitivity of actual evapotranspiration (AET), soil moisture depletion, crop yields, and the maximum expected benefits from irrigated agricultural production; (3) analyze the sensitivity of crop yield and agricultural benefits to CO₂-induced fertilization.

**SOIL-CROP-CLIMATE MODEL**

The soil component of the soil-crop-climate system controls infiltration, actual evapotranspiration, percolation, and capillary rise processes, which are all functions of the soil moisture content. The conceptual model that synthesizes all the hydrologic components into a single soil moisture depletion function is adapted from Córdova and Bras (1979) and Ramírez and Bras (1982, 1985), with the addition of an explicit capillary rise component in order to deal with contributions to the root-zone soil-moisture content from shallow water tables. The water balance inputs are the volume of water infiltrated from rain events, irrigation applications, and capillary rise. Soil-water outputs are actual evapotranspiration and percolation. The one-dimensional water balance in the soil column is governed by

\[
\frac{dθ}{dt} = I(θ) + f(θ) + w(θ) - P(θ) - AET(θ)
\]
where $\theta$ = volumetric soil moisture content; $I(\cdot)$ and $f(\cdot)$ = irrigation and infiltration rates, respectively; $P(\cdot)$ = gravitational percolation rate; $AET(\cdot)$ = actual evapotranspiration rate; and $w(\cdot)$ = rate of capillary rise. A detailed description of this model is given in Appendix I.

Optimal control of irrigation applications requires a crop model capable of encoding the sensitivity of crop yield to moisture stress during the plants' physiological growth stages. Such a model provides the structure for prioritizing the allocation of irrigation water at critical growth stages so as to maximize crop yield at the end of the growing season. The model used in this study describes crop yield as a function of the ratio of actual evapotranspiration to potential evapotranspiration, $AET/PET$ (Stewart et al. 1974; Morey et al. 1975). Given $PET$, $AET$, and the sensitivity of the plants' physiological growth stages to moisture stress, the actual crop yield at the conclusion of the growing season is evaluated as

$$Y = Y_a \sum_{i=1}^{NP} \frac{A_i AET_i}{PET_i} \tag{2}$$

where $Y$ = crop yield at harvest time; $Y_a$ = maximum attainable yield for the season; $NP$ = number of growth stages; $AET_i$ = actual evapotranspiration for growth stage $i$; $PET_i$ = potential evapotranspiration over growth stage $i$; and $A_i$ = sensitivity of crop growth to water stress during growth stage $i$, which is discussed in greater detail in Ramirez and Finnerty (1996). The value of $A_i$ increases as the sensitivity of the growth stage increases, and the $\sum A_i = 1$.

The climate model consists of two components: a potential evapotranspiration function and a precipitation model. The precipitation process establishes the natural random inputs of rain water into the soil column. Rainfall arrivals are modeled either as a nonhomogeneous Poisson process or as a Neyman-Scott cluster process (Ramirez and Bras 1985). Storm characteristics are described by the probability distribution functions of both storm intensity and storm duration. The atmospheric contribution of water to soil moisture storage is defined as a function of the probabilistic descriptions of the rainfall arrival process, storm intensity and duration, and the soil moisture depletion process.

**EVAPOTRANSPIRATION MODEL**

Evapotranspiration (ET) is driven and controlled by the physical climatic conditions that exist at the land-surface-atmosphere boundary, and the physiological characteristics of the vegetation. PET represents the vertical flux of water vapor that exists if water supply in the soil-plant system is not constrained. Plant physiology is important in determining PET rates because stomata on the leaf surface control respiration, CO$_2$ assimilation, photosynthesis, and transpiration. Many ET estimation techniques are available at various temporal and spatial scales. The water balance method is generally used for average annual estimates of evapotranspiration in well-monitored areas. The energy balance method accounts for energy available for ET processes, but usually neglects vegetative processes. The mass-transfer method estimates ET as a function of vapor pressure gradients existing between the soil-plant system and the atmosphere, and accounts for the effects of wind on the turbulent transfers of heat and water vapor.

For this sensitivity analysis, the modified Penman-Monteith equation is adopted. The modified Penman-Monteith equation evaluates PET rates as a function of the plant species' physiological characteristics and climatic conditions. PET is evaluated as (Monteith 1965)

$$PET = \frac{R_e \Delta + (\rho_a C_{pe}/r_a)(e_r - e_a)}{\Delta + \gamma(1 + r_r/r_a)} (1/P_e) \tag{3}$$

where $R_e$ = net radiation; $\Delta$ = slope of the saturation vapor pressure versus temperature curve; $e_r$ = saturation vapor pressure of the air; $e_a$ = actual vapor pressure of the air; $r_e$ = average aerial resistance of the crop canopy; $r_r$ = stomatal resistance of the plant; $\gamma$ = psychrometric constant; $\rho_a$ = density of the air; $\rho_d$ = density of water; $L_e$ = latent heat of vaporization; and $C_{pe}$ = specific heat of dry air at constant pressure. For a more detailed description of this model and its use in evaluating PET rates at the study site please refer to Appendix I.

**POTENTIAL EVAPOTRANSPIRATION RATES**

Irrigated potato agriculture in the San Luis Valley of south central Colorado is selected for this analysis. Based on several field experiments (Szeicz et al. 1967), the stomatal resistance of potatoes was observed to be 1.3 s/cm for a bare moist soil at the beginning of the growing season. It decreased with increasing leaf area to a minimum of 0.5 s/cm for a 2/3 mature crop. Values increased to 1.1 s/cm as the crop underwent wiltting prior to harvest. Stomatal resistance was recorded at 0.4 s/cm for an unstressed crop, and was observed to increase according to changes in soil moisture stress, humidity, and CO$_2$ concentrations (Moorby et al. 1975).

The crop roughness height is approximately 1/10th of the crop height (Szeicz et al. 1967). The height of centennial rutes, the case study potato species, ranges from 10 cm at planting to a maximum height of 65 cm at maturity (Alsodon 1988). The average plant height and average crop roughness height for each growth period are shown in Table 1. The albedo for potatoes is 0.23 and is assumed constant over the growing season (Jensen 1973). Table 1 shows the estimated average daily net absorbed shortwave radiation, $R_n$, and the estimated net radiation, $R_n$, at the study site for each growth period. The historical average daily wind speed, crop canopy aerial resistance, and relative humidity are given in Table 1. Table 1 also shows how temperature and vapor pressure deficits vary over the growing season in the San Luis Valley, for historical climatic conditions and for both a 3°C increase and a 3°C decrease in air temperature. The average historical climate data were obtained from the World WeatherDisc (1988) for the years 1951–83.

<table>
<thead>
<tr>
<th>TABLE 1. Evapotranspiration Model Parameters</th>
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<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>PET (mm/day)</td>
</tr>
<tr>
<td>T Ave (C)</td>
</tr>
<tr>
<td>Rn (MJ/m²/d)</td>
</tr>
<tr>
<td>Rn (MJ/m²/d)</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>Wind speed (cm/s)</td>
</tr>
<tr>
<td>Crop height (cm)</td>
</tr>
<tr>
<td>Z0 (cm)</td>
</tr>
<tr>
<td>r0 (s/cm)</td>
</tr>
<tr>
<td>e0 (KPa)</td>
</tr>
<tr>
<td>e, T + 3 (KPa)</td>
</tr>
<tr>
<td>e, T + 3 (KPa)</td>
</tr>
<tr>
<td>e, T + 3 (KPa)</td>
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<td>r, T + 3 (KPa)</td>
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<td>r, T + 3 (KPa)</td>
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<tr>
<td>r, T + 3 (KPa)</td>
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JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING / MAY/JUNE 1998 / 157
Carbon Dioxide Effects on Plant Stomatal Resistance and Evapotranspiration

Stomata apparently do not respond directly to ambient (atmospheric) CO₂ concentrations, C₅. CO₂ sensors for stomatal action are located in the epidermis, presumably in the guard cells (Mouraviev 1956; Pallaghy 1971), whose inner walls are permeable to CO₂ (Meidner and Mansfield 1965). CO₂ concentrations in the guard cells are dependent on the CO₂ concentration in the intercellular spaces, C₅. The C₅/C₅ ratio has been observed to be nearly constant and equal to 1 for numerous plant species and ambient CO₂ levels (Jarvis and Morison 1981; Morison and Jarvis 1983; Bell 1982). In this work it is assumed that C₅/C₅ = 1.

C₅ and C₅ species have been extensively studied in CO₂-rich environments. Potatoes, a C₅ species, are known to have stomata which are sensitive to changes in atmospheric CO₂. Morison (1987) compiled the results of the effects of 2×CO₂ experiments performed on 16 C₅ species and found stomatal resistance rₛ increased 67%. As CO₂ concentrations increase stomatal resistance increases, which reduces the CO₂ assimilation rate, evapotranspiration, and plant water use (Morison 1987). Table 1 shows the average estimate of rₛ for each growth period of potatoes, and for 50 and 100% increases in atmospheric CO₂ concentrations.

### Sensitivity of Potential Evapotranspiration to Climate Change Scenarios

Accounting for seasonal changes in crop roughness height, stomatal resistance, and climate parameters, mean daily PET rates were evaluated for historical and climate change conditions. Table 2 shows the climate change scenarios analyzed. For the combined scenarios, linear superposition of effects has been assumed. Table 2 shows that all climate change scenarios analyzed reduced PET, with the exception of a temperature increase. PET increases by approximately 14% given a 3°C increase in the mean daily temperature, mostly as a result of increases in the vapor pressure deficit. Likewise, a 3°C decrease in the mean daily temperature causes a 14% decrease in PET. A 50% increase in CO₂ concentrations results in a 15% reduction in PET, which is a larger change than the 3°C temperature decrease scenario. A 100% increase in CO₂ causes PET to decrease by 29%, which is consistent with results in the literature [e.g., Chaudhuri et al. (1990), Kirkham et al. (1991)].

The results illustrate that the CO₂-induced effects on PET are greater than those induced by temperature changes, for the cases considered. An increase in temperature does increase PET; however, the combination of a 3°C temperature increase with a doubling of CO₂ results in an 18.5% decrease in PET. In addition, a 3°C temperature decrease combined with a doubling of CO₂ shows a 39% decrease in PET.

![Fig. 1](image-url)  
**Fig. 1.** Climate Change Effects on PET Rates: (a) Effects of Temperature Changes; (b) Effects of Increases in CO₂ Concentrations; (c) Effects of Combined Temperature and Carbon Dioxide Changes

### IRRIGATED AGRICULTURE

The remainder of this paper studies the impacts of climate variability on soil moisture depletion processes and agricultural benefits. To do so, the soil-crop-climate model is coupled with an optimal irrigation scheduling algorithm. Soil charac-

### Table 2. Effects of Climate Change on PET Rates

<table>
<thead>
<tr>
<th>Climate change scenario</th>
<th>Percent change in PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical</td>
<td>0.0</td>
</tr>
<tr>
<td>Temperature + 3°C</td>
<td>+13.8%</td>
</tr>
<tr>
<td>Temperature - 3°C</td>
<td>-13.8%</td>
</tr>
<tr>
<td>50% increase in CO₂</td>
<td>-15.2%</td>
</tr>
<tr>
<td>100% increase in CO₂</td>
<td>-29.4%</td>
</tr>
<tr>
<td>2×CO₂ and temperature + 3°C</td>
<td>-18.5%</td>
</tr>
<tr>
<td>2×CO₂ and temperature - 3°C</td>
<td>-39.3%</td>
</tr>
</tbody>
</table>

### Table 3. Sandy Clay Loam Soil Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity, n</td>
<td>0.38</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity, K(θ_w)</td>
<td>167.6 mm/d</td>
</tr>
<tr>
<td>Saturated soil matrix potential, φ(θ_w)</td>
<td>254 mm</td>
</tr>
<tr>
<td>Diffusivity index, d</td>
<td>4.857</td>
</tr>
<tr>
<td>Pore size distribution index, n</td>
<td>0.35</td>
</tr>
<tr>
<td>Pore disconnectedness index, c</td>
<td>8.714</td>
</tr>
</tbody>
</table>

### Table 4. Volumetric Soil Moisture Content

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Moisture content</th>
<th>Plant available moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>θₑ</td>
<td>0.38</td>
<td>0.26</td>
</tr>
<tr>
<td>Field capacity θₑₚ</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>Wilting point θₑₚₚ</td>
<td>0.12</td>
<td>0.00</td>
</tr>
</tbody>
</table>
TABLE 5. Growth Stages of Centennial Russet Potatoes

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Description</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Planting to stolonization*</td>
<td>May 7 to June 15</td>
</tr>
<tr>
<td>II</td>
<td>Stolonization to tuber initiation</td>
<td>June 16 to June 23</td>
</tr>
<tr>
<td>III</td>
<td>Tuber initiation of maximum bulking</td>
<td>June 24 to July 17</td>
</tr>
<tr>
<td>IV</td>
<td>Maximum tuber bulking to maturity</td>
<td>July 18 to August 21</td>
</tr>
</tbody>
</table>

*Stolons are the initial "seed" form of tubers. A tuber is a potato.

TABLE 6. Soil Moisture Characteristics Relative to Permanent Wilting Point

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Growth periods 1 and 2 (mm)</th>
<th>Growth periods 3 and 4 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root depth</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>Saturation</td>
<td>91</td>
<td>117</td>
</tr>
<tr>
<td>Field capacity</td>
<td>38.5</td>
<td>49.5</td>
</tr>
</tbody>
</table>

Agricultural Sensitivity to Temperature Change

The results of the foregoing analysis indicated that a 3°C increase/decrease in temperature induces a 14% increase/decrease in PET rates. These effects on PET rates modify the temporal evolution of soil moisture content and, consequently, the optimal irrigation decisions and the optimal benefits from irrigated agriculture. Figs. 2(a), 2(b), and 3 show how actual evapotranspiration and the soil moisture depletion processes are affected by temperature-induced changes in PET. The figures show the evolution of the AET rates and the soil moisture content if the soil is allowed to dry from saturation under the influence of evapotranspiration, percolation, and capillary rise processes (described in Ramírez and Finnerty (1996)). Observe that although the magnitude of the AET rates increases with temperature as a result of increases in PET, the ratio AET/PET decreases with temperature for all soil moisture contents below field capacity. Increasing temperature and PET accelerates the soil moisture depletion rate; decreasing temperature and PET slows the soil moisture depletion rate as shown in Fig. 3. The contribution of 0.88 mm/d of soil moisture due to capillary rise from a water table at $Z = 1.7$ m below the soil surface prevents soil moisture depletion and AET from reaching zero.

Fig. 4 shows temperature effects on crop yield and maximum expected agricultural benefits. It shows that increasing temperature decreases crop yield and agricultural benefits, and decreasing temperature increases agricultural benefits. Increasing available irrigation water increases agricultural benefits as a result of irrigation applications leading to reduced crop moisture stress. Increasing the available irrigation water reduces the relative impact of climatic temperature changes on agricultural production and crop yield.

Agricultural Sensitivity to Increased Carbon Dioxide

As indicated, a 50% increase in atmospheric CO$_2$ concentrations induces a 15% decrease in PET rates, and a 100% increase in atmospheric CO$_2$ concentrations induces a 29% decrease in PET rates. These effects have a positive impact on the optimal benefits from irrigated agriculture. Although the graphs are not shown here, the behavior is analogous to that observed for temperature-induced decreases in PET (Finnerty 1994). That is, AET rates decrease with decreasing PET rates, which have an inverse relationship to CO$_2$ concentrations. The ratio AET/PET increases with CO$_2$ concentrations for all soil moisture concentrations below field capacity. Soil moisture depletion is retarded as a result of the effects of increased atmospheric CO$_2$ concentrations on PET rates.

Fig. 5 shows that increasing atmospheric CO$_2$ concentrations increases crop yield and the maximum expected benefits from irrigated agriculture. Increasing available irrigation water reduces the relative impact of increased atmospheric CO$_2$ concentrations on agricultural production and crop yield (Fig. 5). Here again, a water table at $Z = 1.7$ m contributes 0.88 mm/d to soil moisture.

FIG. 2. (a) Temperature Effects on Actual Evapotranspiration

FIG. 2. (b) Temperature Effects on Percent AET/PET Ratio

FIG. 3. Temperature Effects on Soil Moisture Depletion
TABLE 7. CO₂ Fertilization Effect on Agricultural Benefits

<table>
<thead>
<tr>
<th>Irrigation water, ( Z = 1.7 ) m (mm)</th>
<th>Maximum Expected Net Benefits ($/Acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Historical values</td>
</tr>
<tr>
<td></td>
<td>1.5 ( \times ) Y and current CO₂ ET</td>
</tr>
<tr>
<td></td>
<td>1.5 ( \times ) CO₂ ET</td>
</tr>
<tr>
<td></td>
<td>2 ( \times ) CO₂ ET</td>
</tr>
<tr>
<td>0</td>
<td>370.13</td>
</tr>
<tr>
<td>300</td>
<td>1,365.29</td>
</tr>
</tbody>
</table>

Agricultural Sensitivity to CO₂ Fertilization

Increased concentrations of atmospheric carbon dioxide are known to have a fertilizing effect on many vegetative species by enhancing photosynthetic processes (Kimball and Idso 1983; Idso 1991). Plants’ photosynthetic reactions combine water and carbon dioxide in the presence of visible solar radiation to produce oxygen and glucose. Doubling CO₂ has been experimentally proven to increase crop yield and biomass production by 43–75% in potato crops (Collins 1976). Root and tuber crops are found to increase marketable yield by an average of 52%, as observed in 17 experiments of doubled atmospheric CO₂ concentrations (Kimball and Idso 1983). Thus, increasing CO₂ will significantly increase maximum crop yields and expected agricultural benefits given the same production and irrigation costs that exist today. Actual evapotranspiration is reduced even when biomass and plant leaf area are increased due to increased atmospheric CO₂ concentrations. However, there is uncertainty concerning the effect of increased biomass on PET rates for CO₂-fertilized plants. Because of this uncertainty three cases are analyzed here to investigate issues of CO₂ fertilization and crop water use efficiency. Case 1 is a 50% increase in crop yield, combined with the historical PET rate. Case 2 is a 50% increase in yield, coupled with the reduced PET rate derived from a 50% increase in atmospheric CO₂ concentrations. Case 3 is a 50% increase in yield, coupled with a reduced PET rate derived from a 100% increase in atmospheric CO₂ concentrations.

CO₂ fertilization has a large impact on irrigated agricultural benefits (Table 7). The crop yield increase of 50% combined with a 13–29% reduction in PET results in high agricultural benefits given no irrigation water and a 0.88 mm/d capillary rise rate. Table 7 illustrates how agricultural benefits almost double under doubled CO₂ concentrations, due to a large increase in crop water use efficiency. Thus, CO₂ fertilization can make agriculture economically feasible in regions with high production and irrigation costs, and where the available irrigation water is constrained. Table 7 also illustrates that CO₂ fertilization has a much greater effect on agricultural benefits.
than do the effects of CO₂ on stomatal resistance and PET. Greater crop yields are attained using less irrigation water when CO₂ fertilization effects are incorporated into PET and crop yield functions. The potential fertilizing effect of increased CO₂ on potato yields has a significantly larger positive impact on irrigated agricultural benefits than any of the favorable temperature, CO₂, or combined scenarios analyzed. Finally, it should be observed that as the water available for irrigation becomes more scarce, either as a result of drought or increased demand from competitive uses, the beneficial or detrimental impacts of increased CO₂ and temperature changes is more pronounced. This has tremendous implications for water and other resource planners and decision makers. A thorough agroeconomic sensitivity analysis in the context of climatic variability is performed in Ramírez and Finnerty (1996).

**FINAL REMARKS**

Elevated carbon dioxide will have beneficial effects on irrigated agriculture in semiarid regions like Colorado, as it increases water use efficiency. For the same growth, more water remains in the soil. However, elevated carbon dioxide may have detrimental effects on agriculture, also. In a high carbon dioxide world, quality may be reduced (e.g., less nitrogen in grain). Weeds may be more prevalent because many weedy species are C₃ plants, which are favored in an elevated carbon dioxide environment. If temperature increases along with CO₂, plants will mature faster and pollination may become more difficult. In addition, pests that are normally killed by low winter temperatures may not be killed. Thus, a full impact assessment requires more sophisticated and complex analyses that incorporate all of the above, and other, potential responses of the environment to elevated carbon dioxide concentrations.

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**APPENDIX I. SOIL MOISTURE DYNAMICS**

Soil moisture depletion processes are modeled by considering the hydrologic components of the soil water balance as described by (1). Assuming that irrigation applications and infiltration from storms occur instantaneously, soil moisture depletion during interstorm periods depends only on evapotranspiration, percolation, and capillary rise. Thus the water balance during interstorm periods is

$$\frac{\partial \theta}{\partial t} = w(\theta) - P(\theta) - AET(\theta)$$  \hfill (4)

**Percolation and Capillary Rise**

Percolation is the downward gravitational flux of water through the soil column. Percolation rates are modeled as

$$P(\theta) = K(\theta)c(\theta, \theta_s, f)$$  \hfill (5)

where \(P(\theta)\) = percolation rate as a function of the volumetric soil moisture content \(\theta\); \(K(\theta)\) = saturated hydraulic conductivity; and \(c = \) pore disconnectedness index.

Capillary rise \(w(\theta)\) is the upward flux of water from the water table into the root soil moisture zone, and is controlled by capillary and gravitational forces in the soil's pore spaces. Capillary rise is modeled as a power function of soil moisture bounded by the maximum value, \(w_{\text{max}}(Z)\) and by zero, and whose parameters are defined as a function of the depth to the water table, \(Z\), and soil hydraulic characteristics (Ramírez and Finnerty 1996).

**Actual Evapotranspiration Function**

Actual evapotranspiration is modeled as a function of soil moisture, PET, and the plants' physiological growth stage. AET is assumed to occur at the potential rate for soil moisture contents above field capacity (FC). AET is assumed to decline to zero as the soil moisture content decreases to the plants' permanent wilting point (PWP).

$$AET(\theta) = \begin{cases} \theta^a & \text{PWP} \leq \theta \leq FC \\ \text{PET} & \theta \geq FC \end{cases}$$  \hfill (6)

Parameters \(a\) and \(b\) are a function of PET, soil parameters, and the plant's physiological growth stage.

**Infiltration from Rain Events**

Soil moisture content in the root zone is partially controlled by random infiltration inputs from storm events. The cumulative volume of water infiltrated \(V(i, t)\) from a given rain storm is a function of storm intensity and duration as well as a function of soil moisture content and hydraulic properties. It can be expressed as

$$V(i, t) = \int_{t_i}^{t_f} R_i(t) dt$$  \hfill (7)

where \(i = \) storm intensity; \(t_i = \) storm duration; and \(R_i(t, t_f) = \) volume of surface runoff from the rain storm. Using results from Eagleson (1978b), the volume of rain-infiltrated \(V(i, t)\) from a single storm is

$$V(i, t) = \begin{cases} \frac{\theta}{\theta_s} & t_i \leq t_f \\ \frac{\theta}{\theta_s} + \frac{S(t,t_f)}{2} & t_i > t_f \end{cases}$$  \hfill (8)

where \(t_i = \) ponding time; \(S = \) soil sorptivity; and \(A = \) gravitational infiltration rate. \(S\) and \(A\) are described by the following (Eagleson 1978b):

$$S = 2\frac{\theta}{\theta_s} \left[ \frac{5nK(\theta_s)\phi(\theta_s)\rho(d, \theta_s)}{3n\pi} \right]$$  \hfill (9)

$$A = 0.5\frac{\theta}{\theta_s} \left[ 1 + \frac{\theta}{\theta_s} \right] - \omega$$  \hfill (10)

where \(n = \) soil porosity; \(\phi(\theta_s, \theta_s) = \) dimensionless infiltration diffusivity function; \(d = \) diffusivity index; \(\theta = \) initial soil moisture content; and \(\theta_s = \) saturated soil moisture content.

**MODIFIED PENMAN-MONTEITH EQUATION**

The modified Penman-Monteith equation can be used to estimate daily PET rates using daily, or daily monthly averaged data with 5–15% accuracy (Szeicz et al. 1967; Jensen et al. 1971). The evaluation of the different terms appearing in the modified Penman-Monteith equation is explained in the following section.

The saturation vapor pressure \(e_s\) is evaluated as a function of temperature \(T\) using the Clausius-Clapeyron equation

$$e_s(T) = 611.0 \exp \left[ \frac{L_v}{R} \left( \frac{1}{T} - \frac{1}{273.15} \right) \right]$$  \hfill (11)

where \(T = \) mean daily air temperature; \(R_v = \) gas constant for water vapor; and \(L_v = \) latent heat of vaporization

$$L_v = [2.4907 - 0.002135(T – 273.15)] \times 10^4$$  \hfill (12)

The actual vapor pressure \(e_s\) is the product of the atmospheric relative humidity and the saturation vapor pressure.

The slope of the saturation vapor pressure curve \(\Delta\) is determined by taking the first derivative of the Clausius-Clapeyron equation with respect to the mean daily air temperature.

$$\Delta = \frac{\partial e_s}{\partial T} = \frac{e_s L_v}{R_v T^2}$$  \hfill (13)
The psychrometer constant $\gamma$ is a property of dry air, which expresses the balance of latent and sensible heat in the near-surface boundary layer. $\gamma$ is evaluated using

$$\gamma = \frac{C_r p}{0.6221 \text{a}}$$

where $p$ is atmospheric pressure.

The crop aerial resistance is evaluated using

$$r_c = \frac{k_a \ln(z_a / z_c)}{k_a U_s}$$

where coefficients $k_a$ and $k_t$ are turbulent transfer coefficients of heat and water vapor mass between the atmosphere and the land surface, and are assumed equal; von Kármán constant $\kappa$ is approximately equal to 0.4; $z$ is height above the crop where wind speed is measured; $z_c$ is roughness height of the crop; and $U_s$ is average daily wind speed measured at height $z$.

Plants'photosynthetic production and potential evapotranspiration are proportional to net radiation at the earth's surface. The net daily radiation $R_n$ at the land surface is evaluated as follows (Jensen 1973)

$$R_n = (1 - \alpha)R_i - R_o$$

where $R_n$ is net radiative energy absorbed at the Earth's surface; $R_i$ is net daily incoming solar radiation; $R_o$ is net daily outgoing longwave radiation; and $\alpha$ is average shortwave albedo or reflectivity of the crop-soil surface. The albedo of vegetated areas is dependent on soil moisture content, soil type, canopy density, and plant water stress.

The net daily outgoing longwave radiation is evaluated following Jensen et al. (1971)

$$R_o = \left( a \frac{R_i}{R_w} + b \right) R_w$$

where $R_w$ is daily incoming shortwave radiation under clear skies; $R_o$ is net daily outgoing longwave radiation under clear sky conditions; and $a$ and $b$ are calibration coefficients. For the San Luis Valley, the foregoing calibration coefficients $a$ and $b$ are 1.22 and -0.18, respectively (Charles 1987).

Shortwave daily radiation under clear skies is a function of the relative positions of the earth and sun, and the latitude and altitude of the site. $R_w$ (MJ/m²) is evaluated using equations following Heeran et al. (1985)

$$R_w = A + B \cos \left( \frac{2\pi D}{365} - C \right)$$

where $A = 31.54 - 0.2734 \text{LAT} + 0.0007813 \text{ALT}$ (18a)

$$B = -0.2986 + 0.2678 \text{LAT} + 0.0004102 \text{ALT}$$ (18c)

$C$ is a constant, $C = 2.92$; LAT is latitude in degrees; ALT is altitude in meters; and $D$ is julian day of the year.

The daily outgoing longwave radiation under clear skies is evaluated as

$$R_o = [a_i - 0.139 \sqrt{\rho_{SO2}} (T_s^2 + T_d^2) / 2]$$

where parameter $a_i$ is effective emittance of the atmosphere, $a_i = 0.325$ (Wright and Jensen 1972); $\rho_{SO2}$ is total vapor pressure evaluated at the mean dew-point temperature; $\sigma = \text{Stefan-Boltzmann constant}$; $T_s$ is maximum daily air temperature; and $T_d$ is minimum daily air temperature.

**APPENDIX II. REFERENCES**


