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Bio-Economic Analyses of Biofuel-Based Integrated Farm Drainage Management Systems on Marginal Land in a Salinity and Drainage Impacted Region: The Case of California's Central Valley

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Bio-Economic Analyses of Biofuel-Based Integrated Farm Drainage Management Systems on Marginal Land in a Salinity and Drainage Impacted Region: The Case of California's Central Valley

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

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in

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by

Lucia Ruth Levers

August 2015

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For the wild.

ABSTRACT OF THE DISSERTATION

Bio-Economic Analyses of Biofuel-Based Integrated Farm Drainage Management Systems on Marginal Land in a Salinity and Drainage Impacted Region: The Case of California's Central Valley

by

Lucia Ruth Levers

Doctor of Philosophy, Graduate Program in Environmental Sciences
University of California, Riverside, August 2015
Dr. Kurt Schwabe, Chairperson

Two seemingly separate areas motivate this work. The first is the water scarcity, salinization, and drainage concerns that cause both environmental and private damages in arid regions throughout the world, including the San Joaquin Valley of California's Central Valley. The second is interest in producing bioenergy in an energetically, privately, and environmentally positive manner. These two branches intersect with the growth of highly energetic biofuel crops on marginal, or poor quality, land with saline drainage water as a form of Integrated Farm

Drainage Management (IFDM). To analyze this intersection, this dissertation contains three chapters. The first paper consists of background information on the San Joaquin Valley, marginal land, biofuels, and drainage water, and an arithmetic estimation of potential Bermuda grass (*Cynodon* dactylon) bioenergy production as an IFDM crop. The second paper develops yield as a function of salinity, irrigation systems, irrigation timing, nitrogen, climate effects, and applied water. The functions, which are very flexible, are compared to other functions used in the literature and the results from a field experiment. These functions are used in the third paper, which develops a farm-level bio-economic optimization model of IFDM crops, including the biofuel crop, *Brassica spp.* These works show that growing biofuel crops, and other IFDM crops, on marginal lands in drainage-impacted regions can be privately beneficial and provide environmental benefits relative to traditional approaches.

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Chapter 1: Introduction

The growth of bioenergy crops on marginal land as part of an Integrated Farm Drainage Management (IFDM) system can address both bioenergy production and marginal land impairment. Replacing fossil fuels with biofuels may provide society with a number of benefits, particularly decreased carbon dioxide emissions and increased security from a more domestic fuel production. However, biofuel production using crops has generated concerns, including competition with food crops ("Food vs. "Fuel"), undesirable energy ratios, negative environmental effects, and small net energy output (Hill et al., 2006). In comparison, the use of marginal lands for feedstock production is often viewed favorably (Gelfand, et al. 2013; Hill et al., 2006). In California, marginal or drainage impacted lands occur in the western San Joaquin Valley. This region includes lands with shallow water tables, salts and potentially toxic trace elements including selenium and boron. Approximately 700,000 hectares in the San Joaquin Valley, which comprises 31% of the agricultural land, has become drainage impaired to the extent that the Bureau of Reclamation considers it fit for retirement from agricultural use (Erysian et al., 2005). Of this amount, approximately 100,000 acres have been formerly retired (Annual, 2003).

This dissertation investigates how biofuel production can help address some of these concerns in an IFDM framework in three main chapters.

The first main chapter (Chapter Two) focuses on the growth of Bermuda (*Cynodon dactylon*), a salt-tolerant grass, as part of an IFDM system, where saline drainage water from higher-valued crops is used to grow IFDM crops on marginal land. Included also is background information on the San Joaquin Valley and the drainage issues it confronts. Defining marginal land is discussed, as well as different forms of bioenergy and concerns thereof. County level crop and subbasin level groundwater height data, as well as published crop coefficients are used to calculate potential bioenergy production region-wide.

For a more technical analysis of biofuel production on marginal land, crop yield as a function of water and salinity is needed and developed in the second main chapter (Chapter Three). Following published yield functions from Kan et al. (2002) and Wang and Baerenklau (2014), a model is developed to generate yield functions that are not only functions of applied water and salinity, but also irrigation system, irrigation timing, climate, applied nitrogen and soil characteristics. The flexibility of the functions is accomplished via instantaneous yield reductions with the use of HYDRUS-1D.

The yield functions of Chapter Three are used in the last main chapter (Chapter Four), where a bio-economic farm-level optimization analysis of growing *Brassica spp.* (canola and mustard), as an IFDM crop is performed. *Brassica* is salt tolerant, selenium absorptive, and produces a co-product, seed meal. Two Submodels are run. The first is a baseline scenario with no marginal land, and no requirement for on-farm drainage management. The second submodel includes marginal land and requires on-farm drainage management. Applied water, drainage water salinity, and potential marginal land treatments are varied, producing various different scenarios, the profit, land allocation, and carbon dioxide emission results of which are compared. Sensitivity analysis is performed to examine how fuel prices and potential carbon taxes affect results.

As we investigate the growth of biofuel crops as part of an IFDM system on marginal land in the San Joaquin Valley of California, we develop a flexible modeling framework that can be used in future research.

Chapter 2: An assessment of biofuel production from perennial grasses irrigated with drainage water and grown on marginal land in California's Central Valley

Abstract 2:

Perennial, salt tolerant grasses like Jose tall wheatgrass and Bermuda grass, grown on marginal land irrigated with drainage water in the Western San Joaquin Valley, have the potential to produce 1 million to more than 20 million GJ of bioenergy, depending on the amount of land and drainage water available. In the process, feedstock production may provide remediative effects on the land, in the form of increased soil quality, benefits to wildlife, drainage water reuse, and energy for final concentration and disposal of salts and trace elements. The primary goal of evaluating biomass energy conversion based on the use of these resources is to help defray the ultimate cost of protecting groundwater, wildlife and the larger central valley ecosystem from the adverse effects of irrigation over long time periods, while maintaining the large economic and social benefits derived from farming in California's productive and unique semi-

arid to Mediterranean environment. This is equivalent to improving the sustainability of irrigated agriculture in this region and similarly affected areas in the rest of the world.

Section 2.1: Introduction

The growth of bioenergy feedstocks on marginal lands-frequently encouraged as desirable (Hill et al., 2006 and Liu et al., 2011)-can address both bioenergy production and marginal land impairment. Replacing fossil fuels with biofuels may provide society with a number of benefits, particularly decreased greenhouse gas emissions and increased security from a more domestic fuel production. Biomass produced for power has similar potential benefits. However, biofuel production using crops has generated concerns, including competition with food crops, undesirable energy ratios, negative environmental effects, and small net energy output (Hill et al., 2006 and Levers, 2015). In comparison, the use of marginal lands for feedstock production is often viewed favorably (Gelfand, et al. 2013; Hill et al., 2006).

In California, marginal or drainage impacted lands occur in the western San Joaquin Valley (SJV). This region includes lands with shallow water tables, salts and potentially toxic trace elements including selenium and boron. Approximately 700,000 hectares in the SJV, 31% of the agricultural land, is or has become drainage impaired to the extent that the Bureau of Reclamation considers them fit for retirement from agricultural use (Erysian et al., 2005). Of this amount, approximately 100,000 acres have been formerly retired (Levers, 2015 and Annual, 2003). Drainage impaired lands are considered to be marginal land in this assessment.

This report focuses on the growth of salt-tolerant grasses for bioenergy feedstocks on irrigated, drainage impaired lands in California. Growing perennial grasses, specifically Jose Tall wheatgrass (*Thinopyrum ponticum)* and/or Bermuda grass (*Cynodon dactylon*) with lower quality drainage water, would create a profitable new crop enterprise and result in social benefits from alternative energy production including drainage water reuse, phytoremediation, minimization of "Food vs Fuel" conflicts, and new (green) jobs. This analysis discusses these potential benefits, as well as provides information on marginal lands, the Central Valley, biofuels, phytoremediation, and land retirement. Calculations are performed to estimate energy output from these grasses grown on marginal lands. Land surrounding the Salton Sea in the Imperial Valley will become exposed if the Salton Sea shrinks in size due to anticipated loss of drainage water supplied from the Imperial Irrigation District. This potential land is discussed since it might become another area for biofuel feedstock production.

Section 2.2: Bioenergy Background

Bioenergy production using agricultural land has the potential for both beneficial and adverse effects. The use of marginal lands minimizes the potential for competition with existing food, feed and fiber production, but introduces other agronomic and ecological challenges associated with marginal lands.

2.2.1 Production Method and Desired Fuel

The most commonly produced biofuels in the world are liquid transportation fuels: ethanol and biodiesel. Corn ethanol in the United States is produced on a wide scale by first producing sugar from starch stored in the grain, then converting it to ethanol. Sugarcane stores sucrose directly, so ethanol can be produced from sugarcane juice, leaving residual bagasse to be burned for energy production. Both of these processes are called first-generation, because the potential energy in lignocellulosic biomass is not converted to fuels. Biodiesel from soybean oil (US and Argentina), palm oil (Indonesia and Malaysia) and rapeseed/canola (Europe and Canada), are also considered first generation fuels.

Thermochemical biomass conversion, including simple combustion, pyrolysis and gasification, and anaerobic digestion (AD) are second-generation technologies that can release energy from lignocellulosic biomass; however, except for AD systems, they do not exist at a large scale. Anaerobic digestion, a mature technology that utilizes microbes to decompose high moisture biomass like manures, does exist on a large scale. Unlike the other processes, AD produces a non-liquid fuel, which is called biomethane. These technologies are evaluated in Zhang and Kaffka (2015).

2.2.2 Food vs. Fuel

Biofuel policies and production have been criticized due to supposed competition between the use of feed grains, oilseeds and sugar crops for food and fuel uses (Ruel et al., 2010,), and anticipated concerns for increased land use (Searchinger et al., 2008). Second-generation fuels, using largely lingo-cellulosic feedstocks, are considered to be superior sources for many reasons, including higher energy yields and the chance to use less productive land for their production. However, even for biofuel crops that are not staple food crops, like perennial grasses, the competition for land can have consequences on the production of other crops and uses, especially forages for livestock. Bioenergy production of crops on lands that are either not farmed or farmed intermittently (marginal land) avoids many of these controversies and has become a research area of particular interest (Shortall, 2013). Social benefits associated with the use of marginal land strengthen the justification for their use.

2.2.3 Energy Ratio

The energy ratio of a particular biofuel crop is the energy in the biofuel itself divided by the energy required to produce the fuel (output/input).[1] These ratios should be as high as possible to make biofuel less expensive and more environmentally beneficial, and increase the likelihood of biofuel in offsetting petroleum use. A ratio of one would indicate there is neither energy gain nor loss (Levers, 2015). In addition to issues with food competition, corn ethanol's energy ratio is not particularly high, at least when first generation technology is used. Boland and Unnasch (2014) document and project steady improvement from an initial 20% advantage over gasoline to more than 30% currently, with future improvements up to 40%. *Brassica* biodiesel has an energy ratio of about 5.4 (Levers, 2015). Perennial grasses, on the other hand, have potential energy ratios of 7 to 14, when methane (natural gas), not ethanol, is the final product (Gerin et al., 2008).

2.2.4 Environmental Effects

The potential reduction of greenhouse gas emissions from biofuels substituted for fossil fuels is the most common justification for biofuels. Greenhouse gas emissions are linked with a biofuel's energy ratio, but are not

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[1] Solar energy is not accounted for here.

completely explained by it. The manner of processing the fuel, as well as transportation, and particulars of the location and impacts of production can all affect greenhouse gas emissions (Gerin et al., 2008; Chakravorty, 2009). If the processing plants are coal fired, the total greenhouse gas emissions of a particular biofuel may increase compared to other possible power sources. If the plant matter and/or final fuel must be transported long distances, benefits may decrease. Any time land, marginal or otherwise, is converted to agricultural use, there may be environmental losses. Marginal land use to produce biofuels is often seen as a solution to food vs. fuel arguments, but the ecological impact of conversion must be considered prior to policy adoption. In the case of California, the marginal lands discussed here are previously used agricultural fields, potentially abandoned or in the case of the Imperial Valley, exposed former lake bottom. Deforestation and loss of undisturbed habitat are not concerns. There may be some habitat improvements (and additional environmental benefits) from growing perennial grasses on marginal lands (See Section 4.3). Evans et al., (2015) also argue that feedstock crop production may increase GHG mitigation benefits compared to fallow land or regrowth of native vegetation. This can be expected for the systems studied here.

2.2.5 Local Social Effects

Large-scale biofuel operations can affect the local economy by instigating land-use change and creating new enterprises, jobs, and a need for biorefineries, depending on the fuel type and location (Kaffka et al., 2014). Many of the benefits and costs of bioenergy production are similar to the benefits and costs of agricultural production where processing facilities are involved (see section 3.6).

2.2.6 Potential Energy Output

In order for processing plants and infrastructure to be cost effective, there must be enough potential biomass and it must be readily available. Most estimates of bioenergy production in the United States using perennial grasses emphasize the southeastern US and the upper Midwest as likely feedstock sources (USDA, 2010). Others focus on the drier regions of the Midwest, where increasing year-to-year climate variability and rainfall limitations limit biomass production and make investment uncertain (Gelfand et al., 2013). However, production of cellulosic biomass in California on marginal soils may have advantages over these other locations. Yearly climate is more uniform and irrigation (even with lower quality water) provides a basis for more reliable yield estimates, making biorefinery planning assumptions easier. Adapted crops (here salt-tolerant perennial grasses) may thrive and be highly productive on marginal lands with year-round growing seasons; in turn, this requires fewer acres in more concentrated areas, reducing transport distances.

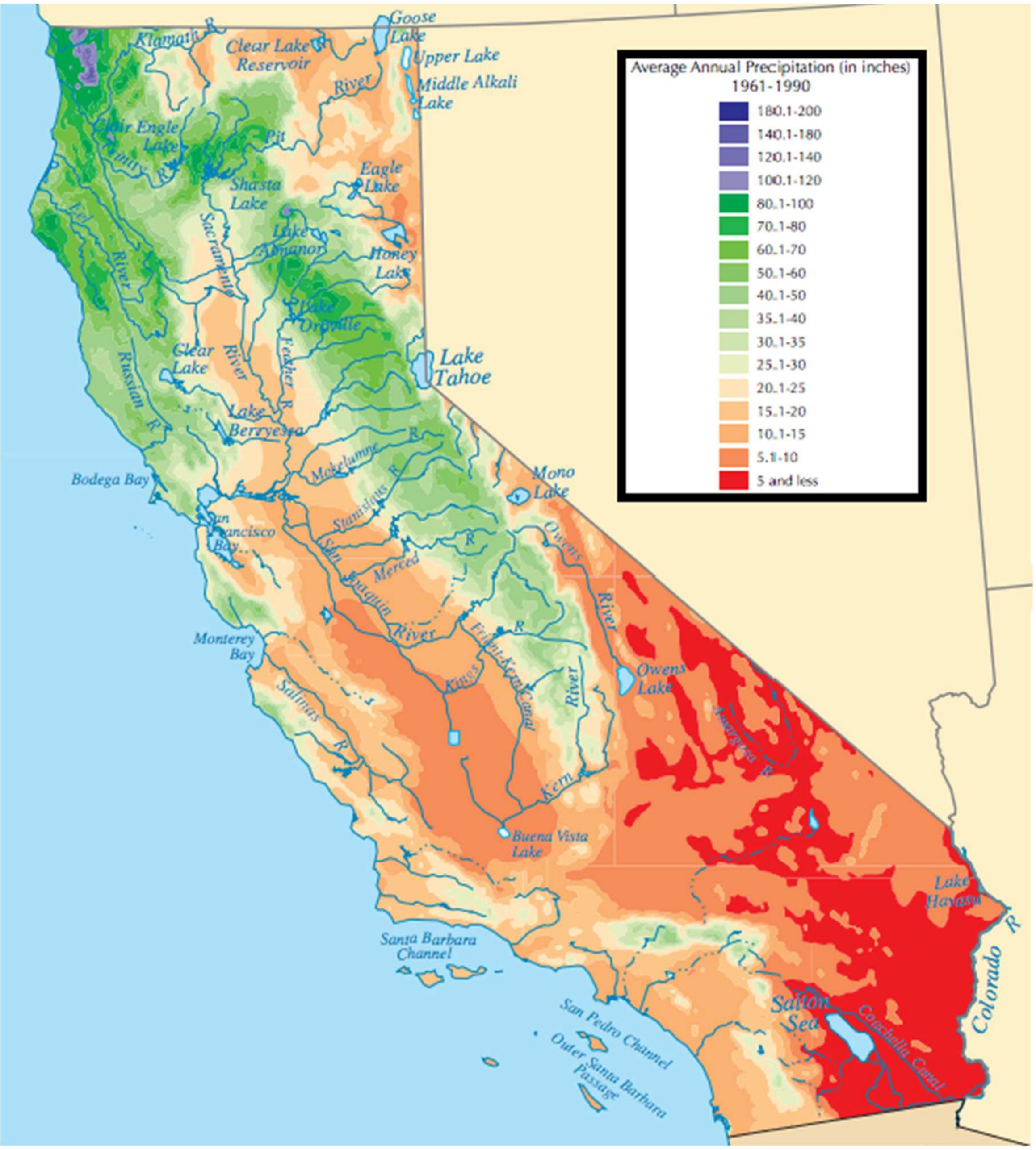
The total potential energy available from a certain type of biofuel feedstock/conversion technology combination must be estimated. Zhang and Kaffka (2015) includes analyses of the bioenergy yield and costs of several different conversion systems that might be used to convert perennial, salt-tolerant grasses to bioenergy. It also includes estimates of the costs associated with final treatment of brine. Following the results of this paper, an economic analysis could be performed to estimate potential energy output from perennial grasses in the SJV.

Section 2.3: California's Central Valley

2.3.1 Background

California's 700 km inland valley is bordered on three sides by mountain ranges—the Tehachapis to the south, the Sierra Nevada to the east, and the coastal ranges to the west. An ancient saltwater sea once existed in the Valley, in part due to naturally poor drainage. After the sea receded and left marine sediment on the valley floor, streams born in the Sierra Nevada found their way into the valley and out into the ocean through the Delta, depositing more sediment as they flowed. These processes produced an area of rich and productive agricultural soils (Galloway and Riley, 1999).

Figure 2- 1: Historic Rainfall in California, 1960-1991



Source: National Atlas (2015). Available at <http://nationalmap.gov/small_scale/printable/printableViewer.htm?imgF=images/preview/precip/pageprecip_ca3.gif&imgW=588&imgH=450>

The Central Valley differs longitudinally and latitudinally in terms of water availability. The East Side is wetter than the west[2] and the north is wetter than the south (Figure 2-1)[3].

Due to geologic and geographic conditions, in addition to having less available surface water, the WSJV has saline soils that contain elements such as boron and selenium (Wichelns and Oster, 2014). The two major groundwater basins in the West Side (and the SJV) are the San Joaquin River Watershed and the Tulare Basin. The San Joaquin River Watershed was historically drained by the river northward through the Delta; the Tulare Basin has no natural outlet (Quinn, 2014). Both consist of a deeper, semi-contained aquifer (semi-contained due to the numerous wells that have been drilled into it) and a shallower, unconfined aquifer (Galloway and Riley, 1999) (Figure 2-1).

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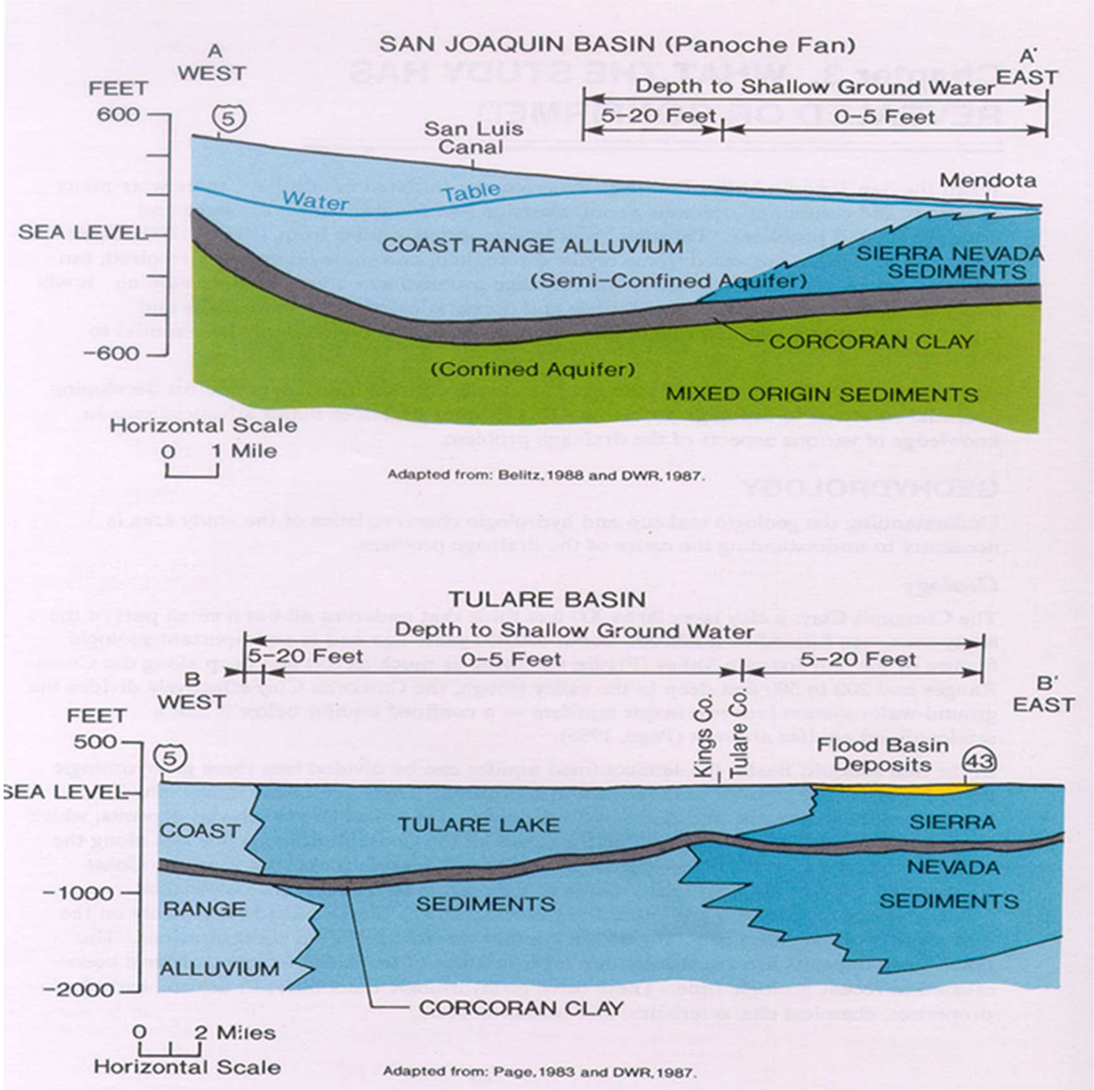
[2] As prevailing winds tend to blow easterly from the Pacific Ocean, the West Side of the Central Valley lies in the rain shadow of the Coastal Ranges. The East Side lies in the windward side of the Sierra and benefits from mountain precipitation runoff (Bertoldi et al., 1991).

[3] The Valley is divided by the Sacramento-San Joaquin Delta into the northern Sacramento Valley and the southern SJV. The Sacramento Valley historically experiences more rainfall and has access to more surface water than the drier SJV.

Figure 2- 2: San Joaquin and Tulare Basins.



Source: San Joaquin (1990). Available at <https://ia601406.us.archive.org/9/items/sanjoaquinvalley01sacr/ sanjoaquinvalley01sacr.pdf>

The WSJV's agricultural fields are irrigated by water diverted through and from the Delta as well as groundwater and San Joaquin River water. As the current drought has worsened, agricultural water availability in the WSJV has decreased (California's Groundwater, 2003). Regulations intended to support local freshwater ecosystems have also led to less water being available to farmers.[4] This has motivated farmers to be extremely pragmatic in their water use, applying available water to the highest value crops. This approach has allowed some crops to avoid impact, like almonds, pistachios and tomatoes (Lee, 2014), but has not completely saved others, largely annual crops like cotton and forages (Fitchett, 2014).

The Central Valley's agricultural dilemmas are not limited to fresh water availability, but they are almost invariably related to it. In the early 1900s, surface water in the San Joaquin Valley was mostly depleted, and what was available was only available seasonally. Some land was becoming unusable due to salt accumulation and water logging from irrigation (Galloway and Riley, 1999; Wichelns and Oster, 2014). Over the next century, ground water and surface water resources were increasingly harnessed for crops. In order to transfer water

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[4] After a Federal District Court in California forced the US Fish and Wildlife Service to produce an updated biological opinion on the Delta Smelt, an endangered fish in the Delta, water deliveries to the San Joaquin Valley from the Delta were restricted to protect the population (Questions, 2014). Drought conditions in California have intensified the contentiousness of the "Fish vs Farms" debate as that decision was upheld by the 9th District Court of Appeals in March of 2014 (Grossi, 2014; Levine, 2014). In October of 2014, opponents of the water restrictions submitted a petition to the US Supreme Court asking for a review of the 9th Circuit's decision (Schiff, 2014). Social impacts of the drought vs legislation supportive the smelt are not clear, but favor the drought for negative labor effects (Howitt, 2009).

from the water-rich north to the water-constrained south for agricultural and urban use, the federal Central Valley Project began in the 1930s, which led to the creation of numerous dams, canals, and water infrastructure (Figure 2-3).[5]

These large-scale irrigation systems help make the San Joaquin Valley into one of the world's most productive agricultural regions. Combined with a number of naturally occurring geo-physical properties, they have also resulted in land subsidence, high water tables and salinization, and some undesirable ecological impacts (Galloway and Riley, 1999; Sneed et al., 2013; Wichelns and Oster, 2014).

2.3.2 Land Subsidence

As farmers developed groundwater sources to irrigate their crops in the early twentieth century, land subsidence began to afflict the valley, mainly through aquifer impaction from ground water overdraft (Galloway and Riley, 1999). By 1970, fifty percent of the San Joaquin Valley's land had sunk at least a

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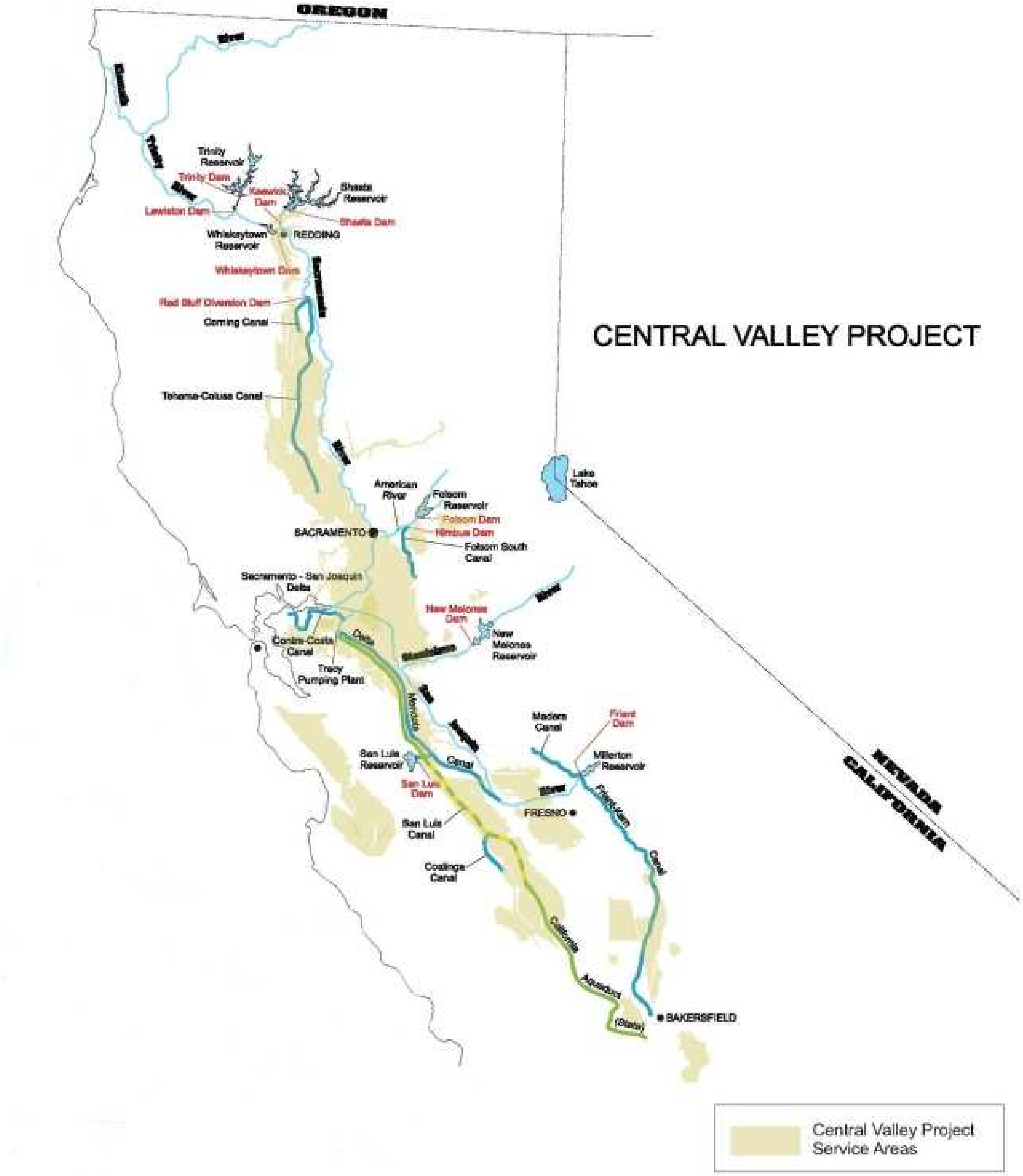
[5] Millerton Lake was created in 1942 by damming the San Joaquin River. The upper Sacramento River was dammed, creating Shasta Lake, completed in 1948. 1955 saw the completion of Folsom Lake, a product of the damming of the American River. In 1961, Trinity Lake was created by damming the Trinity River. The San Luis Reservoir followed in 1967, created by damming the San Luis Creek, but filled with water derived from the Delta during flood flows. The State Water Project (created along with the CVP's San Luis unit in 1960) also engaged in dam building, most notably creating the Oroville Dam from the Feather River, the tallest dam in the United States. The CVP not only dammed rivers, but constructed canals and related infrastructure, including the Delta Cross Channel, which takes Sacramento River Water from the Delta, through a pumping plant, and into the Delta-Mendota Canal.

foot. In the West Side, near the small town of Mendota, the surface has dropped over twenty-eight feet (Sneed et al., 2013; Galloway and Riley, 1999).

Figure 2- 3: Central Valley Project Water Works.



Source: US Bureau of Reclamation (2015). Available at <http://www.usbr.gov/projects/Project.jsp?proj_Name=Central+Valley+Project>.

Since the seventies, the rate of land subsidence in the Valley has generally declined due to surface water deliveries for irrigation from federal and state water projects. The exception is during drought. When there is less surface water available, farmers respond by pumping water out of the deeper aquifer (Galloway and Riley, 1999). The droughts of the 1976 through 1977 and 1987 through 1992 caused renewed land subsidence as people seeking water turned to the deeper aquifer. However, after these drought periods, water table heights returned to levels before the drought and compaction almost stopped. During the late 2000s, drought and surface water delivery limitations due to environmental regulations resulted in land subsidence again becoming a concern (Sneed et al., 2013; Delta-Mendota, 2014). As long as groundwater overdraft from the lower aquifer occurs, land will subside (Sneed et al., 2013).

Land subsidence damages water delivery and flood control systems, roads, pipelines and many other economic resources. Nonmarket costs remain elusive, but damages have been estimated to be about \$90 million (\$25 million in 1978 dollars) per year which does not account for some underreported costs and almost \$300 million (\$180 million in 1993 dollars) which accounts for lost property values, regarding irrigated land, and repair of irrigation systems and wells. (Galloway and Riley, 1999) Millions of dollars in repairs have already been required in several canals in the West Side (Sneed et al., 2013). Surface water deliveries are required to reduce subsidence, but increase the amount of drainage-impaired land and long-term salinization issues. In turn, these require management, or alternatively abandonment of agriculture on some of the world's most productive agricultural land

2.3.3 High Water Tables and Salinization

Seemingly paradoxically, while subsidence occurs, some locations in the West Side also suffer from high water tables. In these areas, the shallow groundwater is saline and contains agricultural contaminants as well as naturally occurring, potentially toxic trace elements (Central, 2014). These soils are naturally saline. Water in excess of the plant's needs has been historically applied to leach salts from the soil and prevent yield reductions. As the potential natural drainage outlets for this water were either nonexistent or no longer viable, the excess, now saline, water built up in the upper aquifer (El-Ashry et al., 1985). Lands afflicted by these drainage problems are limited in the crops they can produce. Even salt-tolerant crops are not completely immune to salt and may still experience yield reductions. The potential for high water tables when irrigating in arid regions is well known and has been acknowledged in the SJV for many years (El-Ashry et al., 1985).

The construction of a drain to alleviate saline high water tables in the upper aquifer was mandated at the federal level as part of legislation enabling the development of the water transfer system. A portion of the drain was built, which resulted in the creation of the Kesterson Reservoir. To help compensate for wetland loss, the federal government subsequently designated Kesterson Reservoir and some surrounding areas as a Federal Wildlife Refuge (1990 SJV). Water deliveries to the Reservoir became composed completely of agricultural drainage water (Wichelns and Oster, 2014). In 1983, deformities and deaths of migratory birds due to selenium toxicity were discovered at the Reservoir (Ohlendorf, 2002). As a result, the Secretary of the Interior ordered the closure of the drain. By 1986, it was sealed (Wichelns and Oster, 2014). [6]

Unable to dispose of drainage water outside of the valley, many different methods of dealing with the drainage water problem emerged (Quinn, 2014,

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[6] The San Luis Drain was to transport drainage water from San Joaquin farms to allocation near the edge of the Delta. Originally intended to drain about 40,000 hectares of farmland (about one-sixth of the size of the Westlands Subbasin), the plans for the drain were expanded to handle drainage from about 120,000 hectares. Environmental concerns of polluted water in the Delta caused a rider to be added to the plans in 1965 that required the drain's plan to meet California state water quality standards. By 1975, the first phase of construction had been completed, which included 85 miles of the drain and the terminal Kesterson Reservoir (1990 SJV). The Central Valley used to contain large areas of wetlands upon which migratory birds and other wildlife supported themselves. Because of development, California has lost over 90% of its historical wetlands (Dahl and Allord, 1997). Until 1978, Kesterson received fresh water deliveries. At this time, the construction of the second half of the drain ending near SF Bay was abandoned due to excessive cost and environmental concern and regulation (Wichelns and Oster, 2014, SJV 1990, History).

Wichelns and Oster, 2014). More efficient irrigation systems and crops with lower water requirements were used to reduce initial water consumption (Quinn, 2014, Ayers and Basinal, 2005). Integrated On-Farm Drainage Management (IFDM) was studied and implemented in one location to test sequential reuse of water. This system is based on the use of drainage water with increasing salt content on fields dedicated to progressively more salt tolerant crops (Quinn, 2014). In concept, salts and trace elements would become progressively more concentrated as they were applied sequentially from one set of fields to another in the process. Final disposal of the water could occur with highly concentrated drainage water using a solar evaporator or evaporation pond (Wichelns and Oster, 2014). Salt-tolerant perennial grasses have been less profitable than traditional crops like cotton, wheat, sugar beets and others. Since the potential for profit (and therefore interest) has been less, interest has been lower. However, if these salt-tolerant crops can be used as biofuel feedstocks, the profit potential may be sufficient to encourage farmers to plant them. Alternatively, power or fuel from biomass produced on salt-affected lands may help reduce the long-term public costs associated with sustainably managing lands where salinity management is a concern, by providing resources for final salt disposal.

2.3.4 Ecological Impacts of Irrigation

Reducing the environmental impact of irrigated agricultural lands is an important public interest. The much publicized wildlife deaths and deformities at Kesterson Reservoir led to other environmental concerns about water movement in the Valley. In particular, the extreme modifications of the hydrological cycle created by the federal, state and other locally developed water conservation and transfer structures had significant impacts on anadromous fish populations (Fisher, 1994) and migratory and shore birds (Shuford et al., 1998).[7] As a response to the mounting concern over ecological issues, the Central Valley Project Improvement Act was passed in 1992. The CVPIA contained a number of provisions, including fisheries and wildlife protection mandates requiring an additional 800,000 acre-feet of water to be dedicated to wildlife each year and a restoration fund for additional wildlife water funded by water and power users. It also included tiered water pricing and allowed water transfers (Gardner and Warner, 1994).

2.3.5 Land Retirement

Land retirement became the primary public response to the salinity drainage issue. A five-year study by the Bureau of Reclamation found that land

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[7] Four impacted species of fish are currently endangered: Chinook Salmon, Coho Salmon, Steelhead, and the Delta Smelt (Threatened, 2014).

retirement resulted in lowering of shallow water tables and a decrease in Se concentrations in shallow soil profiles due to reduced capillary flow at the study sites. If combined with active native plant restoration, increased habitat for several bird, reptile and invertebrate species could be created. Within the five year period of the study, there were no apparent increases in agricultural pests reported, though absent active restoration activity, invasive weed species increased, and could lead to some refuge for agricultural pests. Simple fallowing of land was considered detrimental, but limited arable cropping (e.g., dry farmed barley) was identified as beneficial. (Erysian et al., 2005).

Regardless of these benefits, land retirement combined with active revegetation has not been used on a large scale. Famers will not voluntarily choose land retirement over the production of crops (Levers, 2015, Schwabe et al., 2006). Westlands Water District, the water district that supplies water to large areas of the WSJV, retired about 100,000 acres, in part due to limits on irrigation water supplies.[8] A few thousand more acres have been retired under the Conservation Reserve Program (CRP).[9]

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[8] 33,000 acres out of the total were retired after 19 families in the district sued Westlands and the federal government for damages related to inadquate drainage (Annual, 2003).

[9] Under the CRP, farmers can agree to remove land from production and remediate it. Preferred land is ecologically sensitive. In return for ceasing agricultural production, the farmer is paid land rent and supplemental payments to assist with restoration. The land is not permanently

2.3.6 Benefits of SJV Agriculture

Land retirement certainly eliminates some of the problems associated with trace elements and salts on retired acres compared to the use of these lands for crop production. But, it does not address long-term salinization issues (Shoup et al). Its potential long-run impacts on the local economy are unclear.

Agriculture may account for a single digit percent of California's economy while using the majority of the state's managed water (Pimentel et al., 2004; Sumner et al., 2003), but it also accounts for a large proportion of the economy in the San Joaquin Valley[10], one of California's and the United States' most poverty stricken areas[11]. Children are disproportionately affected by poverty rates.[12] Biofuel production, as an additional revenue stream, in the SJV may help decrease unemployment and poverty rates (Kaffka et al., 2014).[13]

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retired, only for 10 to 15 years at a time. Three counties in the San Joaquin Valley have significant amounts of CRP land—Stanislaus, Merced, and Kern. The total CRP land is between 4,000 and 6,000 acres (Monthly Summary, 2014).

[10] San Joaquin Valley agriculture's direct value added accounts for ~15% of the region's economy. Combined direct, indirect, and induced effects, Ag and Ag processing accounts for ~38% of the region's employment (Agriculture's).

[11] Tulare and Fresno Counties are in the poorest 6% of America's counties (2012 Census).

[12] Child poverty rates range from 32% in Kings County to 39% in Fresno County (Anderson, 2014).

[13] Agriculture is a large proportion of the economy, but many jobs are low paying and seasonal. Additional farm-worker jobs may not help all current SJV residents, but may encourage more immigration (Taylor and Martin, 2000).

The SJV provides a large percentage of America’s nuts, fruit and vegetables (California Agriculture, 2014). When there is less production of these items, prices rise—as they have in recent years due to drought (California). Since fruits and vegetables contain healthful phytochemicals, vitamins, minerals, and fiber, their consumption is heavily promoted by a long list of health-oriented organizations, including the American Heart Association, the American Cancer Society, and the Obesity Society.[14] The societal benefits of a healthier, more prosperous population (less missed days from work, lower healthcare costs, etc.) would seem to indicate that in an efficient scenario, farmland and related jobs creation would be desirable. Domestic crop production is also more affectively regulated and less costly environmentally than imported foods in many instances. Environmental concerns of fossil fuels used in the shipping process, unregulated pesticide use, and labor concerns from produce originating in foreign countries may also make domestic crop production more desirable. In addition, land changes in other countries to make up for lost productivity from farmland in California cause ecological losses and increased carbon emissions elsewhere. Because of the interactive nature of decreased environmental quality

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[14] There is evidence that lower fruit and vegetable prices increase consumption (Powell et al., 2009), but another study (Powell and Chaloupka, 2009) could not find a statistically significant link between vegetable and fruit prices and obesity rates, though lower fast food prices were correlated with higher rates.

and decreased yields, famers can actually remediate damaged land using crop production along with other tailored tactics (Qadir and Oster, 2004). This can provide more income to the farmer than the status quo practices, while at the same time, increase land quality (see section 4.3). Finding successful solutions to drainage and salinity related issues for farmland in the WSJV will help sustain farming and its corresponding public benefits[15].

Section 2.4: Marginal Land

2.4.1 Marginal Land Definition

Many different considerations must be included when defining marginal land for bioenergy production. These can be based in economics or in the natural sciences, in the private or social spheres. No single definition of marginal land is used commonly in non-technical or academic writings (Shortall, 2013; Liu et al., 2011). This can lead to confusion and has been doing so for decades:

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[15] Another unexpected benefit of crops grown in the San Joaquin Valley was explored recently in a study by Lo and Famiglietti (2013). The authors found that the evapotranspiration from the Central Valley's crops contributed substantially to the water cycle—by increasing precipitation in the southwest by 15% and Colorado River flows by about 30%.

> In its various applications, the word marginal has perhaps been too glibly used in recent years. As frequently employed, the phrase "marginal land" is apparently little more than a convenient expression for land that is barren, rough, inaccessible, or possessed of other undesirable characteristics or relationships. Peterson and Galbraith (1932)

Three general definitions reappear in multiple contexts when considering marginal land for the use of land for bioenergy feedstocks and are described by Shortall (2013). They are:

1. The land is unsuitable for food production.

This first definition encompasses the concern that crops raised solely for energy production may affect food prices and negatively impact less affluent populations. By only using marginal land that could not produce food crops, the "Food vs. Fuel" debate can be avoided in part since there are no direct or indirect consequences from the use of land not currently in commercial production. While the complexity of global food and fuel markets results in uncertainty about the effects of crop use for bioenergy on food supply, prices and global land use for agriculture, there are rational concerns about the overuse of agricultural lands for bioenergy feedstock production (Graham-Rowe, 2011; Cassman and Liska, 2007; Hill et al., 2006; Plevin et al., 2013). However unsuitable land may be for some food crops, this definition does assume that the land is nonetheless suitable for bioenergy production and that non-marginal land is used only for food production purposes. This is never completely true since industrial crops like cotton have long been produced on land that also is used for food and feed crops. In addition, many so-called cellulosic crops are perennial grasses, which could be used for forage. Lastly, land which is uneconomic for traditional crops may not provide sufficient profit if farmed for lower-valued bioenergy feedstocks.

2. The land is of lesser quality.

The second definition depends on "lesser quality", an ambiguous term, but which usually means less productive agriculturally, (and by implication insufficiently profitable when used for common agricultural crops). In this sense, the first definition may encompass the second and indicates the kind of semantic difficulties that surround the use of the term *marginal*. In the case of Central California, lesser quality commonly refers to salinized and drainage impacted soils (Wichelns and Oster, 2014; Quinn, 2014). Chemical and physical soil limitations are primary in defining marginal lands.

3. The land is economically marginal.

The third definition is the most traditional and simply means that the land will most likely not produce a profit when farmed. One reason for the inability to produce a profit may be that the land has higher costs of production than average—such as topographically challenging areas, non-contiguous sections of land, soil physical or chemical limitations, or lack of available water. Like with the first two definitions, the third assumes that the use of land in this category would help avoid the "Food vs. Fuel" controversy.

One benefit to the third definition is that agricultural land users will decide not to farm economically marginal land without some intervention such as a policy to encourage its use—it is a privately optimal decision that does not include other social costs and benefits, which are difficult to define accurately. This allows for simpler analyses as unknown nonmarket values are ignored.

However, this definition would possibly allow some marginal land to be defined as usable that should not be allowed to produce bioenergy crops from a social cost perspective.[16] Consequently, this report will define marginal land as:

Land that is economically marginal for incumbent crops, and its use increases social benefits.

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[16] Land producing nonnative bioenergy crops with potential to become invasive, riparian zones, land with high recreation value, and/or rainforests may be economically marginal, but as farming them may have large negative ecological and social consequences, they should not be considered (Barney and DiTomaso, 2008; Lowrance et al., 1984).

2.4.2 California's Marginal Land

Lands that meet this definition include salt-affected, drainage impacted lands in the main agricultural production area in the state of California: the western San Joaquin Valley. Newly available lands resulting from the decline in surface area of the Salton Sea in the Imperial Valley anticipated after 2017 may also qualify. For drainage impacted lands in the West Side of the SJV, a nexus of common property groundwater use, surface water irrigation, environmental degradation, salinity, and decreasing yields occurs. Economically marginal, these lands may help increase societal benefits by supporting perennial crop production, especially salt-tolerant grasses. These crops can have remediative effects on soil quality, may provide ecological benefits for diverse wildlife, and increase regional prosperity. Their use may help remediate drainage water effects on groundwater resulting from irrigation in the larger region (Schoups et al., 2005).

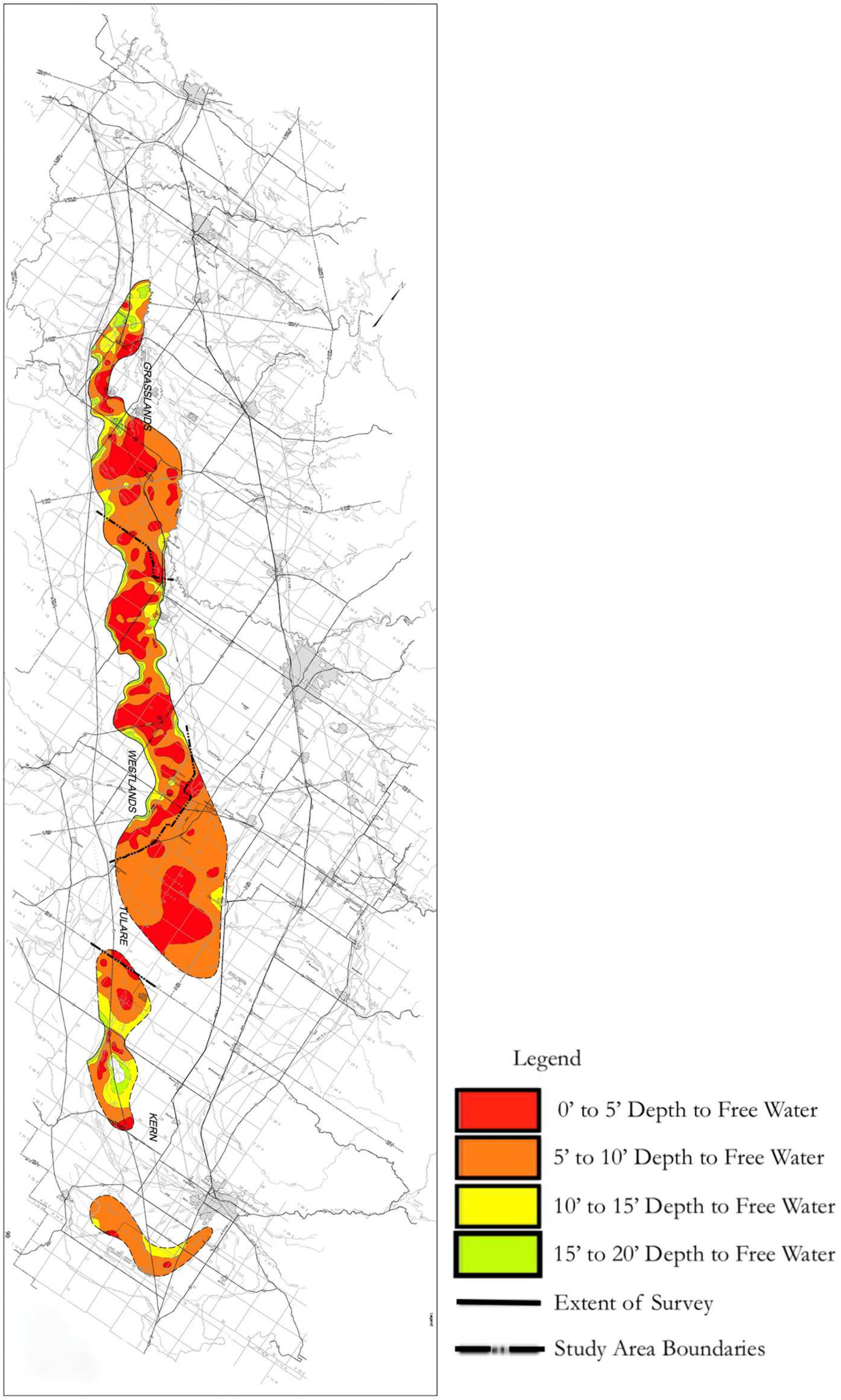
2.4.3 San Joaquin Valley

This hydrological region is divided into four subbasins that have been identified by the U.S Department of Water Resources (Figure 2-4 and Figure 2-5) as containing large amounts of marginal land. These regions are (from north to south):

- Grasslands Subbasin
    - 150,000 hectares
    - Part of the San Joaquin River Watershed.
    - Deliveries from Central Valley Project.
- Westlands Subbasin
    - 640,000 acres
    - Part of the Tulare Watershed.
    - Deliveries from Central Valley Project.
- Tulare Subbasin
    - 1,500,000 acres
    - Part of the Tulare Watershed. .
    - Deliveries from State Water Project.
- Kern Subbasin
    - 1,945,000 acres
    - Part of the Tulare Watershed.
    - Deliveries from State Water Project.

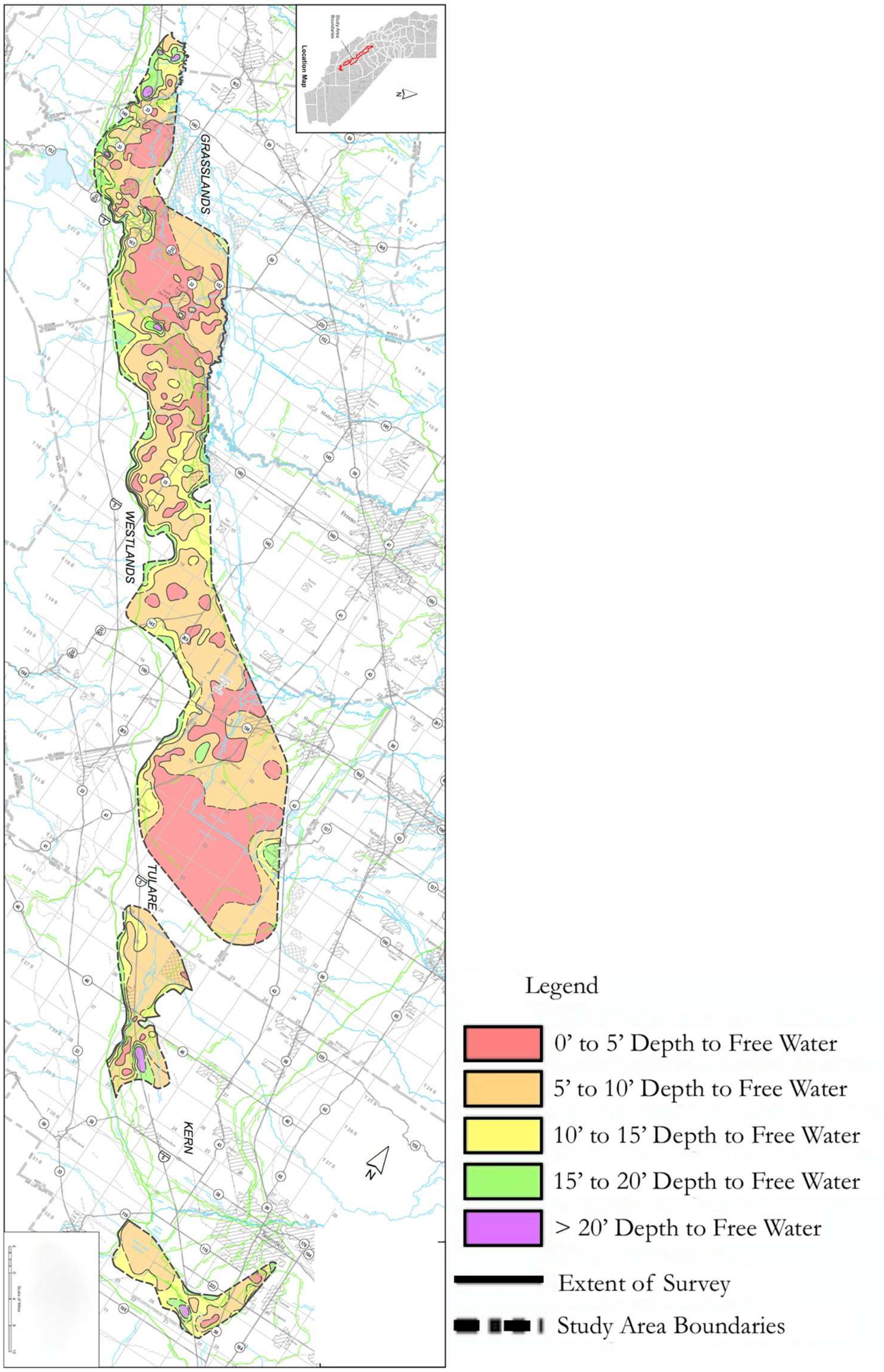
Regional acreage assessments are calculated from San Joaquin, 1990, California's Groundwater, 2003, Central, 2014, Improvement, 2014, and Eacock et al., 2012)

Figure 2- 4: Drainage impacted subbasins: Depths to groundwater in 2001.



Source: Department of Water Resources (2005). Available at http://www.water.ca.gov/pubs/drainage/2001_shallow_groundwater_map__san_joaquin_valley/sgw01.pdf

Figure 2- 5: Drainage impacted subbasins: Depths to water in 2006



Source: Department of Water Resources (2009). Available at <http://www.water.ca.gov/pubs/drainage/2006_shallow_groundwater_map__san_joaquin_valley/06sgw.pdf

2.4.4 Imperial Valley

The Salton Sea's water height is primarily maintained by irrigation water from farms in Imperial Valley. In the early 2000s, the Imperial Irrigation District sought to sell a portion of its Colorado River water allotment to San Diego County, which would have reduced water available to farms and therefore irrigation water to maintain the height of the Sea. To mitigate this, the IID was required to transfer water directly to the sea for 15 years, ending in 2017.

After 2017, the Salton Sea will shrink faster, exposing playa around its edge and causing several environmental and social concerns (Background, 2014). This land will be severely salt-affected but with appropriate management, might be revegetated with biomass stocks possibly consisting of halophytes or Tamarix.

The Imperial Irrigation District has estimated the size of the exposed playa for future years. These values are given in Table 2-1.

Table 2- 1: Expected acres of exposed playa in the Salton Sea.

Salton Sea Playa					
Year	2017	2020	2023	2027	2030
Expected Ac	7,184	17,068	29,890	44,232	50,797

2.4.5 Perennial Grasses and Marginal Land Remediation

The perennial character of two likely salt-tolerant species, Tall Wheatgrass and Bermuda grass, provide some environmental benefits. Perennial crops are protective of soils, typically adding more carbon due to dense root structures, and are not oxidized due to tillage, and may acidify alkaline soils over time, helping to maintain improved soils structure in gypsum rich soils. Corwin and Perry (2013) and Alonso et al. (2013) studied Bermuda grass planted on sixty acres of land in the western SJV that had a water table of less than five feet in 1999. They installed a tile drainage system to remove leached water from the system. Most of the water was utilized by the plant, and runoff was recycled on site or allowed to infiltrate. In the first five years and top four feet of the profile, salinity decreased 21%, the sodium absorption rate (SAR) decreased 19%, boron decreased 32%, and molybdenum decreased 67% which is of higher concern in that area than selenium. Levels continued to decrease, then leveled off by 2009. When drainage water stopped being applied for the last two years of the study, the quality of the soils reverted almost to their pre-study levels. The Bermuda yields on the site were between 1.5 and 2.5 ton DM/ha; the grass grew well, even with the saline soil and drainage water used for irrigation.

The ability of grasses to reduce salinity, SAR, and toxic elements are discussed in several other studies. The increased soil organic matter caused by grass growth is a reason for some of these benefits (Akhter et al., 2003; Zhang et al., 2006). Grasses planted in the former Kesterson Wildlife Refuge following the halt of selenium contaminated drainage imports have demonstrated the ability to reduce selenium levels in the soil. In several decades to several centuries, the selenium levels should return to normal, barring any more importation. Wildlife has not shown any ill effects of the residual selenium in the grasslands (Wu, 2004).

Wildlife may benefit from perennial grasslands as well. Meehan et al. (2010) estimated that while increasing corn and soy crops on economically marginal land in the Midwest would decrease avian populations, planting mixed perennial grass and forbs on these lands would increase populations and possibly help some threatened species recover. Many other species, including the San Joaquin Kit Fox (an endangered species) utilize grasslands as habitat (Gerrard, 2001). Stoms et al (2012) estimated improved wildlife habitat for new perennial grasslands planted for biofuel feedstocks compared to annual crops.

2.4.6 Estimating Marginal Land

This study reports on a specific potential use of poor quality lands, which will be defined here as:

Highly Marginalized Land: Locations where the water table is within five feet of the ground surface.

Moderately Marginalized Land: Locations where the water table is within twenty feet of the ground surface.

These definitions are derived from the Department of Water Resources definitions of “Present Problem Areas” and “Potential Problem Areas” (San Joaquin, 1990). In different years, under different cropping systems, different current irrigation methods, and different surface water deliveries, the quantities of *Highly* and *Moderately Marginalized Land* vary (Figure 2-6 and Figure 2-7).

Figure 2- 6: Total marginal land (sum of highly marginal and moderately marginal) in the subbasins over time (Acres).

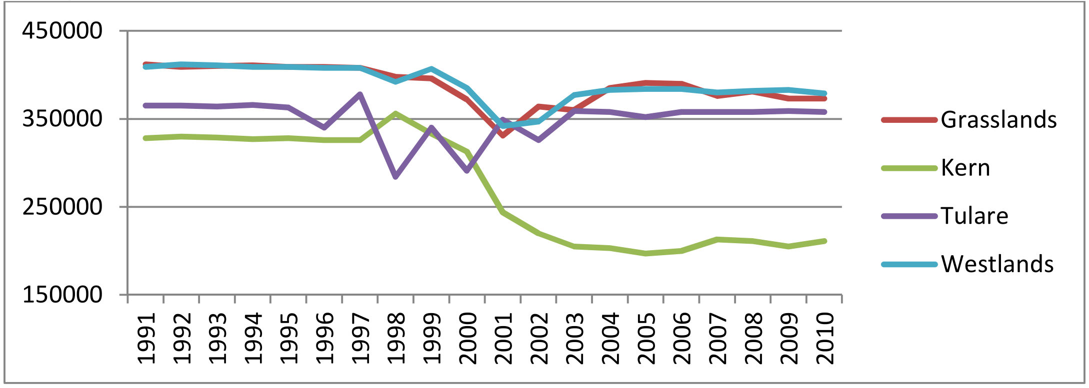
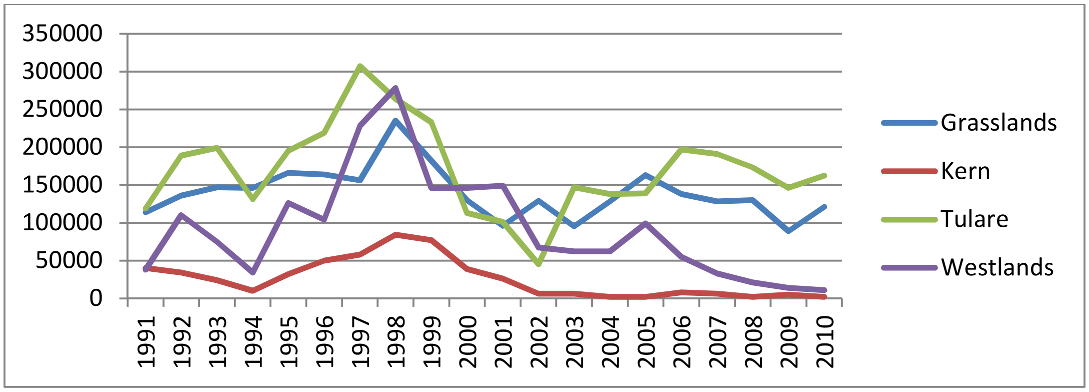


Figure 2- 7: Highly marginal land in the subbasins over time (Acres).



The hydrologic system of the Westside of the SJV is highly complex and geographically heterogeneous. As more imported water is available to farmers, the more water will be applied to fields and the higher the amount of drainage impacted land. In Figure 2-8, using Westlands Irrigation District as an example, the relationships between marginal land and water use are shown. Surface water imports and groundwater use are negatively correlated. The relationship between total marginal land and surface water deliveries and use, however, is not consistent, though total marginal land decreases in the early 2000s, when surface water imports decrease. In Figure 2-9, different elevations of groundwater are presented. Marginal land with water at shallower depths (0 to 5 ft and 5 to 10 ft) are negatively correlated with each other, while at deeper levels (10 to 15 ft and 15 to 20ft) the relationship is positively correlated. This same pattern holds true in the Grasslands Subbasin (Figure 2-10) and the Tulare Subbasin (Figure 2-11). In the Kern Subbasin (Figure 2-12), depths of 0 to 5ft and 10 to 15 ft are negatively correlated, while 0 to 5 ft and 5 to 10 ft are positively correlated.

Figure 2- 8: Imported water, groundwater use, and marginal land in the Westlands Subbasin over time.

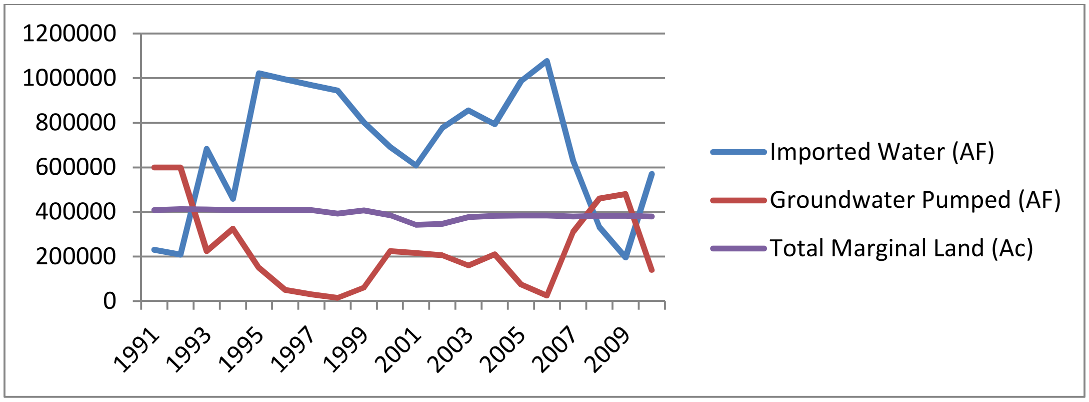


Figure 2- 9: Acres of land in Westlands Subbasin with elevated groundwater table at varying heights below the surface.

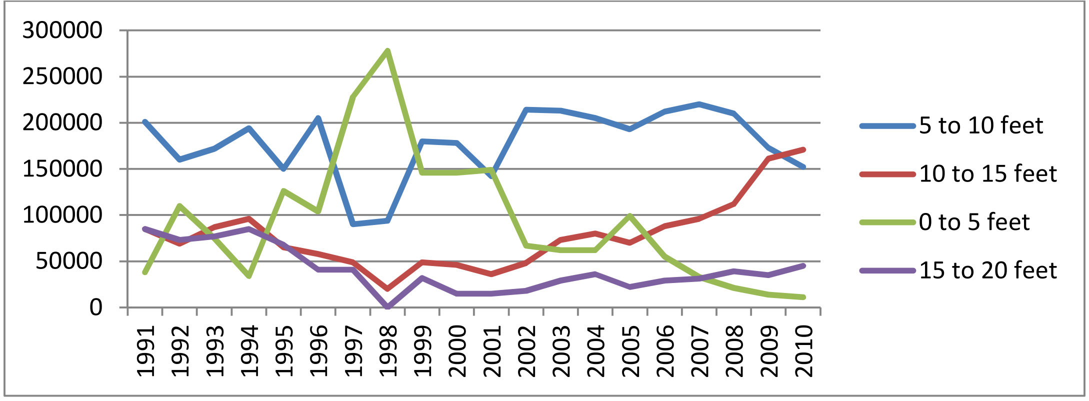


Figure 2- 10: Acres of land with different depths to groundwater over time in the Grasslands Subbasin.

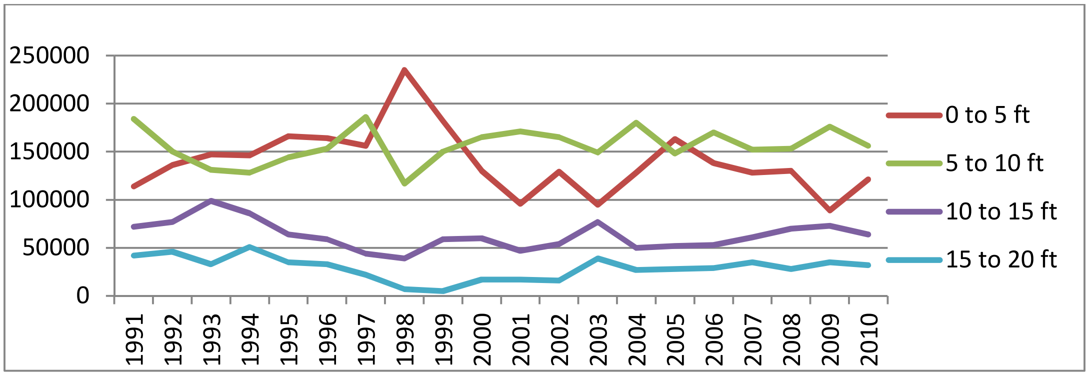


Figure 2- 11: Acres of land with different depths to groundwater over time in the Tulare Subbasin.

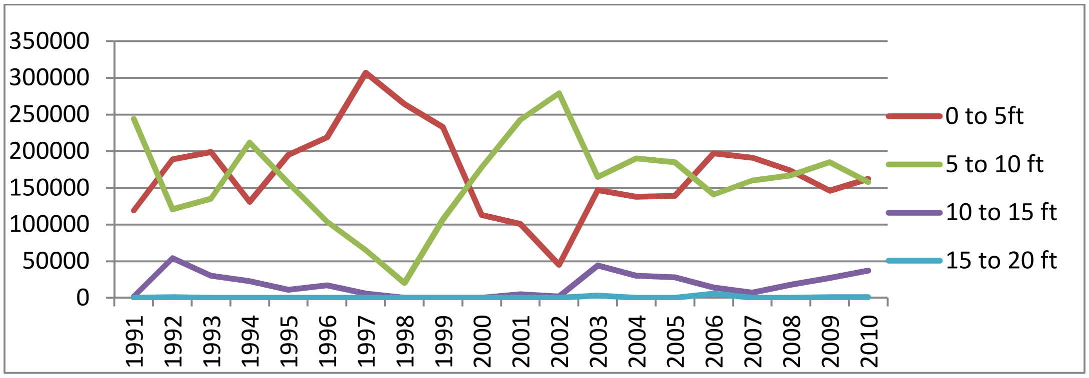
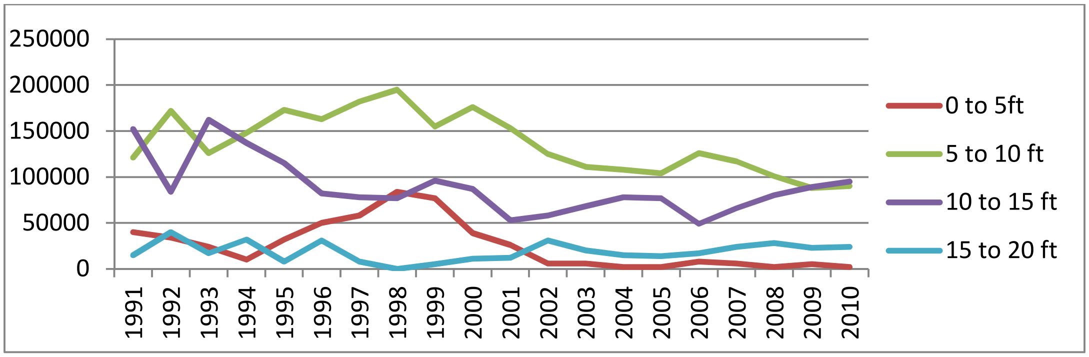


Figure 2- 12: Acres of land with different depths of groundwater over time in the Kern Subbasin.



Section 2.5: Drainage Water

Drainage water is excess water that travels through the root zone. If not recovered, drainage water raises shallow water tables and contributes to groundwater pollution as it acquires naturally occurring salts, trace elements, residual fertilizer, and pesticides (Schoups et al., 2005). Volumetrically, it equals applied water (plus precipitation) minus evapotranspiration from crops and the change in soil profile storage. Subsurface tile drains can be used to capture some portion of this water, reducing and delaying eventual groundwater impacts (Corwin, 2012; Alonso et al., 2013).

2.5.1 Why use Only Drainage Water?

The reason drainage problems exist in the San Joaquin Valley is because of the use of imported irrigation water and subsurface geological conditions that lead to shallow water tables. Integrated Farm Drainage Management (IFDM) was one attempt to solve this difficult management challenge. By using drainage water on salt-tolerant crops, growers can save surface water for higher-valued uses. In this system, the least saline water is used on the least salt tolerant crops on the best quality soils. The drainage water from those fields is then used on a more salt tolerant crop. The drainage water from the secondary crop was then used on an even more salt tolerant crop. This process provides growers with income from salt tolerant crops and an alternative to fallowing (Ayars and Basinal, 2005). Additionally, there are some phytoremediative effects of plant growth on poor quality soils with drainage water (see section 4.3). In order for IFDM systems to be effective in the short term, users must assume that changes in soil salinity conditions can occur rapidly with drainage. However steady-state groundwater salinity concentrations can be extremely slow to occur (Knapp and

Baerenklau, 2006), which may mean that successive concentration of salts (and elements) in smaller areas may take considerable time.

2.5.2 Is Drainage Water Safe to Use?

There are two main ways in which drainage water used for irrigation could present dangers to people and/or wildlife. The first is direct exposure to the drainage water while it is transported from the originating field to the marginal land on which it is to be applied. The second is through trace element uptake by the perennial grasses. Even though the grasses are not to be consumed by people, they may be consumed by cattle or result in wildlife exposure.[17] Cattle were grazed in the project described by Alonso et al. 2013, and Corwin without adverse effects.

The three main potentially toxic elements found naturally in the soils of the Westside of the SJV are boron, selenium, and molybdenum. These three elements can therefore be in any drainage water from the West Side. Boron can be toxic to aquatic life when runoff into water bodies contains high enough concentrations.[18] Boron does not leach from soils easily, so repeated application of drainage water to the same land can concentrate boron in its soils. High

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[17] If the grasses were to be fed to livestock instead of used for bioenergy, potential health affects of consumption would have to be considered, but see Alonzo et al., 2013..

[18] Boron can be toxic to plants. This would be important if other crops were to be grown with drainage water instead of perennial grasses.

concentrations of soil boron can inhibit plant growth. Airborne boron can cause damage to tree species; this should be considered when processing high boron biomass if boron is emitted to the atmosphere in the process (Howe, 1998; Grattan, 2014; Drainage, 1999). Danger to people from consuming plants grown on boron impacted lands has not been shown to be an issue, though it is possible for humans to experience boron toxicity at high enough levels. Boron is not absorbed through the skin and must enter the body through wounds, the digestive track, or airways (Moore and Expert Scientific Committee, 1997); this makes its toxicity potential low.

At low levels, Se is a nutritional requirement for most mammals and birds. Selenium uptake by plants can increase selenium concentrations in humans, but it is unlikely that people will directly consume plants from reuse areas (Drainage, 1999). Cattle, however, have been shown to experience selenium toxicity when fed large amounts of plants grown in high selenium areas (Drainage, 1999). As discussed in Section 4.3, wildlife in the Kesterson Wildlife Refuge has not been shown to suffer any damage from the residual selenium currently in the system, from land planted primarily in grasses. Absorption through the skin does not appear to be likely to cause any serious concern in humans (Potential, 2014). As in the case of boron, selenium bioaccumulation appears to be most dangerous in aquatic systems. Molybdenum interferes with copper use by the body, and excessive molybdenum in the diet can cause issues similar to copper deficiencies (Grattan et al., 2014). It may also cause health effects in birds in an aquatic environment. When molybdenum enriched drainage water is applied repeatedly to the same soil, its concentrations in the soil increases to high levels; however, most of this molybdenum is likely insoluble (Amrhein and Doner, 2014).

Ingestion is the primary method of exposure to boron, selenium, and molybdenum. Because of this, and because drainage water can contain various other elements, pesticides, and agricultural compounds, it would be wise to prevent wildlife or people from drinking drainage water. One way to do this would be to avoid open ditches transporting drainage water, however this may not be feasible or completely necessary.

The marginal fields discussed in Alonso and Kaffka (2013) and Corwin (2012) had tile drainage systems installed. This allowed the leachate from the fields to be removed from the system. In part, this leachate was diluted and immediately recycled back to the field, but some was left in place. This secondary drainage water was more highly concentrated in salts and trace elements. The amount of water affected was significantly reduced from the initial drainage volume and isolated to a much smaller area, but in those places may pose a higher risk than the original drainage water and such waters may require final disposal treatments, considered in Zhang and Kaffka (2015). Final disposal of this secondary water must be addressed in any comprehensive management solution.

2.5.3 Estimating Drainage Water

Many factors affect the amount of drainage water that could be available for reuse, including crop choices, irrigation system, climate, soil type, and hydrologic systems. Data for crop areas in Westlands Water District is available for the years 2000 through 2010. Using these acreage reports and estimated applied water quantities for individual crops from the UC Davis Cost and Return reports, applied water was estimated (see Appendix 2.A). Water intake by a plant is dependent on reference evapotranspiration, ETo. The fraction of ETo that the plant can use is called the crop coefficient, Kc. The crop evapotranspiration, ETc is the product of the two (ETc = Kc(ETo)). To estimate crop ETc, monthly average ETo measurements for 2000 to 2010 were acquired from CIMIS. Crop stage information was retrieved from the FAO, along with Kc values for the stages. The total seasonal crop ETc was then estimated, as described in Appendix 2.B. The values for each crop were summed per year and compared to the calculated applied water amounts. These two values are compared in Figure 2-13. The differences vary between 0.059 and 0.138 meters. For comparison, the desired reduction drainage flows for Westlands published by the department of Water Resources is 0.1067 meters.

Figure 2- 13: Estimated applied water versus estimated ET in Westlands Subbasin (acre-m)

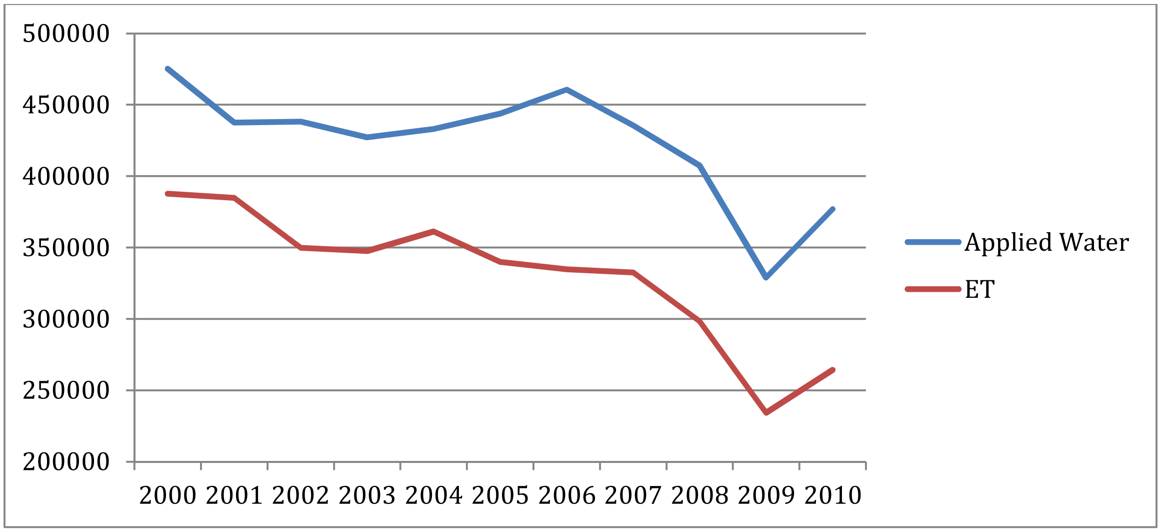
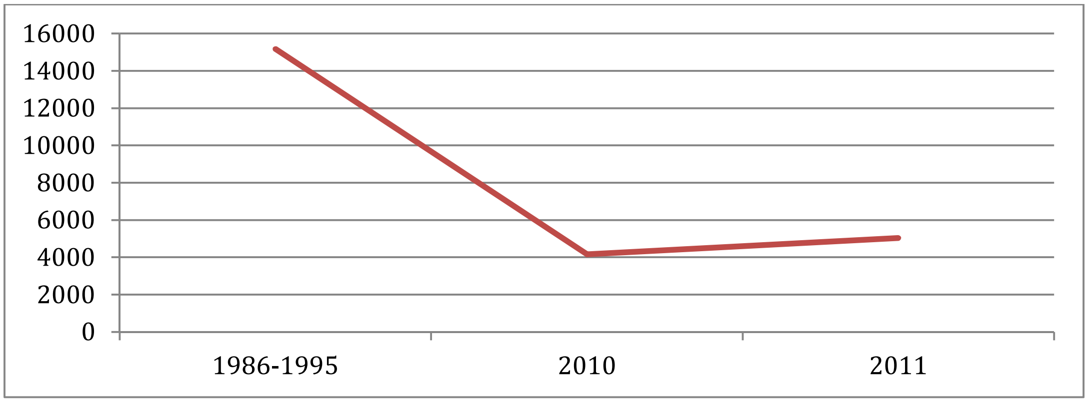


Figure 2- 14: Drainage water (acre-m) in the Grasslands over time.



The Grasslands Water District tracks its drainage water.[19] The total amount has reduced significantly since 1986 (Figure 2-14).

For the Kern and Tulare subregions, crop mixes from the entire county were used to estimate mean drainage water produced per acre in the same manner as for Westlands. The differences between estimated ET and applied water can be seen in Figure 2-15 and Figure 2-16.

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[19] In 1996, the Bureau of Reclamation and the San Luis and Delta-Mendota Water Authority agreed to use a portion of the San Luis Drain to move drainage water from the Grasslands area to the Mud Slough for the purposes of keeping drainage water away from wetlands and improve water quality. This was the beginning of the Grasslands Bypass Project. The drainage water is tracked and its salinity and selenium levels monitored (Eacock and Brown, 2012).

Figure 2- 15: Estimated applied water versus estimated ET in Kern Subbasin (acre-m)

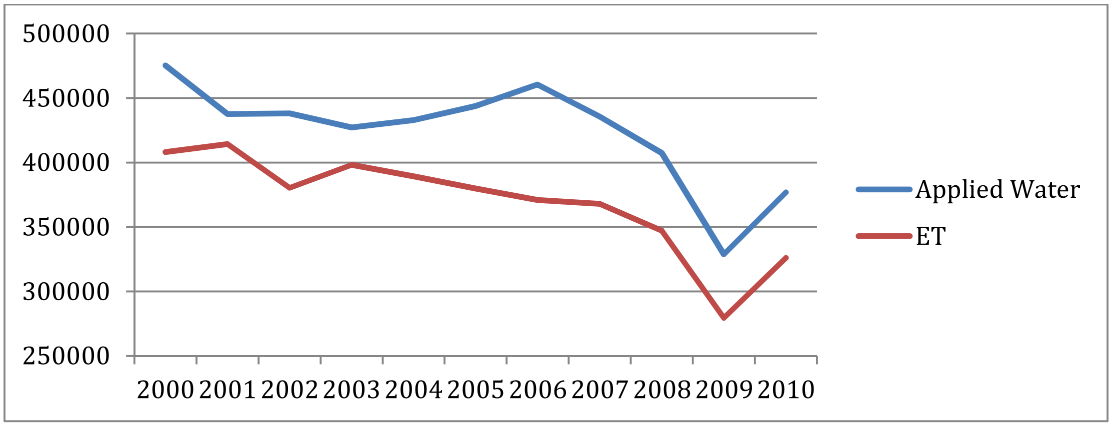

Figure 2- 16: Estimated applied water versus estimated ET acre in Tulare Subbasin (acre-m)

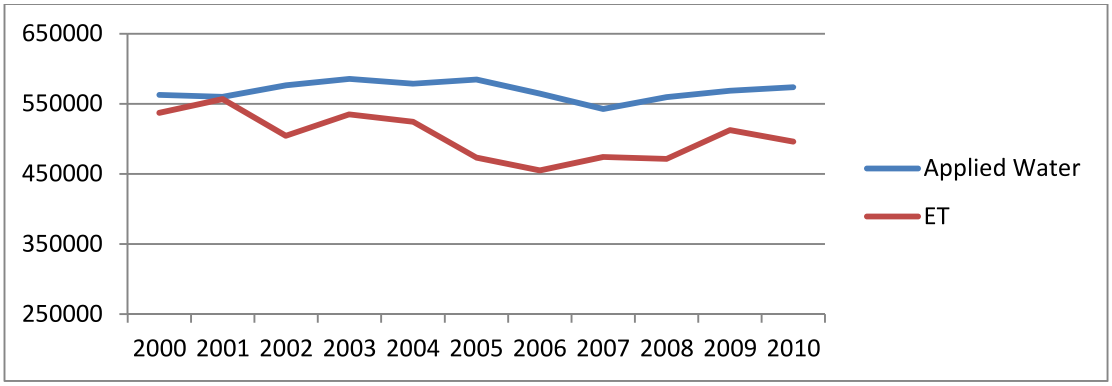

Table 2-2 contains the estimated depth of drainage water per year in each of the subregions. Table 2-3 contains the estimated total drainage water and land available in each region.

Table 2- 2: Yearly average acre feet of drainage water per acre.

Feet of Drainage Water											
Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Grasslands	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Westside	0.55	0.35	0.6	0.53	0.48	0.68	0.82	0.73	0.77	0.87	0.86
Tulare	0.11	0.02	0.31	0.22	0.24	0.5	0.5	0.33	0.41	0.26	0.35
Kern	0.32	0.1	0.25	0.14	0.22	0.32	0.46	0.34	0.33	0.28	0.29

Table 2- 3: Crop acres, drainage water (acre feet), highly marginal land, and moderately marginal land (acres) in the four subregions.[20]

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Westlands											
Crop Acres	522487	497048	484345	489838	490277	499517	501782	466249	461897	358385	429408
Drainage Water	286271	172858	289209	261954	234844	340878	413213	338061	357637	310412	369111
Highly Marg Land	146000	149000	67000	62000	62000	99000	55000	33000	21000	14000	11000
Mod Marg Land	385000	342000	347000	377000	383000	384000	384000	380000	382000	383000	379000
Grasslands*											
Crop Acres	350000	350000	350000	350000	350000	350000	350000	350000	350000	350000	350000
Drainage Water	161909	161909	161909	161909	161909	161909	161909	161909	161909	161909	161909
Highly Marg Land	130000	96000	129000	95000	128000	163000	138000	128000	130000	89000	121000
Mod Marg Land	372000	331000	364000	360000	385000	391000	390000	376000	381000	373000	373000
Tulare~											
Crop Acres	550000	550000	550000	550000	550000	550000	550000	550000	550000	550000	550000
Drainage Water	61352	9022	173228	119094	129921	272474	274278	184055	225558	142552	193077
Highly Marg Land	113000	101000	45000	147000	138000	139000	197000	191000	173000	146000	162000
Mod Marg Land	291000	349000	326000	359000	358000	352000	358000	358000	358000	359000	358000
Kern**											
Crop Acres	684540	763479	774221	657915	657916	643443	638450	643924	598020	576194	575218
Drainage Water	220095	75146	190507	94975	142462	208992	293251	221824	198163	162574	167961
Highly Marg Land	39000	26000	6000	6000	2000	2000	8000	6000	2000	5000	2000
Mod Marg Land	313000	244000	220000	205000	203000	197000	200000	213000	211000	205000	211000

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[20] *The drainage data came from the Grasslands Bypass Project, which is a smaller subset of the Grasslands area. The data was scaled up for the entire Grasslands Subbasin.**Assumes Kern County is the same area as the Kern Water Basin~Acreage from SJV (1991)

Section 2.6: Bioenergy Production

To determine potential biofuel production, the amount of land available, water available, the salinity of the water, the salinity tolerance of the crop, the biofuel conversion rate, and the processing method of bioenergy production must be known (Zhang and Kaffka, 2015).

2.6.1 Yield: Applied Water and Salinity

Crop yield is dependent on many factors, including, of course, applied water and the salinity of the applied water. Crop relative yield (actual yield divided by potential yield) can be approximated by the ratio of actual crop ETc and potential ETc (Levers, in prep). Using the same method described in Section 5.4 and Appendix 2.B, Bermuda's potential Kc values were estimated for 240 days of growth, assuming harvests occur every 60 days. These results were compared to results calculated using the potential Kc values estimated for Bermuda in Alonso and Kaffka (2013). The yearly estimated differed by approximately 5 centimeters (Table 2-4). These estimates provide a good reference for Bermuda's water requirements, but do not address salinity, which can be addressed using the water stress coefficient, Ks, which is multiplied by ETc to effectively lower Kc to account for various stresses. Alonso and Kaffka (2007) estimated Ks as a function of ECe, soil salinity. ECe and ECw, water salinity, are related by a factor that depends on the leaching fraction, the percent of applied water that drains through the root zone (Corwin, 2012). Calculated Ks values for several leaching fractions and ECw values are shown in Table 2-5. If crop yield is approximated by actual ETc/potential ETc, then Ks represents the percent of potential yield possible at varying applied water salinity and leaching fraction levels.

Table 2- 4: Estimated maximum water use by Bermuda in feet.

	Present Analysis	Alonso and Kaffka (2013)
1st Cut (Mar -Apr)	0.7	0.66
2nd Cut (May-Jun)	1.24	1.43
3rd Cut (Jul-Aug)	1.25	1.43
4th Cut (Sep-Oct)	0.81	0.64
Mean	1	1.04
Total for 240 days	4	4.16

Table 2- 5: Calculated Ks for ECw of 4 to 10 dS/m and leaching fractions of 0.1 to 0.3.[21]

Leaching Fraction: 0.1		Leaching Fraction: 0.15 to 0.20		Leaching Fraction: 0.3	
ECw	Ks	ECw	Ks	ECw	Ks
4	0.85	4	1	4	1
5	0.71875	5	0.90625	5	1
6	0.5875	6	0.8125	6	1
7	0.45625	7	0.71875	7	0.9375
8	0.325	8	0.625	8	0.875
9	0.19375	9	0.53125	9	0.8125
10	0.0625	10	0.4375	10	0.75

Alonso and Kaffka (2013) performed field studies to determine yield of Bermuda at different salinity levels. They did not test Bermuda under non-saline conditions. With an ECw of 6 dS/m and ECe of 7dS/m, Bermuda achieved yields of 11.3 to 20.6 ton DM/ha (with different levels of applied nitrogen and trace minerals)[22]. As ECe increases, yields decrease (Figure 2-17). According to Table 2-5, an ECw of 6 dS/m produces an approximately 20% reduction in potential yield with a leaching fraction of .15 to .20. Similarly, an ECw of 10 dS/m produced an approximately 55% reduction. As for the ECw of drainage water, it is understandable that is varies. The average ECw for the Grasslands drainage water was about 0.8 dS/m in 2010 and 1.9 dS/m in 2011—rather low. Articles described in the Drainage Reuse Report (1999) studied drainage ECw from about

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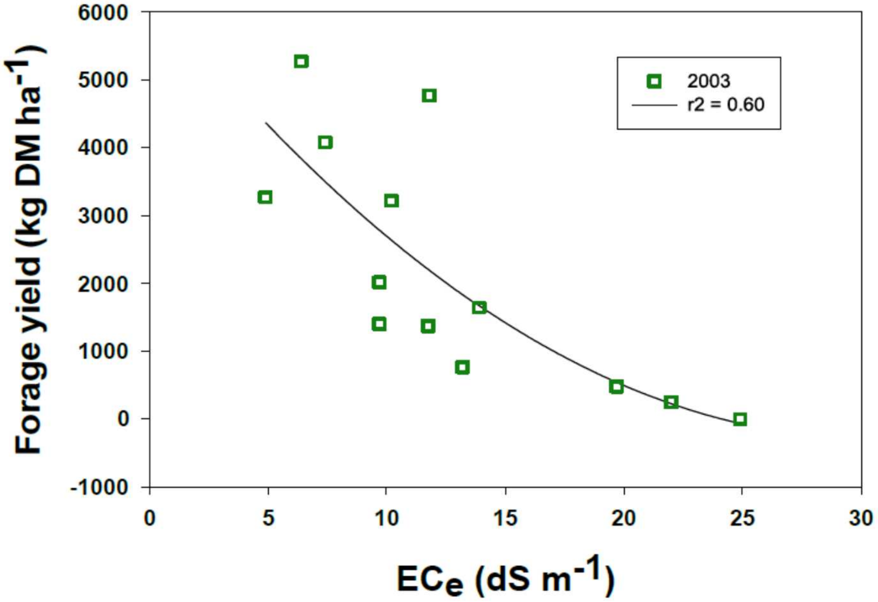
[21] Leaching fractions of 0.15 and 0.2 both have a coefficient of 1.5, which is multiplied by ECw.

[22] Bermuda has high nitrogen requirements. Alonso and Kaffka (2013) applied up to 600 kg/ha. Since most drainage water contains nitrogen, Bermudagrass will be able to utilize this pollutant.

2 to 30 dS/m. The most common seem to be below 10 dS/m, however. This analysis will use two salinity levels to estimate bioenergy production: 6 dS/m and 10 dS/m. The estimated yield ranges for the two levels are based on the ranges of yields found in Alonso and Kaffka (2013) along with the values calculated in Table 2-5, and are given in Table 2-4. Applied water for the Bermudagrass will be assumed to be 1.2 meters (Table 2-6).[23]

Figure 2- 17: Bermuda grass yield as a function of soil salinity. Alonso and Kaffka, 2013.



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[23] As salinity levels increase, plants tend to require more water. This information would be pertinent in a more complex yield function, such as those generated in Levers, in prep. Future analyses can take this into account.

Table 2- 6: Bermuda yield (ton dry matter/acre) range estimates for low and high drainage water salinity levels.

ECw (dS/m)	Low Yield	High Yield
6	4.6	8.3
10	2.5	4.5

2.6.2 Conversion Rates

The conversion rate is the amount of energy that can be expected to be produced from a unit of biomass. For Bermuda converting to energy via gasification, this has been estimated as 10.67 Gj/ton dry matter. For Bermuda converting to energy via cellulosic ethanol, this has been estimated as 79.4 gallons/ton dry matter. For Bermuda converting to energy via biogas, this has been estimated as 210.2 kg methane/ton dry matter. For more information, see Zhang and Kaffka (2015).

2.6.3 Biofuel Production Estimates

As indicated by Bermuda's water requirements of 3.9 feet and the available drainage water and SJV marginal land in Table 2-3 and Table 2-4, marginal land is the limiting factor for bioenergy production in the western San Joaquin Valley. There is never enough drainage water in each subbasin to fully water Bermudagrass on all hectares of marginal land. There may be enough to plant Bermudagrass on all highly marginal land, in some cases

For each of the following scenarios, total bioenergy was calculated for three different sub-scenarios: 1) Only 50% of *Highly Marginalized Land* may be utilized, 2) 100% of *Highly Marginalized Land* 3) 100% of *Moderately Marginalized Land* may be used. In all scenarios, as much drainage water as is available is used.

Low and Salty (LS):

Assumptions: Drainage Water ECw: 10 dS/m

Surface water is low, due to drought and/or policy restrictions; drainage water amounts from 2001, a drought year, are used.[24]

Low and Less Salty (LL):

Assumptions: Drainage Water ECw: 6 dS/m

Surface water is low, due to drought and/or policy restrictions; drainage water amounts from 2001, a drought year, are used.

Medium and Salty (MS):

Assumptions: Drainage Water ECw: 10 dS/m

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[24] A baseline is needed for minimal biomass supplies for planning purposes. To construct a biorefinery, some estimate of reliable feedstock supplies are needed. The amount available and the distance of transport involved will affect the type of conversion system possible. A drought year provides the baseline estimate.

Surface water is low, due to drought and/or policy restrictions; mean drainage water amounts from 2000 to 2010 are used.

Medium and Less Salty (ML):

Assumptions: Drainage Water ECw: 6 dS/m

Surface water is low, due to drought and/or policy restrictions; mean drainage water amounts from 2000 to 2010 are used.

High and Salty (HS):

Assumptions: Drainage Water ECw: 10 dS/m

Surface water imports are high, due to high levels of precipitation and/or policy; drainage water amounts from 2006, a wet year, are used.

High and Less Salty (HL):

Assumptions: Drainage Water ECw: 6 dS/m

Surface water imports are high, due to high levels of precipitation and/or policy; drainage water amounts from 2006, a wet year, are used.

The results for gasification (Table 2-7) range from 1.1 million to 25.8 million gigajoules (Gj). Again, these values are assuming all the available drainage water is used by Bermuda grass. If only 50% were available, then the maximum energy output would drop to about 12.9 million Gj, which is equivalent to enough natural gas for over 260,000 Californians for one year (AGA).

Cellulosic ethanol results are given in Table 2-8 and biogas is given in Table 2-9. Ethanol ranges from 8 million gallons to 190 million gallons. Biogas ranges from 21 million kilograms to 500 million kilograms.

Table 2- 7: West Side Gasification bioenergy production potential in thousands of GJ under different scenarios. Assumes all drainage water is available.

Gasification	Sub-Scenario 1		Sub-Scenario 2		Sub-Scenario 3	
	Low Yield	High Yield	Low Yield	High Yield	Low Yield	High Yield
LS						
Grasslands	1083	1971	1083	1971	1083	1971
Westlands	1156	2104	1156	2104	1156	2104
Tulare	60	110	60	110	60	110
Kern	342	623	503	915	503	915
Total	2641	4808	2802	5100	2802	5100
LL						
Grasslands	2007	3658	2007	3658	2007	3658
Westlands	2142	3905	2142	3905	2142	3905
Tulare	112	204	112	204	112	204
Kern	634	1156	931	1698	931	1698
Total	4895	8923	5192	9465	5192	9465
MS						
Grasslands	1083	1971	1083	1971	1083	1971
Westlands	861	1566	1722	3133	2052	3735
Tulare	1085	1975	1085	1975	1085	1975
Kern	125	227	249	453	1202	2187
Total	3154	5739	4139	7532	5422	9868
ML						
Grasslands	2007	3658	2007	3658	2007	3658
Westlands	1595	2907	3189	5814	3802	6931
Tulare	2011	3666	2011	3666	2011	3666
Kern	231	420	461	841	2226	4059
Total	5844	10651	7668	13979	10046	18314
HS						
Grasslands	1083	1971	1083	1971	1083	1971
Westlands	724	1318	1449	2636	2765	5031
Tulare	1835	3339	1835	3339	1835	3339
Kern	105	192	211	383	1962	3570
Total	3747	6820	4578	8329	7645	13911
HL						
Grasslands	2007	3658	2007	3658	2007	3658
Westlands	1342	2446	2684	4892	5121	9336
Tulare	9612	6197	3399	6197	3399	6197
Kern	195	356	390	712	3634	6626
Total	13156	12657	8480	15459	14161	25817

Table 2- 8: West Side Ethanol bioenergy production potential in thousands of GJ under different scenarios. Assumes all drainage water is available.

Ethanol	Sub-Scenario 1		Sub-Scenario 2		Sub-Scenario 3	
	Low Yield	High Yield	Low Yield	High Yield	Low Yield	High Yield
LS						
Grasslands	81	147	81	147	81	147
Westlands	86	157	86	157	86	157
Tulare	4	8	4	8	4	8
Kern	25	46	37	68	37	68
Total	196	358	208	380	208	380
LL						
Grasslands	149	272	149	272	149	272
Westlands	159	291	159	291	159	291
Tulare	8	15	8	15	8	15
Kern	47	86	69	126	69	126
Total	363	664	385	704	385	704
MS						
Grasslands	81	147	81	147	81	147
Westlands	64	117	128	233	153	278
Tulare	81	147	81	147	81	147
Kern	9	17	19	34	89	163
Total	235	428	309	561	404	735
ML						
Grasslands	149	272	149	272	149	272
Westlands	119	216	237	433	283	516
Tulare	150	273	150	273	150	273
Kern	17	31	34	63	166	302
Total	435	792	570	1041	748	1363
HS						
Grasslands	81	147	81	147	81	147
Westlands	54	98	108	196	206	374
Tulare	137	248	137	248	137	248
Kern	8	14	16	29	146	266
Total	280	507	342	620	570	1035
HL						
Grasslands	149	272	149	272	149	272
Westlands	100	182	200	364	381	695
Tulare	715	461	253	461	253	461
Kern	15	26	29	53	270	493
Total	979	941	631	1150	1053	1921

Table 2- 9: West Side biogas bioenergy production potential in hundreds of thousands of kg under different scenarios. Assumes all drainage water is available.

Biogas	**Sub-Scenario 1**		**Sub-Scenario 2**		**Sub-Scenario 3**	
	Low Yield	**High Yield**	**Low Yield**	**High Yield**	**Low Yield**	**High Yield**
LS						
Grasslands	213	388	213	388	213	388
Westlands	228	415	228	415	228	415
Tulare	12	22	12	22	12	22
Kern	67	123	99	180	99	180
Total	520	948	552	1005	552	1005
LL						
Grasslands	395	721	395	721	395	721
Westlands	422	769	422	769	422	769
Tulare	22	40	22	40	22	40
Kern	125	228	183	334	183	334
Total	964	1758	1022	1864	1022	1864
MS						
Grasslands	213	388	213	388	213	388
Westlands	170	309	339	617	404	736
Tulare	214	389	214	389	214	389
Kern	25	45	49	89	237	431
Total	622	1131	815	1483	1068	1944
ML						
Grasslands	395	721	395	721	395	721
Westlands	314	573	628	1145	749	1365
Tulare	396	722	396	722	396	722
Kern	45	83	91	166	439	800
Total	1150	2099	1510	2754	1979	3608
HS						
Grasslands	213	388	213	388	213	388
Westlands	143	260	285	519	545	991
Tulare	361	658	361	658	361	658
Kern	21	38	42	76	387	703
Total	738	1344	901	1641	1506	2740
HL						
Grasslands	395	721	395	721	395	721
Westlands	264	482	529	964	1009	1839
Tulare	1894	1221	670	1221	670	1221
Kern	38	70	77	140	716	1305
Total	2591	2494	1671	3046	2790	5086

Section 2.7: Conclusion

Perennial, salt tolerant grasses like Jose tall wheatgrass and Bermuda grass, grown on marginal land irriagted with drainage water in the Western San Joaquin Valley, have the potential to produce 1 million to more than 20 million GJ of bioenergy, depending on the amount of land and drainage water available, and policy conditions favoring or discouraging this use. In the process, feedstock production may provide remediative effects on the land, in the form of increased soil quality, benefits to wildlife, drainage water reuse, and energy for final concentration and disposal of salts and trace elements without relying on transfer to the ocean. The primary goal of evaluating biomass energy conversion based on the use of these resources is to help defray the ultimate cost of protecting groundwater, wildlife and the larger central valley ecosystem from the adverse effects of irrigation over long time periods, while maintaining the large economic and social benefits derived from farming in California's productive and unique semi-arid to Mediterranean environment, which is a significant world resource. This is equivalent to improving the sustainability of irrigated agriculture in this region and similarly affected areas in the rest of the world.

When surface water imports are reduced due to droughts and/or policy, drainage water is reduced, as well. If bioenergy production from perennial grasses is restricted to marginal land and drainage water, production will be lower in years with less surface water available. Scalable systems or a slow build out of an in-valley bioenergy industry based on reliable occurring supplies seems prudent under these circumstances (Zhang and Kaffka, 2015).

In the WSJV, there is more marginal land than can be used for perennial grasses, if perennial grasses are restricted to only using drainage water.

This study has provided preliminary information and results, indicating further study is warranted. Particularly useful would be a bio-economic regional optimization model, similar to that of Levers (2015), which would provide information on whether or not this approach is economically viable. A model such as this could include the possibility of using saline, shallow groundwater in addition to drainage water, in order to utilize more marginal land. Additionally, more study on final disposal of marginal land drainage water residuals would be needed to determine the true environmental benefit of biofuel production with reuse water.

Chapter 3: Bio-economics in yield functions for agro-economic modeling: including salinity, nitrogen, instantaneous yield reductions, site specificity, and climate data.

Abstract 3:

Water scarcity and salinization drive the need for accurate and practical yield functions for agro-economic modeling. We develop yield functions that are flexible and capable of providing information on salinity, irrigation systems, irrigation timing, climate effects, and deep percolation. These functions follow the methodology of two published methods of saline water crop yield function generation from Kan et al. (2002) and Wang (2012). Each of these published methods has a different level of data required, and therefore specificity. The current paper builds upon this previous research by developing a model that allows for instantaneous yield reduction within a season, climate and date-specific data, and irrigation system specific evaporation. Examples of our method's capability are given as well as a comparison of the current modeling strategy with results from Kan et al. (2002) and Wang (2012). Results suggest that while the extensions to the previous research allow researchers the opportunity

to more finely-tune their applications and potentially capture salient elements of irrigation management and the biophysical system that occur within a season, it comes at a cost of additional data requirements and researcher effort. As intra-seasonal agricultural water management becomes more important as a response to water scarcity arising from climate change or other factors, such an effort may be worthwhile.

Section 3.1: Introduction

Agricultural sciences and agro-economics became invested in generating crop-yield functions as a way to analyze optimal yields when researchers decided that as crop physical inputs were choice variables and not fixed, they should be handled accordingly. Clearly, water available to the plant is of fundamental importance and cannot be excluded from accurate crop-yield functions. This is particularly true in arid environments where water can potentially be a limiting factor in plant growth. Frequently following limited water availability is salinization, and subsequently decreased yields. Traditionally, water in excess of the plant's needs was applied to the field in an attempt to leach the salts away from the root zone and minimize salinity impacts on the plant, and therefore yield. This approach has two main issues--the first is that arid environments often do not provide enough water for this procedure. The second is that the salts cannot simply disappear, and will end up in groundwater systems. When there is insufficient water for salt leaching, the plant will have to contend with root zone salinity, as they will when provided with saline groundwater.

Accordingly, thorough agro-economic analyses of regions and areas with salinity concerns began to include salinity-related yield impacts. Such seminal pieces of research include Letey, Knapp, and Dinar (1985)'s analysis of salinity by combining a linear relationship between yield and evapotranspiration, Maas and Hoffman (1977)'s classic piece-wise linear relationship between yield and root zone salinity, and Raats (1974)'s relationship between irrigation water salinity and soil salinity in their yield function, which is dependent on a number of crop-specific variables. Using Letey, Knapp, and Dinar (1985)'s work, Letey and Dinar (1986) produced crop-specific production functions using published crop-specific variables, and showed agreement between field data and their results. Kan et al. (2002) continued this work with the inclusion of van Genuchten and Hoffman (1984)'s continuous s-shaped relationship between yield, available water, and salinity, while still utilizing salinity coefficients for various crops given in Maas and Hoffman (1977) and Maas (1991).[25] Including a spatial density function for irrigation infiltration coefficients, they were able to account for nonuniformity at the field level using the plant-level detail described above. They also generated crop-specific variables for use in their yield functions (as discussed in more detail in Section 3.2).

Wang and Baerenklau (2014), alternatively, takes a detour from these previous studies by incorporating the use of HYDRUS-1D [26] (Simunek et al., 2008), a soil water/solute transport software, which allowed the authors to

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[25] This approach was also used in Schwabe et al. (2006) and Schwabe and Knapp (2014).

[26] This approach was also used in Wang (2012).

include three variables in there yield functions: applied water, applied nitrogen, and salinity of applied water. Also incorporating van Genuchten and Hoffman (1984)'s and Maas and Hoffman (1977)'s crop growth-salinity relationships, HYDRUS requires climate, crop, and soil data, and is process-based, iteratively solving the Richards equation[27] (as discussed in more detail in Section 3.2). HYDRUS, therefore, allows for a higher level of specificity.

By including HYDRUS, which has merits for its computational capabilities alone, the authors were able to include nitrogen as an input in their final crop-yield functions. Such an addition was a unique and important extension to the literature given nitrogen is necessary for plant growth and is the main fertilizer component (and a significant environmental pollutant). Its inclusion provides for potential environmental impact analyses to be linked to the yield functions, and brings yield functions in bio-economics closer to the methodologies used in other agro-sciences (Ayars, 2013, and Hutmacher, 2013), which may become more important as the probability of water scarcity increases.

While the Kan et al. (2002) work does not address nitrogen, it does include deep percolation--or the water neither transpired nor evaporated. This allows for analyses that address groundwater and drainage water management,

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[27] The Richards equation is a partial differential equation that represents water movement in unsaturated soil. It has no closed form solution.

as well as allows one to keep track of water table levels more accurately, which is of particular importance in arid environments facing water scarcity and salinization and which overlay aquifers.

While there is a desire to make crop-yield functions as accurate as possible, there is also a push to make them repeatable and usable. These somewhat conflicting preferences have generated a continuum in the literature between programming-intensive process-based simulation models (e.g. Wang, 2012), which provide a high degree of accuracy, but are time-intensive and more difficult to recreate, and analytical functions (e.g. Kan et al., 2002), which may capture fewer characteristics of the problem, which often make them less flexible, but are more usable and more able to be included in agro- or bio-economic regional models.[28] The degree to which one approach is preferred to another is a function of what is lost and gained by incorporating one approach relative to another. For researchers wondering which approach to adopt, it is important to understand how well each approach compares to one another and captures (or doesn't capture) important characteristics of the specific problem, as well as to determine exactly what information is desired.

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[28] For a detailed discussion of this issue, see Skaggs et al. (2014) and Wang and Baerenklau (2014).

The objectives of this research are to build up and extend this earlier research by further developing upon the research of Wang (2012). In particular, we create yield functions that are functions of salinity and nitrogen, in a manner similar to that of Wang and Baerenklau (2014), but also incorporate instantaneous yield reductions, irrigation method-specific evaporation rates, and year-specific climate data.[29] Including instantaneous yield reductions increases realism without significantly altering workload. It also allows different irrigation timing methods to be examined more accurately for the same irrigation technology. By allowing for year-specific climate data, we allow the model to be tailored to a specific time and place. We are also able to create water uptake functions, which allow us to generate deep percolation functions that adhere to water balance similar to Kan et al. (2002). Given increasing attention to groundwater resources, the implications of crop-water production modeling on the representation of deep percolation flows to the aquifer have obvious importance.

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[29] This is not the first agro-economic analysis to include daily changes. Dinar et al. (1986) generated cotton yield functions by first estimating daily ET from field data on pan evaporation, soil water content, and soil salinity, then estimating ET dependent yield functions. Muralidharan and Knapp (2009) calculate optimal applied water amounts for a fixed irrigation schedule by including daily ET functions that are dependent on soil moisture and maximum potential ET. Muralidiharan and Knapp (2009) do not consider salinity, but do make a distinction between plant-and field-level by including field-level spatial variability, much like in Kan et al. (2002).

To illustrate the implications of the extension provided in this paper, we show the flexibility and potential use of our model in Section 3.3, the development of which is shown in Section 3.2, Section 3.3 includes analyses on different irrigation timing systems, deep percolation, and seasonal variations. In Section 3.4, we show a comparison of our model with that of Kan et al. (2002) and Wang and Baerenklau (2014) for the relationship between crop yield and applied water for two different crops and two different irrigation systems under alternative salinity concentrations. Conclusions regarding the applicability of our model, as well as how the choice of model matters are discussed in Section V.

Section 3.2: Modeling Techniques:

Our model is most directly related to that of Wang and Baerenklau (2014), though it shares similarities with that of Kan et al. (2002) as well. In this section, we summarize the models of Kan et al. (2002), Wang and Baerenklau (2014), and this research.

3.2.1 Kan et al. (2002): *The Letey Model*

The Letey Model develops yield equations that are functions of crop type, irrigation system, applied water, and applied water salinity. To do this Kan et al. (2002) perform a two-step process: a data generation step and a response function generation step.

In the first step, they use a steady-state seasonal model to estimate evapotranspiration and yield as a function of water, salinity, and maximum evapotranspiration. This model has no closed-form solution. Field-level results are generated by assuming a spatial distribution function of applied water over the field (accounting for irrigation nonuniformity). Applied water, along with salinity, are inputs of their plant-level vegetative yield response, which is dependent on plant-level evapotranspiration. Using published parameter rates (Table 3-1), this steady-state model generates sets of data of applied water, salinity of irrigation water, actual evapotranspiration, and yield data for different non-uniform application rates. Consequently, the authors end up with a data set for each crop-irrigation system combination.

In the second step, the authors fit response functions to each data set. Assuming functional forms consistent with the agronomic and crop science literature (Letey and Dinar, 1985; van Genuchten and Hoffman, 1984), they generate a crop-water-salinity production function for each crop-irrigation system combination though nonlinear regression analysis, which provides the necessary estimated coefficients.[30] These functions can then be imported into

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[30] The Letey Model coefficients, therefore, are for field-level yield, which has accounted for irrigation nonuniformity. In Wang (2012), nonuniformity is included, much the same way, prior to the use ofthererelative yield functions in an economic model. However, as we are concerned

their agro-economic analyses. Finally, and somewhat uniquely and importantly, The Letey Model generates deep percolation as the difference between water uptake (evapotranspiration) and applied water.

3.2.2 Wang and Baerenklau (2014): *The Wang Model*

The Wang Model also employs a two-step process of fitting generated data to analytical functions. For five levels of applied water (25 to 200% max evapotranspiration), applied nitrogen (25 to 200% max nitrogen uptake), and six levels of salinity (0 to 100% maximum plant salinity tolerance), the authors use HYDRUS[31] to estimate water uptake and nitrogen uptake over the season. Max evapotranspiration is calculated using mean seasonal ET_0 and the crop coefficient, and this is inputted into HYDRUS as transpiration. Mean crop evapotranspiration was estimated with CIMIS mean monthly reference crop evapotranspiration and FAO single crop coefficients. No soil evaporation was included.[32] Daily nitrogen potential uptake was inputted as total potential

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solely with yield in this paper, we have not included there nonuniformity treatment, not have we addressed nonuniformity in the current model.

[31] HYDRUS uses the same Maas and Hoffman (1983) salinity relationships as Kan et al. (2002).

[32] HYDRUS allows for separate transpiration and evaporation inputs, both of which the current model uses. Wang calculated potential evapotranspiration and included this as the transpiration input, leaving soil evaporation as zero. Soil evaporation varies with irrigation systems. As potential transpiration is the same regardless of irrigation system, different irrigation systems will not produce different results when the same irrigation timing is used if there is no evaporation included.

nitrogen uptake divided by season days.[33] For each crop-irrigation system, then, the Wang Model runs HYDRUS 150 times.

HYDRUS outputs data on water and nitrogen uptake through the season. Actual total water uptake over the season is compared with potential total seasonal uptake. Likewise, actual total nitrogen uptake over the season is compared with potential total nitrogen uptake. These two ratios are compared. Whichever is smaller is considered to be the limiting factor and is assumed to equal relative yield. Wang takes these relative yield data, along with their respective water, nitrogen, and salinity inputs and runs regressions to estimate the parameters of a published yield functional form. The yield functions with these generated parameters can then be used in agro-economic models.

3.2.3 Current Model

The methodology presented here follows that of Wang and Baerenklau (2014), but instead of seasonal yield reductions, instantaneous yield reductions throughout the growing season are used.[34] Consequently, this means that throughout the growing season, nitrogen or water, whichever is the limiting

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[33] This is the same nitrogen treatment employed here. If one were to tailor potential nitrogen uptake to specific plant growth cycles, more accuracy could be achieved.

[34] To avoid the need to manually input data into HYDRUS for each run, Matlab code was written to run HYDRUS in a loop. This can also be done with Python and other programs. This adjustment allows one to save significant time when altering inputs and running HYDRUS repeatedly.

factor at any particular time, will reduce the potential relative yield accordingly. This is a more accurate representation of how plants grow. As an example, a plant given a certain amount of water all in the last day of its growing season cannot possibly obtain the same relative yield as a plant given the same amount of water spread throughout the season. This additional specificity opens the analysis up to include changing the distribution of irrigation applications for a given irrigation technology as well as accounting for seasonal variation in climate. The importance and flexibility of allowing for intra-seasonal differences in irrigation application for the same irrigation technology will be given below.

Deep percolation, meanwhile, is calculated by a process similar to that of yield. Data of seasonal water uptake (the integration of instantaneous water uptake throughout the season) and actual evaporation are generated by HYDRUS at the same time the data for relative yield is generated. This data is examined for functional form, and then it is fit to analytical functions of that form, generating appropriate parameters.[35]

Similar to the definition of the Letey Model, our definition of deep percolation is the difference between the sum of water uptake (transpiration) and

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[35] HYDRUS provides this information, and then we fit functions that are dependent on salinity and applied water.

evaporation and the sum of precipitation and applied water.[36] See Appendix 2.B for more information on deep percolation function generation.

Potential daily water uptake was assumed to equal potential daily crop transpiration. Individual years' climate data were included, which accounts for precipitation. For this particular analysis, data from 2011 in Five Points, CA was used.

The FAO procedure for estimating transpiration and soil evaporation separately was used with CIMIS and FAO data and parameters. For a given season, a crop's potential transpiration remains the same with different irrigation systems, but potential soil evaporation changes.[37] Daily nitrogen potential uptake was inputted as total potential nitrogen uptake divided by season days.

3.2.4 Summary of Model Differences

The main difference between the models is that Kan et al (2002)'s analytical functions are fitted to data simulated from a steady-state seasonal process model, whereas in Wang and Baerenklau (2014) and the current analysis, functions are fit to data simulated with HYDRUS-1D[38] and, therefore, do not represent steady-

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[36] We assume there is no change in soil profile storage.

[37] Potential transpiration changes when climate data changes. Because we are using relative water uptake as part of our proxy for relative yield, this may necessitate varying levels of potential maximum yield.

[38] More details and equations for all three models are provided in Appendix 4-A.

state solutions. Due to the nature of the methodologies, the models all require different inputs--the Letey Model the fewest, and the current model the most (Table 3-1).

The current model uses instantaneous yield reductions instead of the seasonal yield reductions used in Wang and Baerenklau (2014). Other important distinctions between the current model and the Wang and Baerenklau (2014) model are the use of daily data instead of mean data, use of transpiration instead of evapotranspiration as a proxy for water uptake[39], inclusion of evaporation data, inclusion of specific climate data, and generation of water uptake functions, which allow for deep percolation functions to be formed.

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[39] All models employ functions with water uptake as a variable. Kan et al (2002) and Wang (2012) assume water uptake is equal to ET. We assume water uptake is equal to transpiration.

Table 3- 1: Required Variables

Crop & Irrigation	**Kan et al. (2002)**	**Wang (2012)**	**Current Research**
Salinity Parameters	✓	✓	✓
Maximum Yield	✓	✓	✓
Minium ET	✓		
Maximum ET	✓		
Rooting Depth		✓	✓
Maximum Nitrogen		✓	✓
Kc		✓	
Initial Stage Kctab			✓
Development Stage Kctab			✓
Final Stage Kctab			✓
Nitrogen Uptake		✓	✓
Max Plant Height			✓
Evaporation Coefficient (Kr)			✓
Irrigation Schedule		✓	✓
Infiltration Coefficients	✓		
Climate			
Mean ET0		✓	
Daily ET0			✓
Daily Wind Speed			✓
Daily Precipitation			✓
Daily Min Humidity			✓
Soil			
Type		✓	✓
Profile Depth		✓	✓

Section 3.3: Current Model Validity and Analytics

Here we provide some model validity evidence by comparing results from the current model with field-level data. Then, we provide an illustration of the flexibility such a model provides in capturing additional management and biophysical elements of the problem. Specifically, we illustrate how relative yield changes with 1) different years and their respective climates[40] and 2) different irrigation timing for the same irrigation system, and how those same differences affect water uptake and deep percolation flows.[41]

3.3.1 Field Data Comparison

For perspective, the current model was compared with field measured tomato crop data. In Malash et al. (2008), field tomatoes in El-Kom, Egypt[42] were watered with three different levels of saline water (0.55 dS/m, 3 dS/m, and 4 dS/m), using both drip and furrow irrigation. The 0.55 dS/m and 4 dS/m trials were watered only with water of their respective salinity level. The 3 dS/m trials consisted of 40% 0.55 dS/m water and 60% 4 dS/m water. These trials were produced with both cyclical water applications (0.55 dS/m, then 4.5 dS/m) and

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[40] We could also examine different areas with different soil types. All runs in this paper assume biophysical characteristics present at Five Points, CA with a loam soil

[41] For all results in this section, as well as Section 3.4, we set applied nitrogen equal to the max level. Max N uptake is 171 kg for tomatoes and 280 kg for wheat.

[42] EL-Kom is located at about 30.5 North. Five Points is at about 36.4 North.

blended. The watering schedule and amounts were based on water content of the soil, but the exact amounts and dates of irrigation events were not provided.[43] Results that were given included fruit yield per plant (kg) and water use efficiency (kg/m^3).

We attempted to reproduce their experiments, but with climate date from Five Points in 2011. For comparison purposes and given their results were in kilos, and ours were in relative yield terms, we set the median yield results of each equal to one another.

Figure 3-1 presents the results from Malash et al. (2008) in relative yield terms, and our own results for the different scenarios analyzed by Malash et al. (2008). As shown in Figure 3-1, for six of the eight scenarios, our model provides higher relative yield estimates than those presented in Malash et al. (2008). For the other two scenarios, our model provides a slightly lower estimate (Drip 0.55 dS/m) and a similar estimate (Drip 3 dS/m Cycle).

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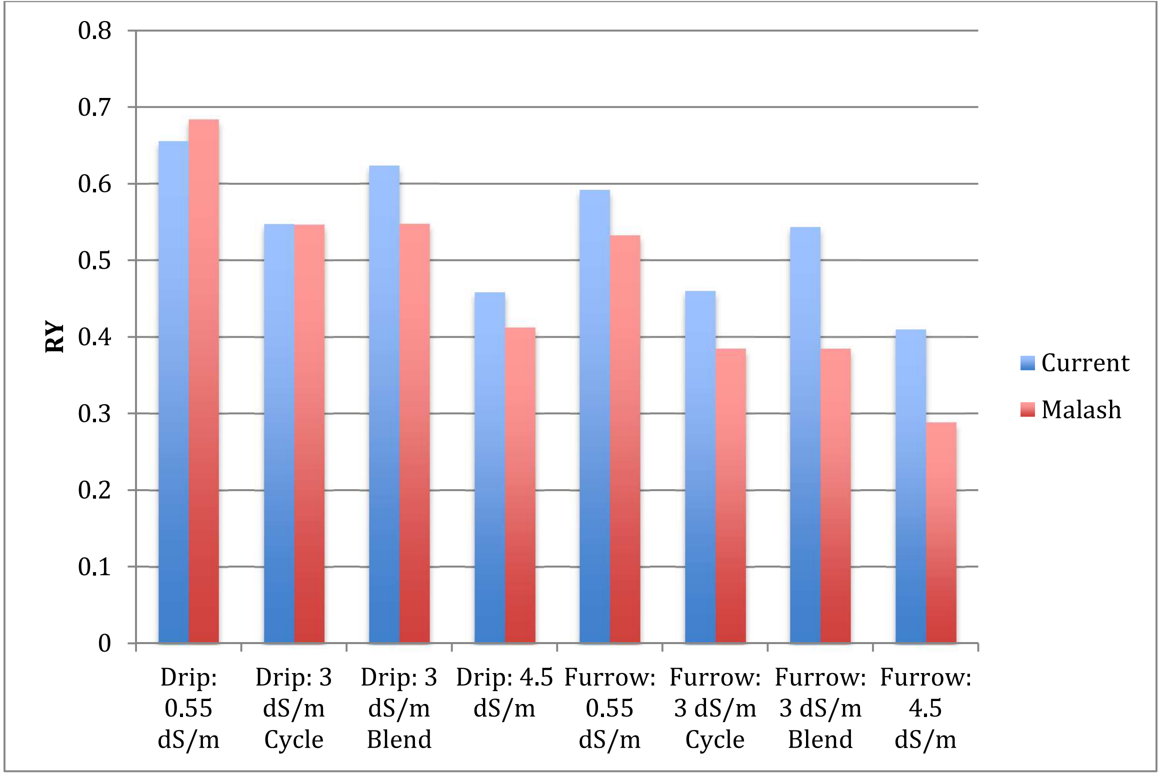
[43] It appears as though water is available to farmers cyclically in that region. So, they may have water for between five and ten days, then have no water for five to ten days. Malash et al. (2008) did not provide information about exactly how often farmers watered the crops.

While the differences are not great, and likely due to differences in climate variability and irrigation scheduling (which was not provided), one does observe a qualitative similarity. That is, if one were to rank the trials by the magnitude of yield results, those rankings would be exact ordinally across the two models.[44]

Figure 3- 1: **Malash et al. (2008) vs. Current Model (2011 data)**



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[44] Two sets of two trials of Malash et al. (2008) produced the same yields. We set these pairs in the rankings together and what we claim holds.

3.3.2 Relative Yield Differences due to Yearly Climate Changes

To investigate how different climate-related characteristics influence relative yield, we downloaded climate data from CIMIS for the years 2006, 2011, and 2014. The particular climate-related parameters we chose to include are daily reference evapotranspiration, humidity, wind speed, and precipitation. Daily and cumulative precipitation is shown in Figures 3-2 and 3-3, respectively. From wettest to driest, the years are 2006, 2011, and 2014.

The crop-irrigation system use for this analysis is tomatoes irrigated with a drip system (See Table 3-2 for salinity coefficients). For the three years we have identified potential transpiration for tomatoes, which is presented in Figure 3-4. The shape of the curve mirrors the growth curve of tomatoes. The initial stage lasts until about 35 days, after which growth occurs the fastest until day 75. While higher precipitation translates into more water for the plant, it does not constitute an extremely high percent of the crop's transpiration--roughly 6% for 2006 and 1% for 2014 [45] Higher ET_0 could also be due to lower humidity levels and higher temperatures. The results, shown in Figure 3-5, indicate that 2006 has the highest relative yield, followed by 2014, then 2011, which does not follow the relative total precipitation of the years. The differences between the yields

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[45] If this exercise were repeated with a crop and season where the precipitation to crop potential transpiration ratio were higher, total precipitation would likely be more significant.

diminish as salinity increases, but the ranking remains the same. Likely, the daily variability of the inputs was the main driver of these results, which would indicate that daily values are an important element to account for in the model.

Figure 3- 2: Daily Precipitation during Different Years

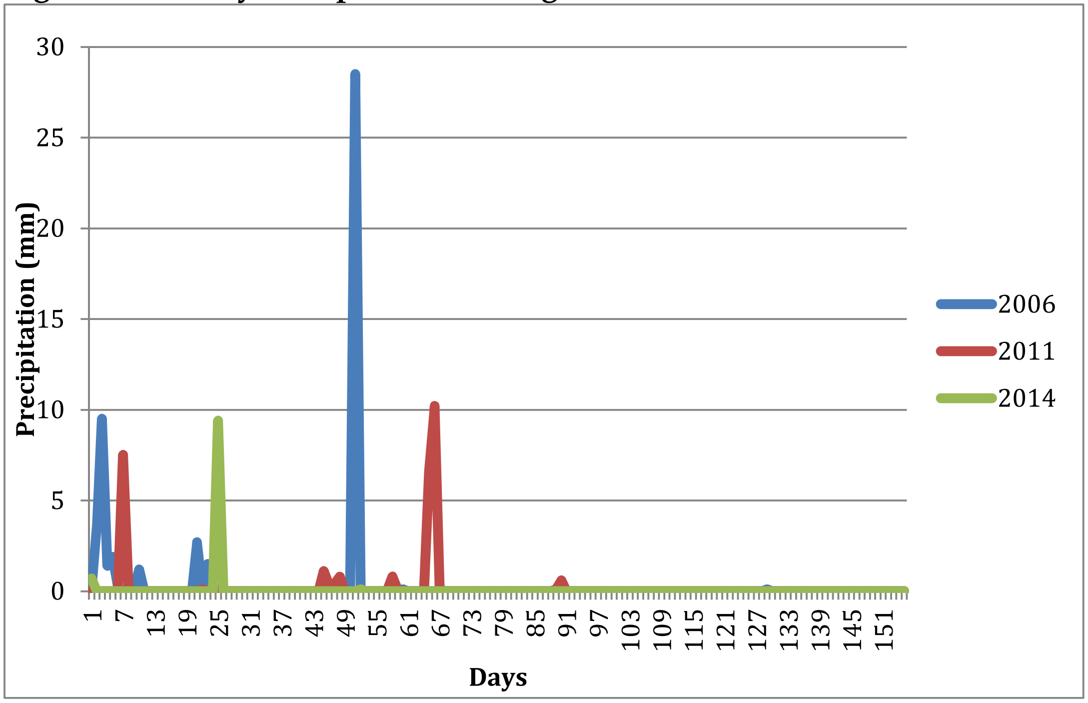


Figure 3- 3: Cumulative Precipitation for Different Years

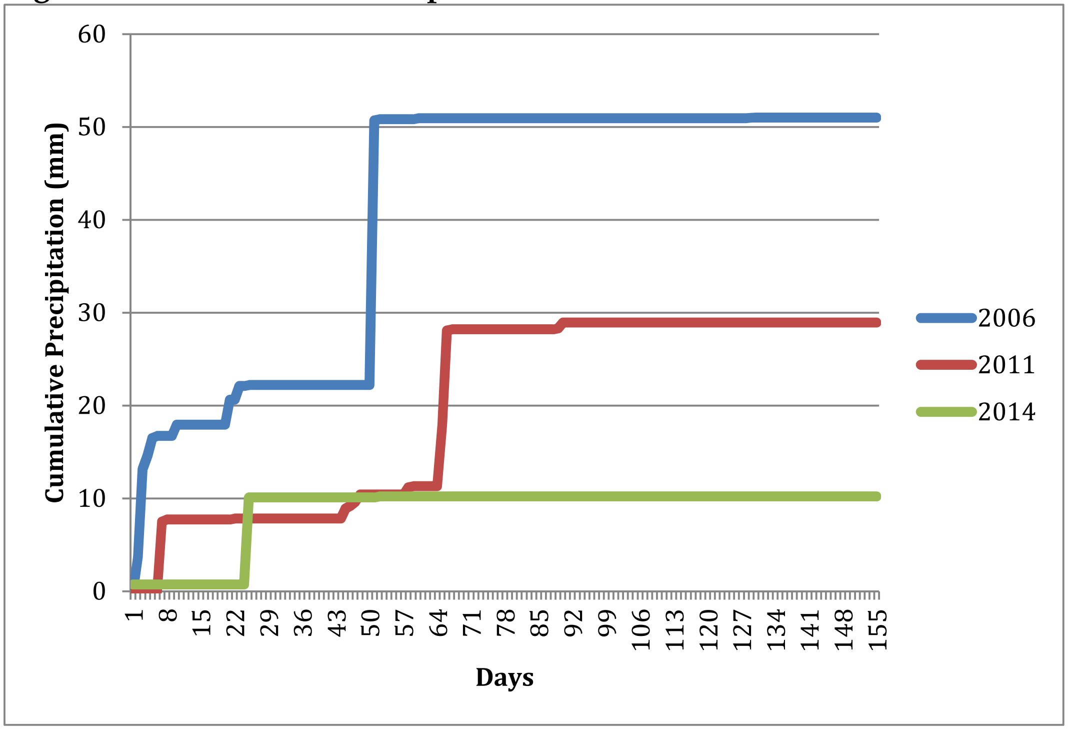
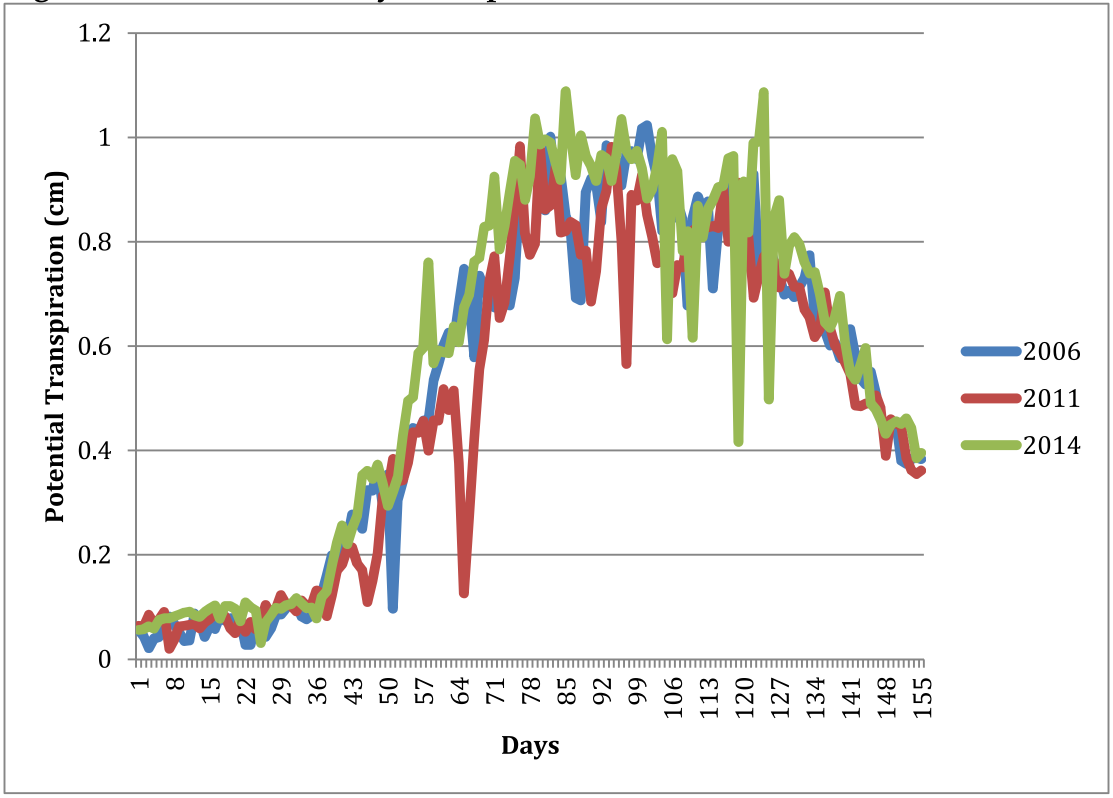


Figure 3- 4: Potential Daily Transpiration Across Different Years



3.3.3 Irrigation Timing as it Affects Relative Yield

As different irrigation timings can be evaluated with the current model, we have generated relative yield functions for tomatoes grown with three different intervals of furrow irrigation: 1 day, 10 days, and 20 days. The yearly data is from 2011. As shown in Figure 3-6, 10 day intervals produce the highest relative yields when deficit irrigation does not occur.[46] 1 day intervals have the highest

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[46] With low salinity, 1 day interval relative yield is virtually as high as 10 day interval relative yield when water is very high--about two times the potential transpiration, where both reach a plateau.

potential evaporation, affecting their efficacy. With more severe deficit irrigation (below 60 cm), the longest interval irrigation timing (20 days) produces the highest relative yield. This is likely also due to the effects of evaporation-potential evaporation decreases as irrigation interval length increases. 20 day intervals are shown to have lower potential evaporation. Even though more water will travel through the root zone, the lower potential evaporation has a larger effect when applied water is low (i.e. a high potential evaporation and low applied water means a higher percent of the water will evaporate). This is not as much of an issue when higher quantities of water are applied, as evaporation has less of an impact relative to the available water.

3.3.4 Deep Percolation

Deep percolation rates will vary according to irrigation timing, as deep percolation is a function of evaporation (which is dependent more on watering schedule, than on watering amounts)[47], water taken up by plants, applied water and precipitation (as described in Section 3.2 and Appendix 3.B). Potential evaporation does not vary across salinity levels. Actual evaporation does vary, as shown in Figure 3-7. The magnitude by which actual evaporation varies will depend on the plant water uptake (water uptake does vary with salinity). Actual

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[47] There are slight differences, but it does not significantly alter results. The important factor is when wetting of the soil occurs which does not depend on quantity, but timing.

evaporation is higher with higher salinity levels—plants take up less water, leaving more to evaporate (and drain). These differences decrease as watering amounts increase. With different irrigation intervals, potential evaporation rates change, and therefore actual evaporation rates will change significantly, as shown in Figure 3-8. When water is exposed to the atmosphere on fewer days (more days between irrigation events), the potential evaporation is lower.[48]

As shown in Figure 3-9, different irrigation intervals and salinity alter relative water uptake rates. RW, relative water uptake, is the ratio of actual water uptake to the potential water uptake (this is calculated similarly to relative yield and is described in Appendix 4.C). Salinity has a larger effect on water uptake rates than interval length. This is because salinity decreases water uptake due to osmosis effects. Relative water uptake is highest for the largest interval, 20 days, for lower water levels. Once applied water is greater than about 100 cm, relative water uptake is higher for the 10 day interval. At this point, applied water begins to be greater than potential evapotranspiration. Evaporation for 1 day interval is always higher than for 10 day interval, which may explain why it always has a lower water uptake (refer back to Figure 3-8).

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[48] Evaporation rates are not a function of nitrogen.

Water uptake, evaporation, and precipitation are all inputs of deep percolation, which is shown in Figure 3-10. A few trends are evidenced here. The first is that higher salinity levels produce higher deep percolation rates. This is because water uptake decreases with higher salinity levels. The second is that more frequent interval irrigation scheme produces lower deep percolation rates. This is due to the increased evaporation rates with more frequent interval schemes. Also, when more water is applied at larger intervals, some water infilitrates below the root zone. Perhaps the most important takeaway is that irrigation greatly affects deep percolation.

Figure 3- 5: Tomato Relative Yield Across Different Years and Salinity Levels with 10-day Interval Drip Irrigation

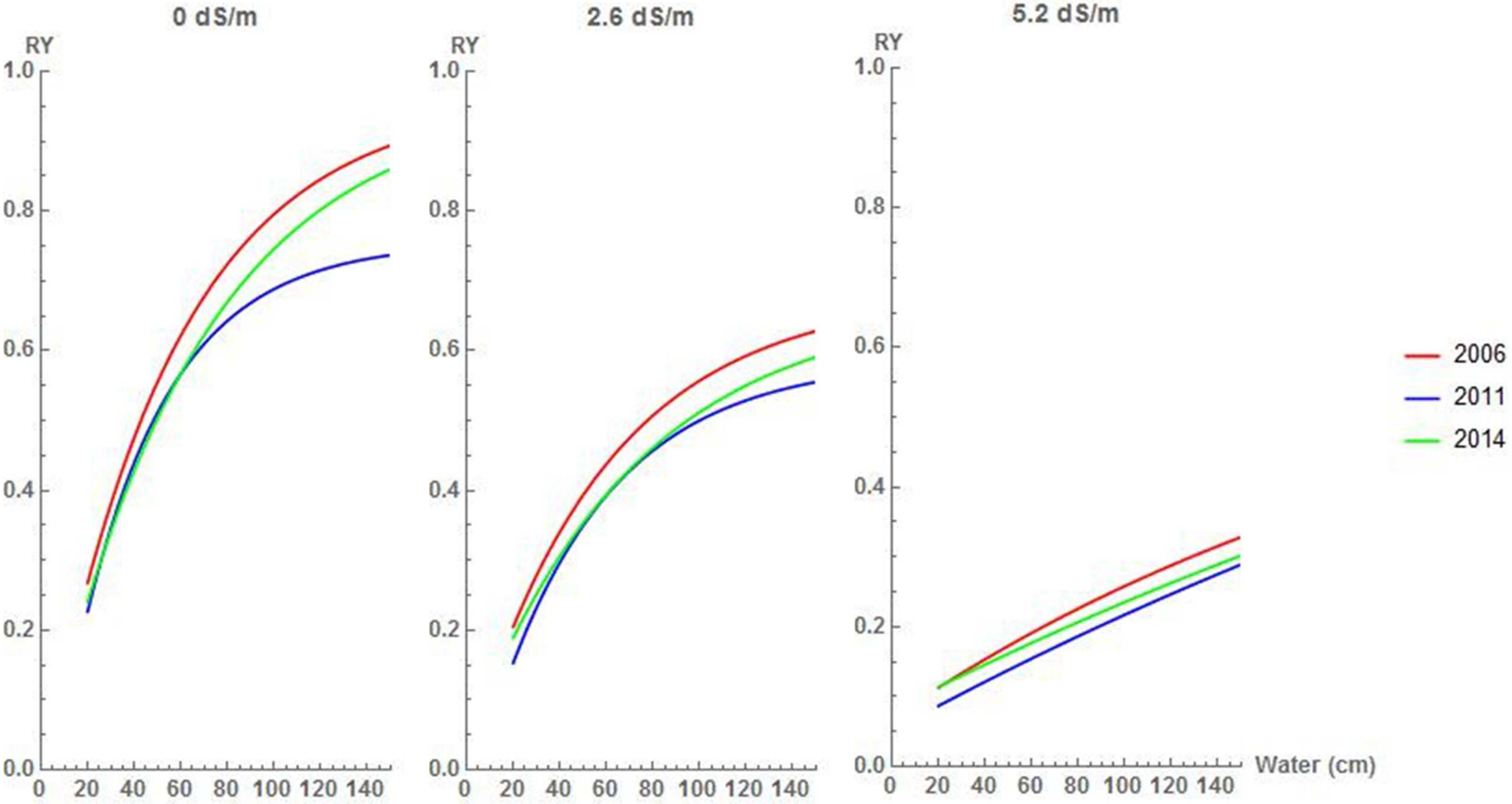


Figure 3- 6: Relative Yield of Tomatoes with Different Furrow Irrigation Timing across Different EC Levels with 2011 Data.

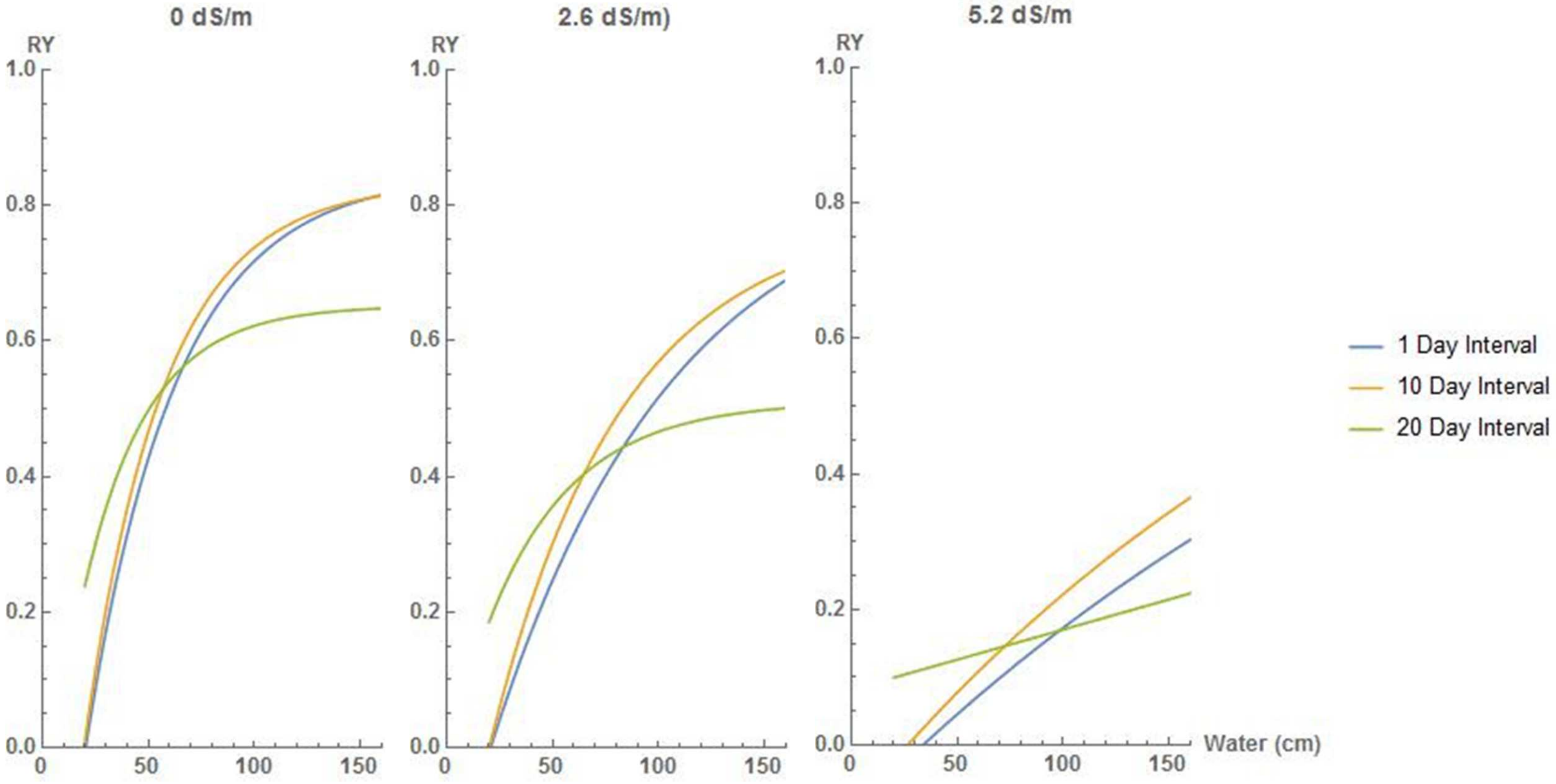


Figure 3- 7: Evaporation Rates at Different Salinity Levels with Furrow Irrigation and 2011 Data

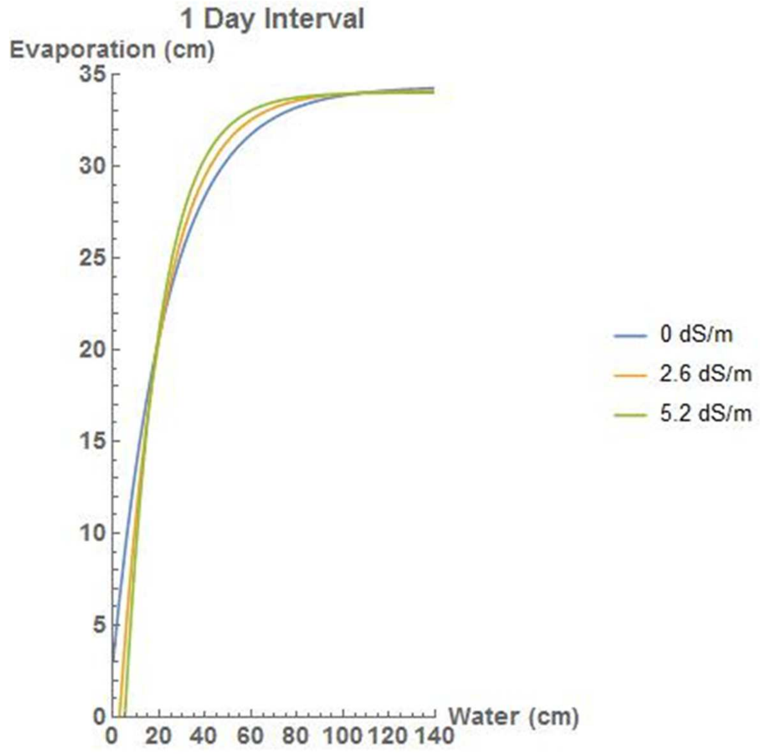


Figure 3- 8: Evaporation Rates at Different Intervals with Furrow Irrigation and 2011 Data

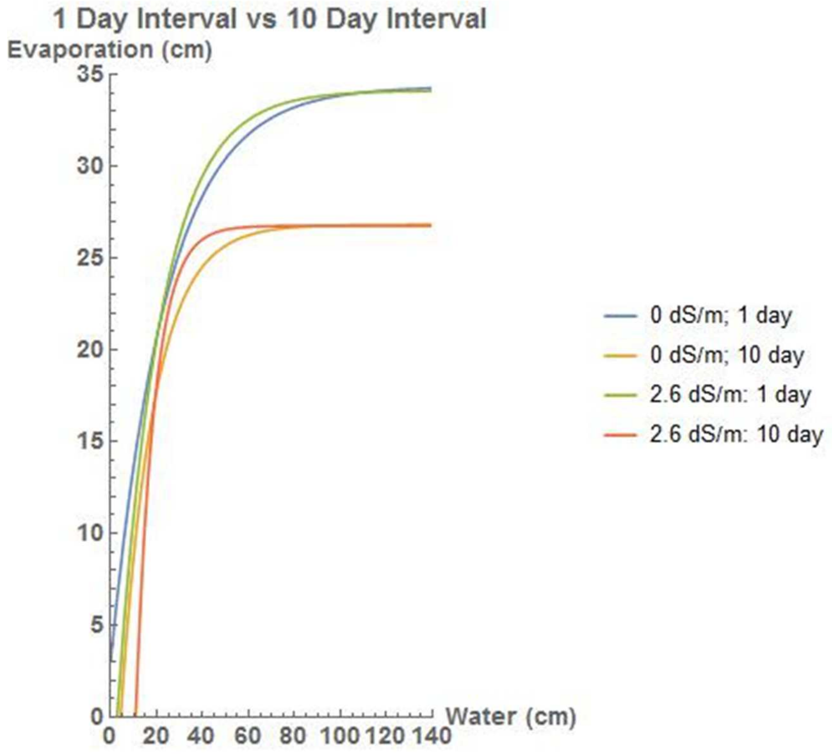


Figure 3- 9: Relative Water Uptake at Different Intervals and EC for Tomatoes Irrigated with Furrow and 2011 Data

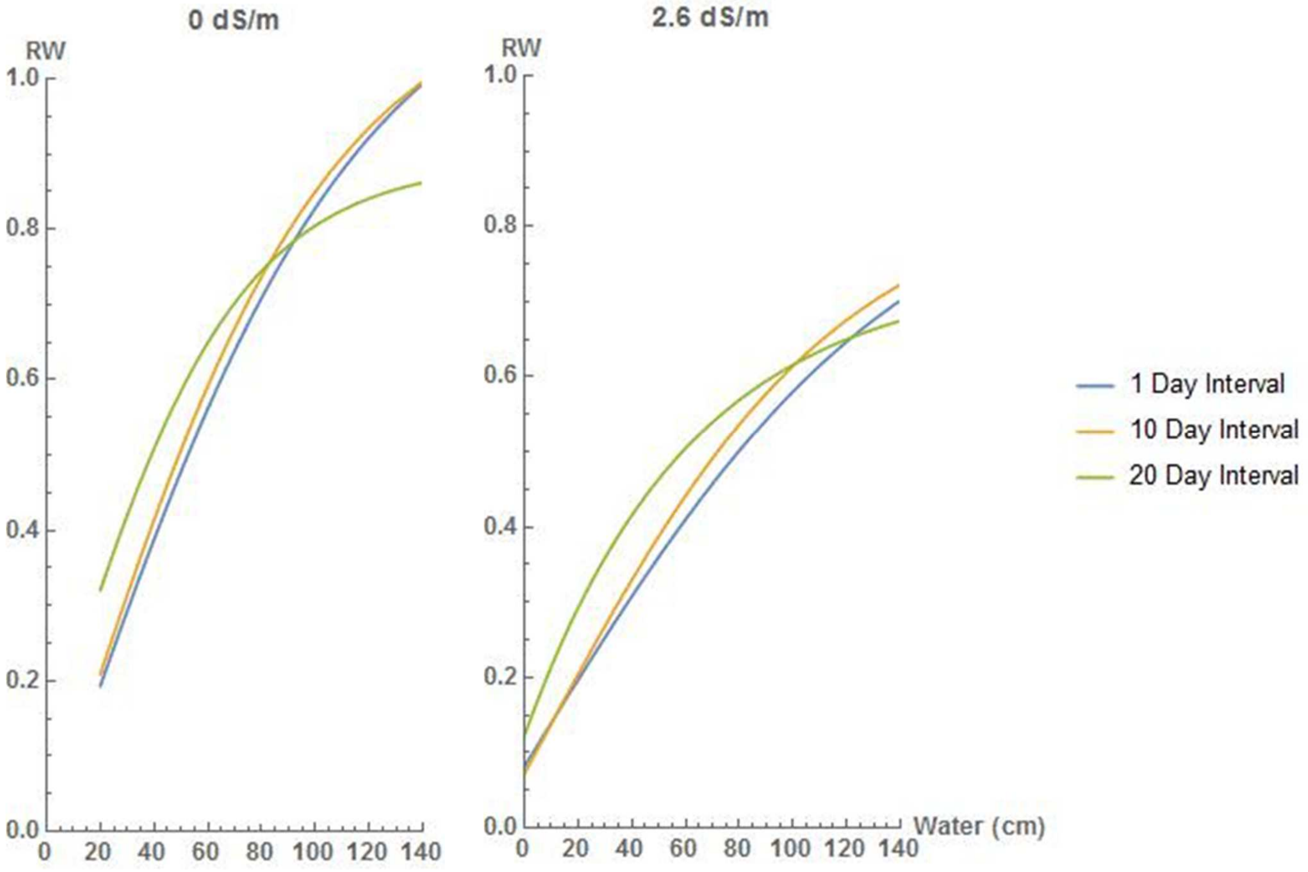
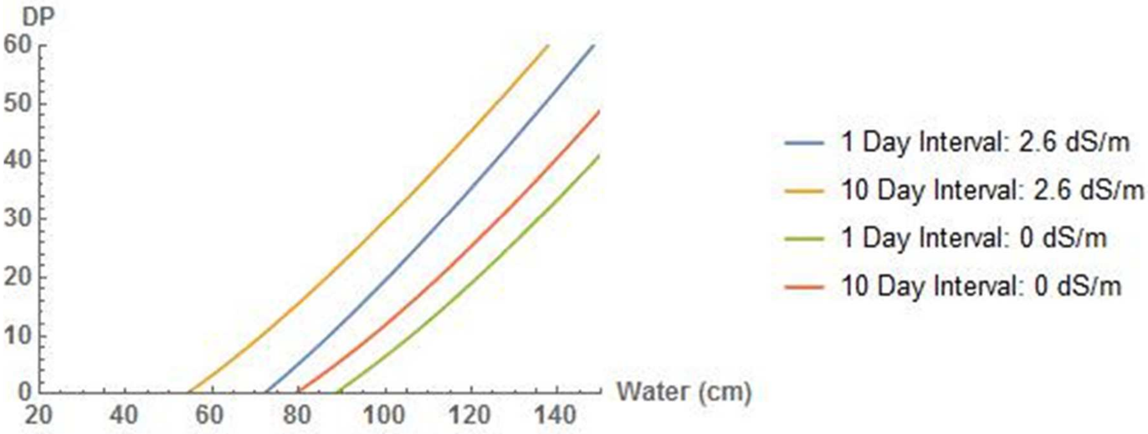


Figure 3- 10: Deep Percolation with Furrow Irrigation and 2011 Data



Section 3.4: Model Comparison:

In this section, we compare results between the current model, the Letey Model, and the Wang Model. The models have different data requirements and flexibility--generally, the more data required, the more flexibility, but also the more time commitment and specificity.

We use two crops for our comparison: tomato (*Solanum lycopersicum*) and wheat (*Triticum spp.).* Both are annual crops. Wheat is fairly salt tolerant and tomatoes are not. Wheat has a lower water requirement and is grown in the winter months, whereas tomatoes have a higher water requirement and are grown during the spring. Comparisons for both drip and furrow irrigation systems are included for tomatoes. Wheat is analyzed with furrow irrigation. See Table 3-2.

Table 3- 2: Maas Salinity Coefficients, Potential ET, T and E[49]

	Wheat	Tomatoes
(a) Threshold	6	2.5
(b) Slope	7.1	9.9
Max EC	20.085	12.601
Potential ET (Wang)	49.26	97.16
Potential ET (Letey)	46.91	60.02
Potential T (Current)	47.77	75.64
Potential E (Current)	11.22	27.51

For the comparison of the models in Section 3.4, we used the published yield and evapotranspiration functions of Kan et al. (2002) (Equations A1 and A2 in Appendix 3.A), as well as their estimated coefficients.[50]

While we use a version of HYDRUS that is modified for instantaneous yield reductions, the data can be aggregated to calculate total seasonal water uptake and total season nitrogen uptake as in the unmodified version in the manner adopted by the Wang Model. In terms of irrigation timing, the drip scheduling for tomatoes assumed an irrigation event once every ten days

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[49] Values for the current and Wang models are given from year 2011. For wheat, values are with 20 day furrow irrigation. For tomatoes, values are given for 10 day interval furrow irrigation.

[50] Permission was granted by Kurt Schwabe to use estimated coefficients (Schwabe, 2015).

following UC Davis Crop Return Study findings. For furrow scheduling of wheat and tomatoes, irrigation events were assumed to be once every twenty days, again, following UC Davis Crop Return Study findings.

Because the Wang and current models use relative yield and the Letey Model uses kilos, the maximum yield from the Letey Model was adjusted to be equal to the maximum relative yield of the Wang Model.

In Figure 3-11, relative yield results of furrowed wheat are seen from all three models. Wheat results are given for salinity levels of 0 dS/m, 4 dS/m, and 8 dS/m (wheat's max salintiy level 20.1 dS/m). Tomatoes, which have a max salinity level of 12.6 dS/m, are simulated with both furrow (Figure 3-12) and drip irrigation (Figure 3-13) with salinity levels of 0 dS/m, 2.6 dS/m, and 5.6 dS/m. The Wang and current models have a different shape than the Letey Model--a possibly logarithmic curve vs. a sigmoidal shape. The Letey Model has a steeper slope, indicating an increase in water causes a larger increase in yield.

For wheat, the Letey Model shows more sensitivity to deficit water--requiring more to produce yields. This effect is not as strong in the tomato figures. Wheat has a smalerl difference in ET between the two models, while tomatoes have a larger difference (see Table 3-2). The lower effective tomato water requirement for the Letey Model pushes it back towards the origin, making is more closely match the Wang and current models, and decreasing the apparent sensitivity effect.

Even more striking differences occur when the salinity is increased. While all three models tend to flatten as salinity increases (indicating a decreasing efficacy of water), the Letey Model is much less overall sensitive to salinity. The current model seems to be the most sensitive. In the Letey Model, high salinity levels can be combated, at least partially, by higher water levels (max RY for wheat 0 dS/m is ~0.90, max RY for wheat 8 dS/m is ~0.85). This trend is true for the Wang and current model with tomatoes, of both irrigation varieties, but not so for wheat. With wheat and 8 dS/m salinity, the Wang model reaches a plateau quickly, at around 15 cm of water. The current model actually decreases slightly as water in increases. The Wang model's steady relative yield is likely due to the linear relationship between salinity and yield (the highest relative yield in the 8 dS/m figure is right at 60% of the relative yield of 0 dS/m. 8 dS/m is 60% of wheat's maximum EC). The negative slope in the current model is probably due to two factors: the first is that fact that wheat receives about 50% of its maximum transpiration as precipitation, the second is nitrogen absorption. Nitrogen is delivered in the irrigation water. As such, when there is a constant nitrogen load, but less water, the water is more highly concentrated, which means that there may be more nitrogen polluted down the soil column as more water is applied. At any rate, the current model and the Wang model produce a much lower potential yield than the Letey Model when salinity is higher. The current model produces the lowest rates of all.

The differences between Figure 3-12 and Figure 3-13 also show us how the models predict yield rates changing with irrigation systems. As expected, furrow produces lower relative yield values than drip. We did include evaporation in the current model examples--a subsurface drip would decrease the potential evaporation amounts, which would enlarge the dichotomy of furrow and drip irrigation systems.

Overall, the Letey Model is less salt sensitive than the HYDRUS models. The current model produces lower results than the Wang Model and its results depend more heavily on daily inputs, due to the difference between instantaneous yield reductions and seasonal water vs. seasonal nitrogen uptake.

Figure 3- 11: Wheat Furrow Relative Yield Across Models and Salinity Levels (0, 4, and 8 dS/m) with 2011 Data

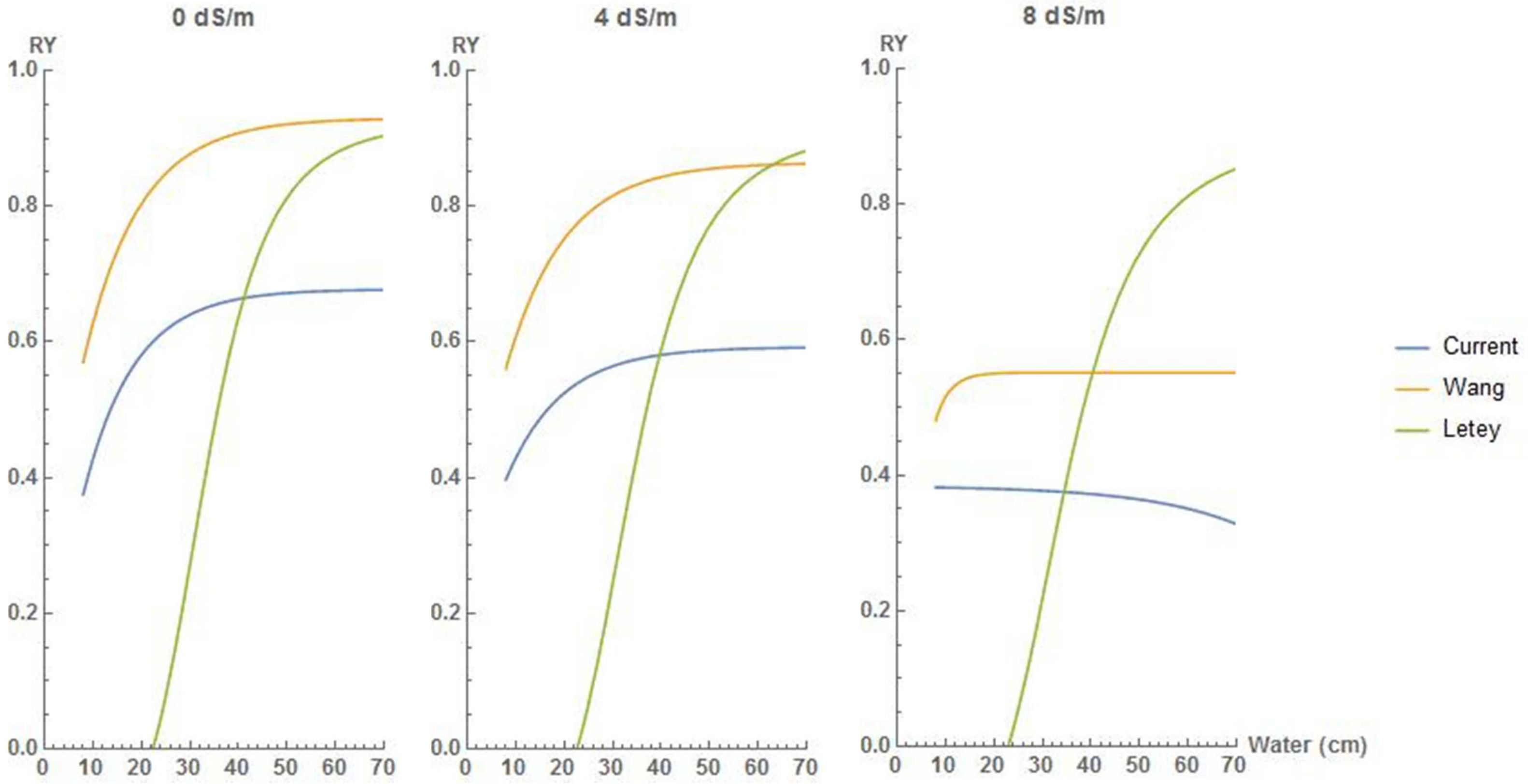


Figure 3- 12: Tomato Furrow Relative Yield Across Models and Salinity Levels (0, 2.6, and 5.2 dS/m) with 2011 Data

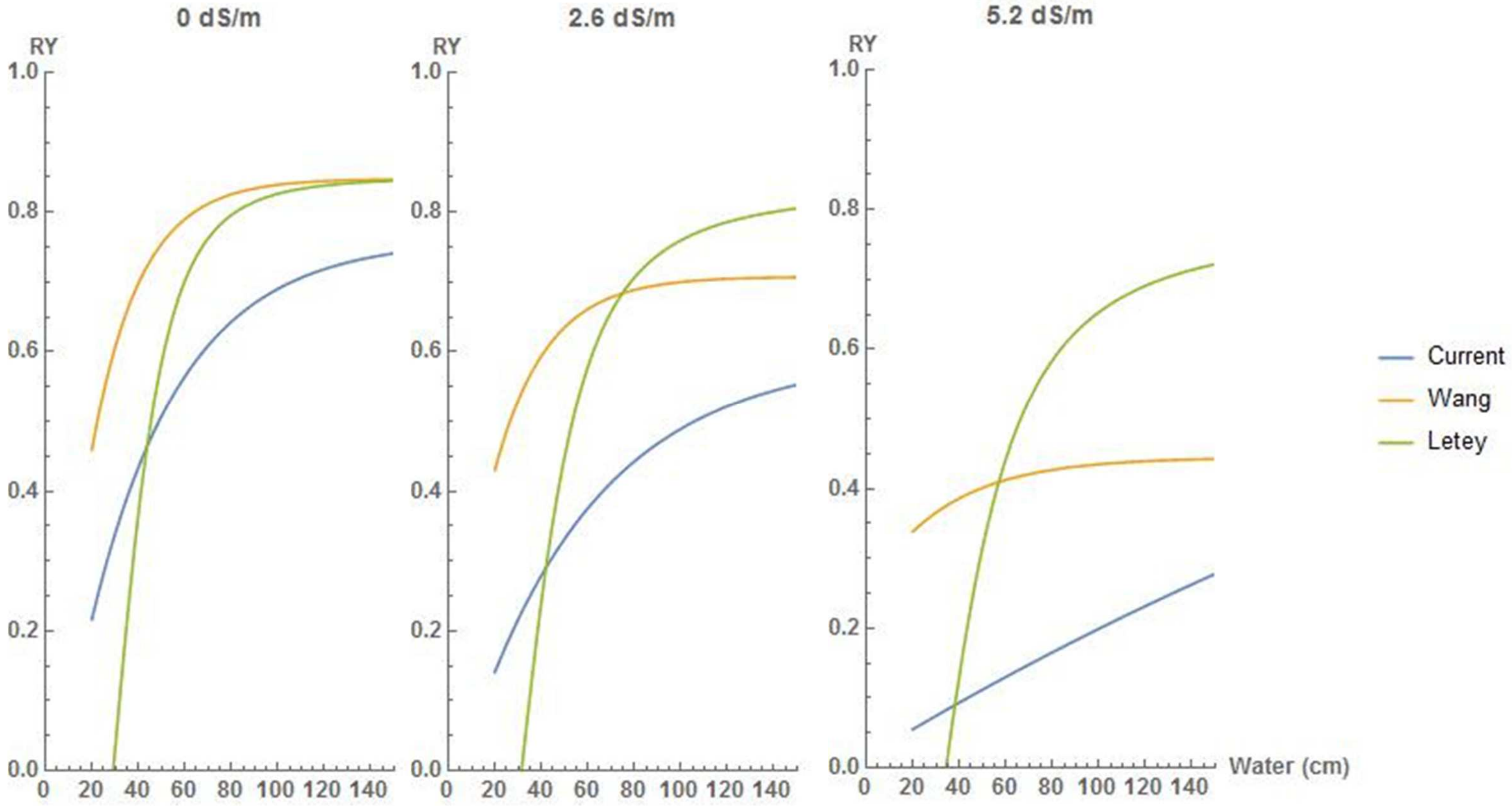
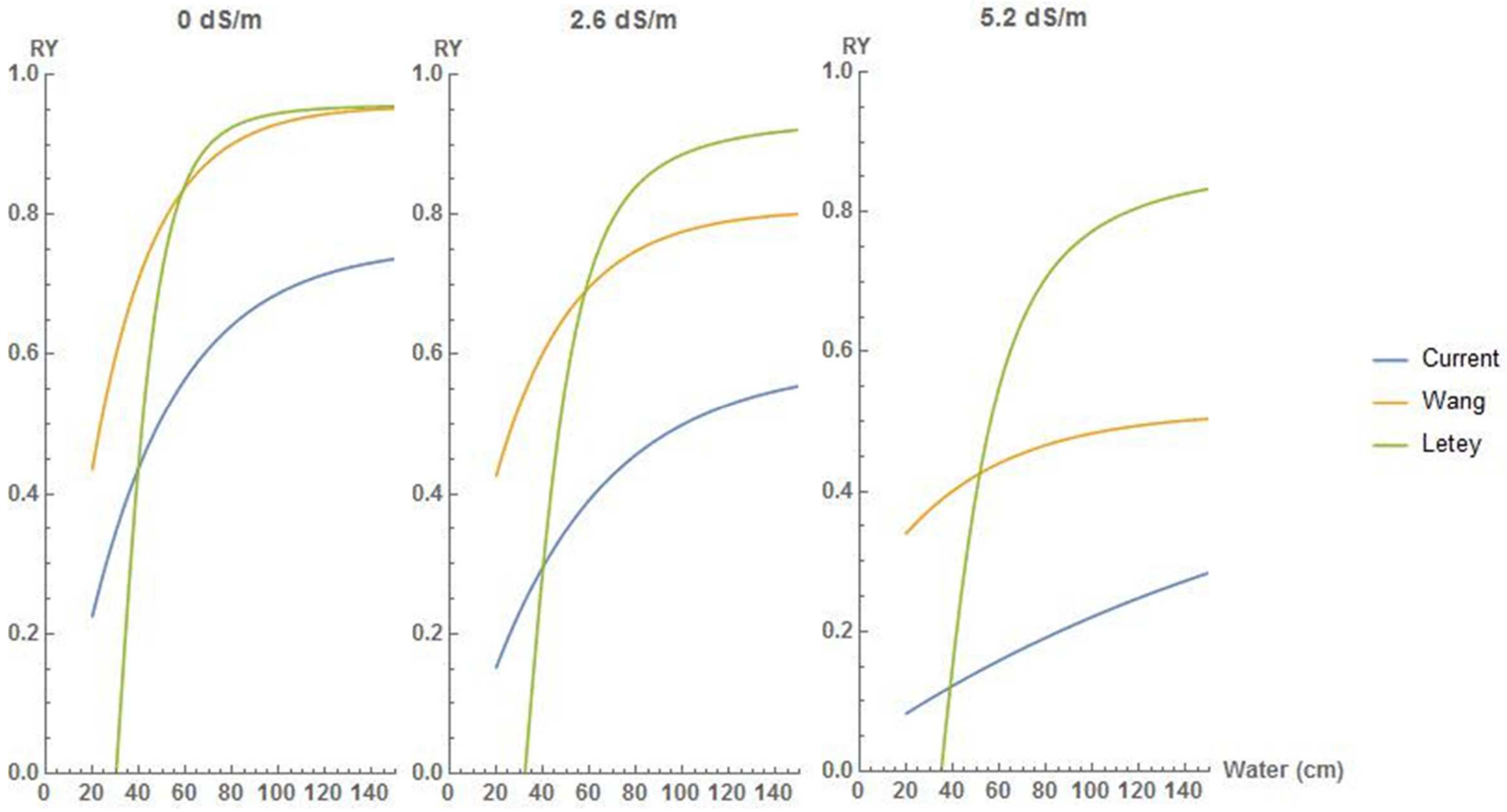


Figure 3- 13: Tomato Drip Relative Yield Across Models and Salinity Levels (0, 2.6, and 5.2 dS/m) with 2011 Data



Section 3.5: Conclusion

Following the agro-economic literature on salinity-water yield function generation, we develop a model that builds upon the models of Kan et al. (2002) and Wang and Baerenklau (2014). Using instantaneous yield reductions in HYDRUS, the current model has a high sensitivity for intra-seasonal data, and is therefore very flexible. The model, which matches field data well, can detect potential yield, water uptake, evaporation, and deep percolation[51] differences for different crops, of course, but also for climates, years, irrigation systems, and irrigation timing.

The Letey and Wang Models produce different results from the current model, which could have significant impacts were these models to be included in any bio-economic analysis or agro-economic optimization. The three models could produce similar results when water salinity is low and water levels are high (by ratcheting the relative yield values up or down to match field data). With the same inputs, the Wang and Levers models are similarly shaped, but the current model produces lower relative yield values due to its inclusion of instantaneous yield reductions and evaporation. At higher salinity levels, the HYDRUS models begin to differ more, again due to the current model's

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[51] Nitrogen released into the environment is also tracked, though we do not provide examples here.

instantaneous yield reductions, which pick up on crop specifics (like precipitation and transpiration), and may be more significant at higher salinity levels. Both the HYDRUS models are more salt sensitive than the Letey Model. The Letey Model consistently estimates higher relative yield levels with high salinity. This is likely because the model assumes that high salinity can be largely overcome with excess saline water (which may be more correct at lower salinity levels and is highly crop dependent).

The Letey Model does not account for precipitation, and has different potential evapotranspiration amounts, which is one reason why it produces lower relative levels at low water levels. This is particularly pronounced with wheat, which has a high seasonal precipitation to transpiration ratio.

However, none of this makes it clear which model is "better." The answer to that question lies in what the individual researcher is hoping to accomplish. Certainly, including more inputs like the current model requires a larger time investment, but the ability to program can diminish these requirements substantially.

If researchers were looking at long time horizons in a regional analysis and were interested in groundwater, the Letey Model may be a good choice even if the extra data and time were available, as the intra-seasonal information or specific climates/dates would possibly not be as important. Likewise, for long time horizons or non-specific years combined with an interest in nitrogen, the Wang Model may be preferable.

However, as salinization and drainage concerns heighten, the capability of the current model may prove useful when very specific irrigation methods and climate scenarios come into question.

Chapter 4: Bio-Economic Farm-Level Analysis of Growing *Brassica* as a Biodiesel Crop in the West-side of the San Joaquin Valley of California

Abstract 4:

Brassica[52], a salt-tolerant, phytoremediative, biofuel crop, is considered alongside wheat cultivation as part of an integrated farm drainage management (IFDM) system in the San Joaquin Valley (SJV), California. A bio-economic mathematical programming model of irrigated agricultural production with a nonlinear optimization framework is used to examine the role *Brassica* might play at the farm level in a drainage impaired region. The model is patterned after a SJV farm of 2000 hectares producing tomatoes (*Solanum lycopersicum*), almonds (*Prunis dulcis*), cotton (*Gossypium hirsutum*), lettuce (*Lactuca sativa*), and pistachios (*Pistacia vera)*. The drainage water produced by these crops can be used on two

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[52] The common names mustard and canola refer to several species and cultivars of Brassicacea, the mustard family. These include Indian mustard (*Brassica juncea*), white mustard (*Sinapis alba*, *B. alba*, or *B. hirta*), field mustard (*B. rapa*), and rapeseed (*B. napus*). Canola oil is typically produced from *B. rapa* or *B. napus*. Mustard, the condiment, is typically produced from *B.* juncea, *B. alba/B. hirta/S. alba*, or *B. nigra*. The seeds of all of these crops are similar in their oil content and biofuel potential. Production methods are similar; these crops will be treated the same in this analysis and collectively referred to as *Brassica*.

IFDM crops, *Brassica* or wheat (*Triticum* spp.); remaining drainage water can be disposed of via a solar evaporator or evaporation pond. Yield equations that are functions of irrigation scheme, water, nitrogen, season, and salinity are generated using Hydrus-1D, a soil water and solute transport software. Our findings illustrate that under reasonable assumptions regarding biophysical parameters representative of the region, *Brassica* production provides higher profits and greenhouse gas benefits than the cultivation of wheat or no IFDM crops, when land quality prevents the growth of higher-valued crops and drainage water salinity is high.

Section 4.1: Introduction

Throughout the world, salinization and rising water tables follow the arid land agricultural trifecta of saline soils, inadequate drainage outlets, and irrigation (Salt, 1988). The SJV, California's main agricultural region and the US's main fruit and vegetable producing region, exemplifies these concerns. The 450 km valley's geologic history left it with productive soils, as well as potentially toxic trace elements including Selenium (Se)[53]. Farming the SJV requires much more water than is naturally available, which led to extensive twentieth century waterworks construction and the title "Largest Human Alteration of the Earth's Surface" (Galloway, 1999).

Wide spread irrigation in the SJV combined with the region's natural characteristics have led to environmental degradation which affects wildlife habitat, soil productivity, and aquifer quality. Much research has been driven by these concerns (Chang, 2014). A promising approach to mitigate the negative environmental and agricultural impacts from farming in this region arising out of this research is called Integrated on-Farm Drainage Management (IFDM).

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[53] Se is a naturally occurring element in the soils of the SJV. Irrigation water can leach Se from the soils. Reuse of these waters can concentrate Se in the upper soil profile. Excessive Se causes severe symptoms, particularly in bird or aquatic species, most famously at Kesterson Reservoir in the early 1980s. Se laced drainage water resulted in embryotoxicosis, dead or deformed embryos, in many bird species. Over half of eared grebes' (*Podiceps nigricollis)* nest deaths were a consequence of excessive Se. (Levers and Kaffka, 2015; Ohlendorf, 1989).

IFDM is a system by which farmers produce higher-valued crops with fresh water on land that is less affected by salts and high saline (often polluted) water tables[54] (nonmarginal land), then use the saline drainage water from the nonmarginal land to produce salt tolerant crops on lower quality, more salt affected (marginal) land. In the SJV, marginal land is extensive and of sufficient impairment that the Bureau of Reclamation considers about 700,000 hectares (~30% of SJV agricultural land) fit for retirement.[55] As alternatives to retirement, as well as a manner in which to treat drainage water, IFDM researchers have suggested many different crops that can be grown with saline drainage water.[56] Preferably, growers would want to grow a crop that is salt tolerant enough to handle the salinity of the drainage water, capable of withstanding trace elements, and commercially viable.

One crop that has the potential to fulfill these requirements is *Brassica*. *Brassica* has a maximum salt tolerance of about 20 dS/m (typical drainage water is in the 5 to 10 dS/m range). It absorbs Se and is not sensitive to other local trace

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[54] These saline water tables often also contain toxic compounds from natural and anthropogenic sources.

[55] For a more thorough discussion of marginal land in California, see Levers and Kaffka (2015).

[56] IFDM crops include vegetables like asparagus (*Asparagus officialis*) and zucchini (*Cucurbita pepo*), forages like bermuda grass (*Cynodon dactylon*) and jose-tall wheatgrass (*Thinopyrum ponticum* or *Agropyron elongatum*), and halophytes like dwarf glasswort (*Salicornia bigelovii*) and salt grass (*Distichlis spicata*). Typically, as salt tolerance increases, market size decreases (Westside, 2005).

elements. The seeds from *Brassica* can be pressed to produce biodiesel, which can then replace fossil diesel on-farm and potentially provide both environmental benefits and reduced energy expenditures. The non-oil portion of the seed can be used to produce Se enriched meal or, with certain species, a sulfur rich biofumigant, either of which might generate revenue (Bañuelos, 2010).

Finally, and perhaps one of the more attractive elements of growing *Brassica*, and other crops for that matter, on the marginalized land in the SJV is that it does not compete with food crops for land. A significant concern regarding many biofuel crops is that they displace food crops, thereby putting additional pressure on scarce land resources to meet a rising global demand for food production. If *Brassica* were to be produced as part of an IFDM system on marginal land with drainage water, its biofuel could avoid the “Food vs. Fuel” dilemma simply by not being in direct competition with food crops for either land or water.

4.1.1 Objectives

The goals of this research are to investigate the role *Brassica* might play as an IFDM biofuel crop in a farm-level agricultural system. We examine farmers' incentives to grow *Brassica*, and potential energy production. We develop a bio-economic farm-level model of irrigated agricultural production of a representative farm within the SJV and evaluate the impacts of growing *Brassica* relative to growing other crops or land retirement.[57] The farm-level model includes two crop types and two water types—higher-valued crops that use low salinity imported water and IFDM crops that use high salinity drainage water. Our analysis evaluates profit-maximizing choices regarding crop allocations and water application rates. We compare farm-level profits in which *Brassica* is grown as an IFDM crop to alternatives that include growing wheat as an IFDM crop or growing no IFDM crops. Incorporating *Brassica* into a programming model of optimization has not been analyzed systematically within an IFDM setting.[58] We expand the literature by developing a farm-level model of an IFDM system, where the IFDM crop is not merely a drainage water sink, but also can serve to generate general farm-level profits and environmental benefits.

This work is similar to the analyses developed in Knapp et al. (1986), Posnikoff and Knapp (1996), Kan et al. (2002), and Schwabe et al. (2006), all of which use programming models to address drainage water issues. This analysis extends Kan et al. and Schwabe et al. through consideration of biofuels as a potential profitable and environmental friendly option within IFDM. Posnikoff

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[57] Land retirement has been proposed as a solution to salinization and overtaxation of the water supply by the Bureau of Reclamation. For discussion, see Levers and Kaffka (2015).

[58] An alternative to IFDM is to simply retire the land. For discussions on land retirement, see Levers and Kaffka (2015) and Erysian et al. (2005).

and Knapp (1996), meanwhile, developed a similar model, which included a biofuel crop—eucalyptus—that was irrigated with drainage water. Like here, water was not allowed to enter the groundwater system. Eucalyptus can potentially be used as a biofuel, though it cannot be processed on farm, and can instead be burned to produce electricity at off-farm facilities. As a perennial tree crop, eucalyptus is rather different from the annual *Brassica.*

4.1.2 Representative Farm

We use the Red Rock Ranch (RRR) in the SJV as our representative farm. RRR is approximately 2000 hectares, one quarter of which is impaired and considered marginal (Arroyo, 2012). The owner, John Diener, has partnered with the USDA-ARS Water Management Research Laboratory (WMRL) and California State University, Fresno, since 2005 to research a green process titled Selenium Phytoremediation. Selenium Phytoremediation involves the growth of crops like prickly pear cactus (*Opuntia ficus-indica*) and *Brassica*, both of which are saline tolerant and can uptake selenium. The growth of these types of plants is therefore remediative.

4.1.3 Brassica

The seed of *Brassica* can be broken down into two components: oil (40%) and meal (60%) (Bañuelos, 2012). The oil can be converted into biodiesel, and is one of the more efficient sources of bioenergy measured by net energy ratio (energy out vs energy in) (Fore et al., 2011; Hill et al., 2006).[59] The incorporated Se accumulates in the seed meal, not in the oil. Even though it is toxic at high doses, Se is a required nutritional element. Indeed, Se deficiency is a concern as it can lead to muscle weakness, pain, and cardiomyapathy in both human and non-human animals (Koller and Exon, 1986). The WMRL has identified a number of possible uses for Se-enriched canola seed meal, including as a feed additive for cows, chickens, and tilapia.

Brassica has an unpalatably high concentration of glucosinolates[60] in white mustard that make it incapable of being a source of edible meal, its seeds are can be used as a biofumigant in organic agriculture, particularly in higher-valued crops such as strawberries (Bañuelos and Hanson, 2010). These co-products, Se-enriched feed additive and glucosinolate-enriched biofumigant, provide additional income possibilities from growing *Brassica* relative to growing a non-biofuel crop for the purposes of disposing of saline drainage water. Price estimates were found for canola meal of around $0.40/kg and for organic mustard meal of around $2.00/kg (Boursier, 2012; Johnson, 2011; US Canola,

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[59] Biodiesel from canola has a net energy yield of over 11,000 MJ/ha and a net energy ratio of 1.88 (Fore, 2011). For comparison, corn ethanol has a net energy ratio of 1.25 (Hill et al., 2006).

[60] These are the organic compounds that give cruciferous vegetables their sulfurous flavor.

2014). Producing a biofumigant as opposed to meal for use in the meat and dairy industry may have some environmental and health benefits as well.[61]

4.1.4 Regulatory Considerations

The use of biofuels, and *Brassica* in particular, may facilitate producers' and agencies' efforts to meet both federal and state regulatory mandates. At the federal level, the Energy Policy Act of 2005 created the Renewable Fuel Standard (RFS) program that established a renewable fuel mandate, the first of its kind in the United States. The Environmental Protection Agency (EPA), which is responsible for implementing the RFS program, decreed that in 2013, 1.28 million gallons of biomass-based biodiesel shall be produced in the United States (Renewable, 2013).[62]

In California, Assembly Bill Number 32 (AB 32) tasks the California Air Resource Board with implementing the Low Carbon Fuel Standard (LCFS) program. LCFS requires the carbon load of transportation fuels that are sold, offered for sale, or supplied in California to be reduced by at minimum ten percent by 2020 (Assembly, 2013). Biofuels have been considered as part of the portfolio of strategies agencies are considering.

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[61] Meat and dairy production has been linked with nitrogen pollution, greenhouse gas emissions, and decreased health (Godfrey et al., 2010; Weber et al., 2008; Walker et al., 2005).

[62] The EPA is behind in setting the RFS. Compliance reports for 2013 were due in September of 2014. 2014 values have not yet been set (EPA, 2014).

Section 4.2. Framework

A farm-level analysis is performed through the development of a mathematical programming model of irrigated agricultural production with a nonlinear optimization framework using several software programs, including General Algebraic Modeling System (GAMS), Hydrus-1D, Matlab, and Mathematica. Crop-water production functions relating yield to crop type, irrigation scheme, season, water and nitrogen application rates/availability, and salinity are generated. The optimization model generates data on fuel use, water use, nitrogen outflows, carbon dioxide emissions, profit, and biofuel production.

4.2.1 Model Farm

Mirroring the study site, the model farm develop in this research is set to 2000 hectares. Higher valued crops, as shown in Table 4-1, include tomatoes (*Solanum lycopersicum*), almonds (*Prunis dulcis*), cotton (*Gossypium hirsutum*), lettuce (*Lactuca sativa*), and pistachios (*Pistacia vera)*, chosen out of crops that are regularly grown in the SJV and suitable for cultivation at the Red Rock Ranch.[63]

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[63] Crop choices were based on the County Agricultural Commission Annual Reports from Fresno, Madera, San Joaquin, Tulare, Kings, Kern, Merced, and Stanislaus Counties, and Arroyo (2012). We settled on tomatoes because they are a high-labor and fuel crop, are very popular, have been utilized in the literature (Kan et al., 2002) and are an annual that is grown in *Brassica*'s preferred season. Almonds were chosen as they are not fuel intensive, are also popular, are a perennial, and are less saline tolerant than pistachios. Pistachios were chosen as a counterpart to almonds--though one with a higher salt tolerance. Lettuce was chosen to balance tomatoes—i.e., lettuce is high-valued, but has a low salt tolerance and low water requirement relative to tomatoes. Cotton

Wheat was chosen as an alternative to *Brassica*, as it has a similar salt tolerance and water requirement, and is regularly grown on the west-side.[64] All crops are "planted" on the date within a season that the FAO and the UC Davis Cost and Return studies recommend.[65]

Surface water and precipitation values were collected from 2011. Only drainage water from the higher-valued crop production and precipitation will be used to water the marginal land. Any drainage water from the marginal land and excess drainage water from both higher-valued and IFDM crops must be disposed of via a solar evaporator or evaporation pond.[66] Drainage water of the higher valued crop production is assumed to have a salinity of 4 dS/m to 12 dS/m. These values were chosen as similar values are given in a variety of research on drainage water (Levers and Kaffka, 2015) Salinity is not an output of the model, but rather exogenous.[67]. Finally, crop hectarage of the higher valued

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is the most popular crop in the west-side, and has been included in several previous works. While we label these crops "higher valued" crops for the purposes of this research, we understand that such labels can be temporary.

[64] We chose 2011 as the representative year. Mean yearly precipitation (from CIMIS) from 2001 through 2014 is 22.6 cm. 2011 had 21.3 cm.

[65] *Brassica* is "planted " on November 1st, wheat and lettuce on December 1,and tomatoes and cotton on April 1. Almonds and pistachios begin receiving water on April 15.

[66] We assume that all drainage must be dealt with on farm (i.e., no off-farm). Such an assumption is in line with the no out-of-region drainage disposal restrictions on the west-side of the SJV.

[67] Drainage water salinity is not only function of applied water and water uptake, both of which are endogenous here, but of soil salinity, for which we do not include data. As drainage water

crops is restricted to historic ranges, whereas no constraints are placed on IFDM crop hectarage.[68]

Table 4- 1[69]

Crop	Irrigation	T_P (cm)	EC max (dS/m)	Fuel (g/ha)	Range: Low (%)	Range: High (%)
Tomatoes	Sprinkler, then furrow	76	13	146	20	50
Almonds	Drip	95	7	59	10	25
Cotton	Furrow	97	27	71	15	60
Pistachios	Furrow	55	16	76	5	8
Lettuce	Drip	10	8	165	5	20
Brassica	Furrow	16	19	16	N/A	N/A
Wheat	Furrow	30	20	16	N/A	N/A

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salinty affects IFDM yields, its variability is important which is why we include three likely salinity levels here.

[68] Data from Fresno County Agricultural reports from 2000 to 2010 was used to determine the range of percentages of total cropped hectarage of each higher-valued crop. See Table 1.

[69] T_P is potentialtranspiration.

4.2.2 Submodels

To illustrate the role *Brassica* might play as part of an IFDM system within a salinity and drainage impaired region, we develop two submodels: a no marginal land with no on-farm drainage treatment model (referred to as Submodel A), and a marginal land model with on-farm drainage treatment (referred to as Submodel B). Each is described in turn.

Submodel A assumes land quality that is uniformly high (all non-marginal land) throughout the farm. Drainage water does not have to be disposed of on farm, and is assumed to have an external outlet. IFDM crops are not allowed to be grown with drainage water, but they can be grown with fresh water. This scenario represents a hypothetical longterm steady-state situation where groundwater and soil quality are not concerns and out-of-region drainage water disposal is possible.

Submodel B, alternatively, more accurately captures conditions as they appear currently. That is, land quality in the west-side is highly variable. The aquifer is a complex and heterogeneous system that, when combined with past irrigation practices, has led to certain areas being more highly affected by high saline water tables than other areas. Elements like Se and Boron vary in the region, and across individual farms. In an attempt to capture these conditions, as well as align with the Bureau of Reclamation's estimation of land fit for retirement and the RRR's characteristics, we assume 25% of our farm's land is marginal and only capable of growing *Brassica* or wheat.[70] Finally, any drainage water must be dealt with on-farm through IFDM and/or evaporation systems.

The SJV experiences a variety of available imported water quantities both due to natural water availability (including droughts) and environmental regulations. Generally, when surface water is less available, more groundwater is used. (Levers and Kaffka, 2015). Over the past ten years, about 90 cm of water has been applied to crops in the west-side.[71] We use this value as our de facto water limit. Yet there are many years in which water availability is reduced. Supply reductions often lead to less irrigation and, consequently, potentially lower deep percolation flows and drainage. To illustrate the degree to which the drainage problem and possible solutions vary with the availability of water supplies, we also run the submodels with a limit of 72 cm (20% reduction) and 54 cm (40% reduction).

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[70] An intermediate analysis between these two cases is designate marginal land as a choice variable. This goes beyond the current analysis and will be considered in future research.

[71] Water units are usually given as a depth measurement multiplied by an area measurement (acre feet, for instance), in order to produce a volumetric quantity. We report water units soley in depth, here. The area measurement comes from the area of land to which that amount of water is applied. So, the average amount of water one hectare of land received was 90 cm-hectares.

Finally, for each submodel, we run scenarios representing four different options for IFDM treatment: the growth of *Brassica*, the growth of wheat, land retirement, and efficiency. Each of these is run under three different levels of drainage water salinity: 4 dS/m, 8 dS/m, and 12 dS/m. Our intention in providing such a wide array of analyses is to provide a broader understanding of the drainage problem as it varies with the biophysical characteristics of the region and choices by agents and, consequently, how those factors and choices may affect *Brassica* and IFDM's benefits. A description of the different scenarios is presented in Table 4-2.

Table 4- 2: Run Designations[72]

Submodel A: No Marginal Land

Drainage treatment occurs off-farm.

Scenarios	Total ha-m Available Water		
	1800 (100%)	**1440 (80%)**	**1080 (60%)**
Retirement			
Land is allowed to be retired to allow concentration of water on un-retired parcels.	A: W100	A: W80	A: W60

Submodel B: Marginal Land

Drainage treatment occurs on-farm. 25% of the farm (500 hectares) is marginal land.

Scenarios	Drainage Water dS/m	Total ha-m Available Water		
		1800 (100%)	**1440 (80%)**	**1080 (60%)**
Retirement				
Marginal land is retired. It may be used for evaporation, but not for crops.	**4**	B_R: S4-W100	B_R: S4-W80	B_R: S4-W60
	8	B_R: S8-W100	B_R: S8-W80	B_R: S8-W60
	12	B_R: S12-W100	B_R: S12-W80	B_R: S12-W60
Brassica				
Marginal land may be used to grow Brassica as an IFDM crop, but not wheat.	**4**	B_B: S4-W100	B_B: S4-W80	B_B: S4-W60
	8	B_B: S8-W100	B_B: S8-W80	B_B: S8-W60
	12	B_B: S12-W100	B_B: S12-W80	B_B: S12-W60
Wheat				
Marginal land may grow wheat as an IFDM crop, but not Brassica.	**4**	B_W: S4-W100	B_W: S4-W80	B_W: S4-W60
	8	B_W: S8-W100	B_W: S8-W80	B_W: S8-W60
	12	B_W: S12-W100	B_W: S12-W80	B_W: S12-W60
Efficiency				
Efficient solution. May equal one of the previous scenarios, or be a combination.	**4**	B_E: S4-W100	B_E: S4-W80	B_E: S4-W60
	8	B_E: S8-W100	B_E: S8-W80	B_E: S8-W60
	12	B_E: S12-W100	B_E: S12-W80	B_E: S12-W60

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[72] "A_R" stands for Submodel A_Land Retirement. "B_W:S8-W100" stands for Submodel B, with wheat as the biofuel crop under drainage water salinity of 8 dS/M and 100% water allocation. The remaining designations are similarly defined.

Section 4.3: Methods

4.3.1 Objective Function and Constraints

The model is solved as a constrained maximization problem where the grower is assumed to maximize profits subject to land and water constraints.[73]

For the chosen season, the objective function is defined as:

$$[4.1] \quad \pi = \sum_{i \in \{f,d,b,e\}} \pi_i x_i + (p_b^f - c_b^f)\sigma^f y_b x_b + (p_b^{co} - c_b^{co})\sigma^{co} y_b x_b - E \,,$$

$$[4.2] \quad \pi_i = p y_i - h_i - q_i - l_i p^l - n_i p^n - f_i p^f - I_i - w_i p^w \,,$$

where the land use, $i = \{f,d,b,e\}$ is f, higher-valued crops irrigated with fresh water, d, IFDM crops irrigated with drainage water (wheat) , b, a biofuel crop (*Brassica*), or e, evaporation ponds or solar evaporators. π_i is per hectare profit, while x_i is hectares. p is crop price, y_i is yield. p^f_b is price of biodiesel[74], c^f_b is the cost of producing biodiesel, σ^f is the conversion ratio between yield and biodiesel, p^{co}_b is price of *Brassica*'s co-product, c^{co}_b is the cost of producing the co-product. σ^{co} is the conversion ratio between yield and the co-product. E is the cost of

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[73] Our general model follows the framework employed in Kan et al. (2002), and Schwabe et al. (2006) in that we look to maximize net returns to land and management subject to drainwater considerations / impacts. Knapp and Baerenklau (2006) and Schwabe and Knapp (2008) had similar approaches, but employ dynamic models, with the latter focusing on nitrogen rather than salinity and the former linking their production model to a lumped-parameter groundwater model.

[74] The price of biodiesel is set as equal to the market price of fossil diesel. This allows the higher-valued crops to choose to use biodiesel instead of fossil diesel when the cost of producing a gallon of biodiesel is less than the price of fossil diesel. Accordingly, it is not a true, market price, but a modeling technique. For more information, see the results section.

evaporation ponds or solar evaporators, h_i is the harvest costs, q_i is production costs excluding other explicit costs, which include labor, l_i (p^l is the wage rate), nitrogen, n_i (p^n is the price of nitrogen), fuel gallons, f_i, (p^f is the price of purchased diesel fuel), and irrigation costs, I_i. Applied water is w_i and the price of water is p^w.

Production and harvesting costs, including fuel and labor data, were generated using Cost and Return Studies from University of California Cooperative Extension. Irrigation costs and labor requirements were also derived from these studies.

Land constraints are defined to represent hectarage allocations at the Red Rock Ranch currently.[75] The sum of crop system areas in any period cannot exceed total land available for irrigated production (2000 hectares):

[4.3] $$\sum_i x_i + x_e \leq 2000$$

Equation [4.3] states that total cropped acreage and land allocated to drainage disposal (x_e) cannot exceed overall available acreage. Individual crops are limited to a historic range.[76]

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[75] For the purpose of this study, land is assumed to be constrained at current levels and thus we ignore land markets.

[76] Data from Fresno County Agricultural reports from 2000 to 2010 was used to determine the range of percentages of total cropped hectarage of each higher-valued crop. See Table 4-1.

Water is purchased from the local water district at a fixed price. We maintain water balance and track the drainage water with the following generalized drainage water function:

[4.4] $d_i = f(r, w_i, T_i^a, V)$,

where *r* is precipitation, T^a is transpiration that actually occurs (as opposed to potential), and *V* is evaporation. Total applied water is subject to three scenarios. The first restricts the applied water to 90 hectare-centimeters per hectare of higher-valued crop.[77]

[4.5] $\sum_i w_i \le 90(2000)$

The second restricts the applied water to 80% of the maximum allocation, 72 hectare-centimeters per hectare of higher-valued crop.

[4.6] $\sum_i w_i \le 72(2000)$

The third restricts the applied water to 60% of the maximum allocation, 54 hectare-centimeters per hectare of higher-valued crop.

[4.6] $\sum_i w_i \le 54(2000)$

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[77] The average amount of water available to west-side farms over the years 2000 to 2010 was about 90 cm per hectare

Drainage water in excess of the marginal crop's needs must be placed in an evaporation pond or solar evaporator, which forces the model farm to give up cultivated area.[78]

4.3.2 Yield

Unique crop-water production functions are generated using nonlinear regression analysis in Mathematica of simulated data generated with HYDRUS-1D, a water flow and solute transport software package.

Our approach for developing crop-water production functions are based on a combination of the approaches found in Kan et al. (2002) and Wang and Baerenklau (2014). Kan et al. (2002), whose approach derived from Letey and Dinar (1986) and Letey et al. (1985) and which has been subsequently used in Knapp and Baerenklau (2006) and Schwabe et al. (2006), estimates yield as a function of evapotranspiration, and evapotranspiration as a function of water, controlling for salinity.[79]

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[78] For each hectare-meter of water devoted to evaporation ponds the farm must devote a hectare of land to compensating habitat. Costs/capabilities of evaporation ponds/compensating habitat were adapted from Kan et al (2002). Solar evaporator costs/capabilities were adapted from Faria (2009).

[79] In most cases, yield is estimated as a linear function of evapotranspiration (except when an excessive amount of vegetative growth is present, as is the case with cotton), and evapotranspiration as a nonlinear function (sigmoidal) function of water.

Wang and Baerenklau (2012) use HYDRUS to estimate relative yield (ratio of actual yield to potential yield) as a function of water and nitrogen uptake, which are functions of salinity, nitrogen, and applied water. We extend Wang and Baerenklau (2012) by allowing for variation in daily water applications. Thus, we essentially use the same framework employed in Kan et al. (2002) but replace their growth model with a modified moddel based on that of Wang and Baerenklau (2014). Daily watering amounts and different irrigation timing can then be evaluated.[80] See Chapter 3 for more information.

4.3.2.1 Evapotranspiration

HYDRUS requires transpiration values in order to calculate water uptake. Daily actual reference evapotranspiration values (ET_0) are available from California Irrigation Management Information System (California Irrigation, 2014). We use data from weather stations in Five Points, CA. K_c, the crop coefficient, is a dimensionless crop value that represents the ratio of crop evapotranspiration (ET_c) to ET_0. ET_c can be used as the transpiration value (as in

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[80] The framework of this analysis includes the capability of analyzing different irrigation systems and timings within the same crop system. These irrigation systems are explored in Levers (in draft). See Table 4-1 for the irrigation systems used here. Systems and timing follows that recommended by UC Davis Cost and Return Studies. Furrow produces higher amounts of drainage water than drip irrigation, but less potential evaporation than sprinkler irrigation.

Wang and Baerenklau, 2012), but it ignores evaporation, which is an important component of evapotranspiration.

To increase accuracy in the evaporation/transpiration division, the FAO has published a procedure for splitting K_c into its components: K_{cb}, the transpiration coefficient, and K_e, the soil evaporation coefficient (Crop, 1998). For each crop and irrigation method, we have calculated daily K_e and K_{cb} values to input into HYDRUS. Potential transpiration values do not vary by irrigation method, but soil evaporation does. See Appendix E.

4.3.2.2 Relative Yield

In order to calculate relative yield, we first simulate relative yield values with HYDRUS. These simulations require a substantial amount of daily data, including evaporation and transpiration values. Daily rather than seasonal values capture more accuracy as plant growth is dependent on water received in previous time periods. We then estimate parameters to fit the simulated data to a published general relative yield equation with Mathematica. The estimated parameters and the general relative yield equation form the calculated relative yield equations that are used in the optimization program in GAMS.

4.3.2.2.1 Simulated Relative Yield using HYDRUS

Wang and Baerenklau (2012) calculate maximum daily evapotranspiration, then input this (along with salinity and various soil profile and system characteristics) into HYDRUS. HYDRUS generates data on water uptake and solute uptake (nitrogen). Once these data are generated, yield is calculated by following Pang and Letey's (1998) relative yield definition on a seasonal basis. In order to make the simulations more accurate, flexible, and able to account for different irrigation schemes and limiting factors at different times in the plant's life, HYDRUS was modified for this project by Dr. Jirka Simunek, HYDRUS's creator, making simulated relative yield, which accounts for instantaneous yield reductions throughout the growing season:

$$[4.7] \qquad RY^{s} = 1 - \int_{0}^{T} yr(t)dt,$$

$$[4.8] \qquad yr(t) = \max\left[\frac{T^{p} - T^{a}}{w^{p}}, \frac{R^{p} - R^{a}}{n^{p}}\right],$$

where *T* is season length, T^a is actual transpiration at time *t*, T^p is potential transpiration at time *t*, R^a is actual nitrogen uptake at time *t*, R^p is potential nitrogen demand at time *t*, and *yr(t)* is yield reduction at time *t*.

At each time step, HYDRUS calculates actual nutrient uptake and actual water uptake, and finds the difference between these values and their potential uptake equivalents. The ratio between these differences and the respective cumulative potential uptakes are compared. The larger value defines the limiting factor and HYDRUS considers it to be the instantaneous yield reduction for that time step. The relative yield at the end of the growth season is found by subtracting the summation of all the instantaneous yield reductions from one. See Appendix 4.B.[81]

4.3.2.2.2 Calculated Relative Yield using Mathematica

Parameters in a general relative yield function [4.9] are calculated in order to fit the simulated relative yield data, following Wang and Baerenklau (2014).

[4.9] $RY = f(n_{ij}, w_{ij}, P)$,

where *P* is a vector of parameters that are each a polynomial function of salinity, *s*.

Using the estimated relative yield data generated by HYDRUS, Mathematica is used to estimate the parameters using nonlinear regression and least squares analysis (see Appendix B). *P* is substituted into the general relative yield [4.9] to form calculated relative yield functions, which are used in the general mathematical programming model in GAMS. See Appendix 4.C.

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[81] This process is extremely time intensive. Alternatively, we developed a program using Matlab to automate the process as illustrated in Appendix D.

RY can be used to estimate the percentage of potential transpiration that the plant actually transpires over the season, RW:

[4.10] $\mathrm{RW} = \mathrm{T}^{\mathrm{p}} / \mathrm{T}^{\mathrm{a}}$.

RY provides an underestimate of RW (See Section 3.2.2.1). Instead we use HYDRUS to calculate the RW and Mathematica to generate RW functions. See Appendix 4.C.

4.3.3 *Brassica* and Carbon Dioxide Emissions

The seeds of *Brassica* are pressed and split into oil and meal. Red Rock Ranch processes its own seed press, which simplifies biofuel production costs. The oil is assumed to be converted on-farm into biodiesel, a simple process involving transesterification with the addition of an alcohol and an alkaline or acidic catalyst (Apostolakou et al., 2009). The resulting biofuel will be used to supplant fossil biodiesel on-farm,[82] decreasing the carbon dioxide emissions for the farm. We compare the carbon dioxide emissions of the different scenarios (Table 4-1) by examining the amount of fossil diesel and biodiesel used. There are a number of pollutants that have stronger greenhouse affects than carbon dioxide, including oxides of nitrogen. Because of this, a more thorough and site-

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[82] We do not consider the possibility of excess biodiesel being sold off-farm. This would require additional costs of production concerning standards, distribution, etc. In Submodel B, there is never enough *Brassica* to produce excess, at any rate.

specific GHG analyses would include fertilizer and pesticide application, as discussed in Hill et al. (2006). For this analysis, a $C0_2$ equivalent of 10.21 kg per gallon of fossil diesel was used (Emission, 2014). Biodiesel was assumed to be 59% of the CO_2 equivalent per gallon of fossil diesel (Fore, 2011).

We then perform a sensitivity analysis to examine what effect fossil diesel prices and potential carbon taxes would have on *Brassica*'s growth and greenhouse gas emissions. For comparison, we run the B_B: S4-W100, B_B: S4-W80, and B_B: S4-W60 scenarios (*Brassica* with 100%, 80%, and 60% water and drainage water salinity of 4 dS/m) with three fossil diesel prices: $2, $3, and $4 (our baseline price is $4). We chose these prices based on recent estimated red diesel prices.[83] We also include a carbon tax of $0.05 and $1.00 per gallon of fossil diesel.[84] Biodiesel still releases a variety of pollutants, just like fossil diesel, when it is combusted. However, as its carbon is from atmospheric carbon dioxide and not long deceased organisms, its carbon dioxide emissions are effectively reduced compared to fossil diesel's emissions. We use the same value

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[83] Red diesel prices were estimated by subtracting federal and state excise taxes (about $0.65) from reported diesel prices over the last 15 years. Prices and taxes are from the US Energy and Information Administration (US-Federal, 2015, and US-California, 2015).

[84] We examined carbon taxes from several countries and converted them to cost per gallon of diesel. The represented a large range, from $0.02 in Japan and $0.006 to $0.03 in Mexico to $0.69 in Switzerland and $1.70 in Sweden. We chose two values that represent the high and low values.

of 59% to assume that any biodiesel used must pay 59% of the carbon tax and any fossil diesel used must pay 100%.

Section 4.4: Results

In this section, we compare the profits and land allocations under Submodels A and B for alternative water allocation levels, including 100% de facto allocation, and an 80% and 60% allocation (relative to the de facto). For Submodel A, the presented solutions include no marginal land and no drainage restrictions/constraints. For Submodel B, results include a land retirement outcome, in which 25% of the land is considered "marginal" and retired (the model reduces allowable acreage by 25%). Any surplus drainage must be disposed of via a solar evaporator or an evaporation pond. Submodel B scenarios also include two IFDM solutions, in which a single IFDM crop—either wheat or *Brassica*—can be grown on 25% of the land. This land is irrigated only by drainage water that is generated by crop production on the other 75% of the land. Similar to the land retirement scenario under Submodel B, any surplus drainage water must be disposed of via a solar evaporator or evaporation pond. The last scenario run under Submodel B is efficiency, where the model can chose retirement, wheat, *Brassica*, or any combination thereof as a marginal land treatment. To illustrate how changes in the salinity of the drainage impact the relative attractiveness of the above solutions, model solutions for drainage water salinity levels of 4, 8, and 12 dS/m are generated and compared.

We also compare the carbon dioxide emissions, profits, and *Brassica* biofuel production under different fuel prices and carbon taxes in a sensitivity analysis of the model. For this analysis, we use Submodel B, the *Brassica* scenario. Assumptions and limits are the same as detailed above. See Table 4-2 for clarifications on different runs.

4.4.1 100% Water (1800 ha-m total) Allocation

In this subsection, we discuss solutions that were generated given a maximum water allocation of 90 cm, or 1800 ha-m across the farm, which is the average amount of water available to the west-side since 2000. Submodel A with an allocation of 100% water represents a status quo where drainage is dealt with off-farm. This can be viewed as a long-term steady-state if out of region disposal and historical water deliveries were a reality. Submodel B represents the choices a farmer may make when he or she is required to address drainage water on farm and has the additional concern of marginal land, which cannot be used for higher-valued crops.

Tables 4A-2, 4A-5, and 4A-8 (in Appendix 4.A) and Figure 4-1 show the profits per hectare under 100% water allocation. As shown, Submodel A (A: W100) produces the highest profits ($2144/ha) while including some retirement as part of the optimal solution. Relative applied water (ratio of actual applied water to potential water uptake [potential transpiration]) across the higher-valued crops is at its highest levels[85]. Retirement inclusion is likely due to the relatively high profit potential of the crops we have chosen.[86]

The difference in profit between Submodel A and scenarios in Submodel B is therefore the potential benefit to a farmer of having external drainage handling and no marginal land.[87] When IFDM crop scenarios are run in Submodel B, the difference between the profits of Submodel A and Submodel B are lower than when solely retirement is an option (Figure 4-1). The difference is the lowest, when Submodel B profit is the highest ($1288/ha), which occurs under the

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[85] The model chooses to apply slightly more than 1.5 times the potential water uptake of all crops with the exception of cotton. This is consistent with watering levels for ideal conditions as outlined in UC Davis Cost and Return Studies. Cotton's water level is lower as it is not as profitable as the other crops, as such applied water causes a larger marginal increase in profit when applied to other crops.

[86] The prices of the crops are: almonds - $8/kg, pistachios -$6, tomatoes - $0.11/kg, and lettuce - $0.85/kg, and cotton (acala)- $2/kg. We performed a sensitivity analysis varying the higher--valued crop prices to price levels from the last 20 years, however, we have not included these results as while the crop mix changes, the results of our analysis do not vary significantly.

[87] We do not address the pathways and final disposal of various elements and chemicals found in drainage water in our IFDM scenarios. Dealing with this would introduce different costs, but would be required to address a true steady state incorporating IFDM systems.

growth of wheat with drainage water salinity of 4 dS/m, B_W: S4-W100. This scenario produces the exact results of the efficient solution (B_E: S4-W100), even though both *Brassica* and retirement are also allowed in efficiency (we see a pattern where the solutions of the efficient run are exactly equal to the soultion of an IFDM run repeated throughout the analysis). The scenario's profits are still only about 60% of the Submodel A results (Figure 4-4).

Under all the IFDM crop scenarios, there is enough drainage water from the higher-valued crops to allow for the full 500 hectares of marginal land to be used--the vast majority of which grows the IFDM crop, while the remainder is devoted to solar evaporator. Evaporation ponds are never chosen.[88] *Brassica* has both a lower water requirement and higher potential precipitation than wheat, which is why the *Brassica* results show a lower applied water level and a higher solar evaporator hectarage (i.e. there is more "leftover" water). Higher-valued crop mix is consistent across all scenarios in Submodel B.

Salinity is a factor neither in Submodel A nor in the retirement scenario of Submodel B, but it becomes important when the IFDM crops are grown. Increasing salinity causes IFDM crops yields to decrease, which causes their

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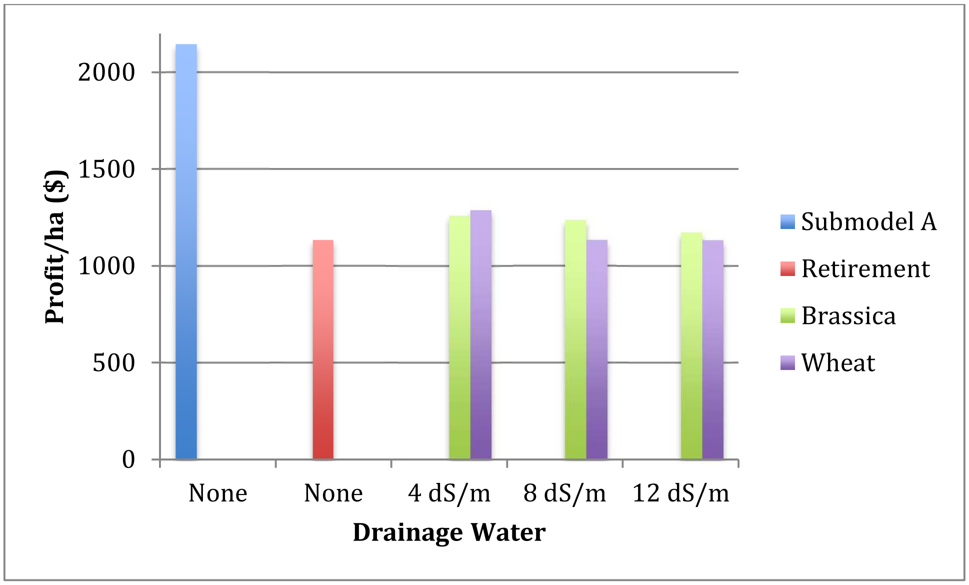
[88] This is likely a reasonable result, as evaporation ponds are more expensive, require compensating habitat to be built, and require substantial regulation (they must be kept at certain levels of water) due to potential wildlife deaths. They are not likely to be built regularly, anymore (Benes, 2009).

profitability to decrease. In the case of wheat, the salinity categories beyond 4 dS/m cause the yields to be so low that its growth is no longer profitable at all. In these scenarios (B_W: S8-W100 and B_W: S12-W100), the solution and therefore profits ($1132/ha) are equal to that of retirement (B_R: W100).

The two higher drainage salinity levels (8 dS/m and 12 dS/m) are more forgiving on *Brassica* (likely due to its water requirements, available precipitation, and salinity coefficients). Both B_B: S8-W100 and B_B: S12-W100 are equal to the efficient solution under their respective drainage salinity (again, we see no mixing of *Brassica*, wheat, and retirement in the efficient solution) (Figure 4-1), producing $1234/ha and $1171/ha, respectively.

Figure 4- 1: 100% Water (90 cm) Profits/ha



4.4.2 Profits: 80% Water (1440 ha-m total) Allocation

In this subsection, we discuss solutions that were generated given a maximum water allocation of 72 cm, or 1440 ha-m across the farm, which is 80% of the maximum water allocation. Submodel A with an allocation of 80% water represents a reduced water availability situation where drainage is dealt with off-farm. Submodel B represents the choices a farmer may make when he or she is required to address drainage water on farm, has marginal land, which cannot be used for higher-valued crops, and has a 20% water reduction from the de facto level.

Tables 4A-3, 4A-6, and 4A-9 (in Appendix 4.A) and Figure 4-2 show the profits per hectare under 80% water allocation. Submodel A (A: W80) produces the highest profits ($1735/ha), and includes more retirement hectarage than in the higher allocation, and a reduction in pistachio hectares.[89]

Again, when IFDM crop scenarios are run in Submodel B, the difference between the profits of Submodel A and Submodel B are lower than when solely retirement is an option (Figure 4-2). The difference is the lowest when Submodel

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[89] Pistachios have a high water requirement, equivalent to that of almonds and cotton. They are less profitable than almonds, and cotton hectares cannot be reduced further as they are at their area's low limit, already.

B profit is the highest ($1248/ha), which occurs under the growth of wheat with drainage water salinity of 4 dS/m, B_W: S4-W80. This scenario produces the exact results of the efficient solution (B_E: S4-W80).

While the profits for Submodel A are reduced by about 19% with respect to A: W100, Submodel B's maximum profits are only reduced by about 3% relative to B_W: S4-W100. Accordingly, the difference between Submodel B and Submodel A's profits are also decreased-- Submodel B's results are about 72% of Submodel A's (Figure 4-4).[90]

Similarly to the 100% water allocation, all the IFDM crop scenarios see full use of marginal land--the difference is a slight shift from solar evaporator area to IFDM crop area. This is due to the reduced water, which means there is less drainage water to evaporate. Again, *Brassica* results show a lower applied water level and a higher solar evaporator hectarage. The higher-valued crop mix is again consistent across the Submodel B scenarios, but it has changed from the mix of the higher water allocation scenarios. Some hectares shift from tomatoes to lettuce, which has the lowest water requirement.

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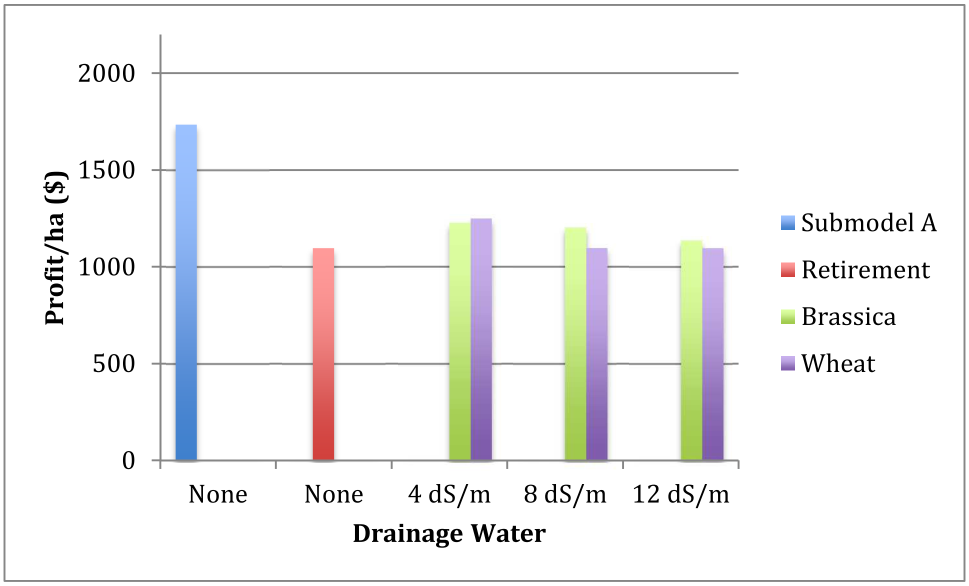
[90] Increased salinity levels have lower potential profits, but not hugely so. B_B:S8-W80 (same as B_E: S8-W80)'s profit is about 69% that of A: W80. B_B: S12-W80 (B_E: S12 -W80) is 65% of that of A: W80.

Salinity effects do not change in this water allocation. Wheat is still not profitable with drainage salinity of 8 dS/m and 12 dS/m, therefore in B_W: S8-W80 and B_W: S12-W80, the solution and therefore profits ($1132/ha) are equal to that of retirement (B_R: W80), and both B_B: S8-W80 and B_B: S12-W80 are equal to the efficient solution under their respective drainage salinity (again, we see no mixing of *Brassica*, wheat, and retirement in the efficient solutions) (Figure 4-2), producing $1207/ha and $1136/ha, respectively.

Figure 4- 2: 80% Water (72 cm) Profits/ha



4.4.3 Profits: 60% Water (1080 ha-m total) Allocation

In this subsection, we discuss solutions that were generated given a maximum water allocation of 54 cm, or 1080 ha-m across the farm, which is 60% of the maximum water allocation. Submodel A with an allocation of 60% water represents a even more reduced water availability situation where drainage is dealt with off-farm. Submodel B represents the choices a farmer may make when he or she is required to address drainage water on farm, has marginal land, which cannot be used for higher-valued crops, and has a 40% water reduction from the de facto level.

Tables 4A-4, 4A-7, and 4A-10 (in Appendix 4.A) and Figure 4-3 show the profits per hectare under 60% water allocation. Submodel A (A: W80) produces the highest profits ($1136/ha), and includes more retirement hectarage than in the higher allocations, and we see almond hectares go down.

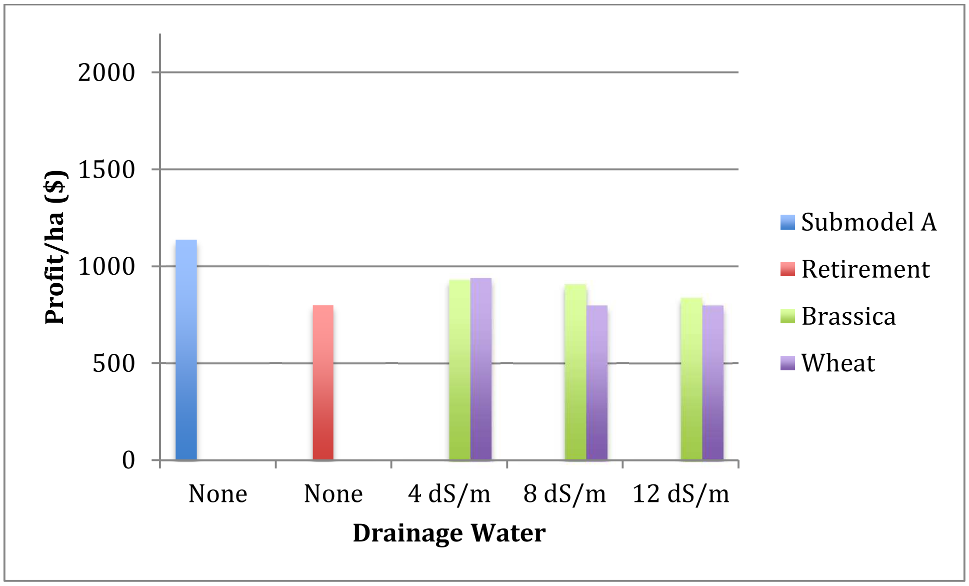
Again, when IFDM crop scenarios are run in Submodel B, the difference between the profits of Submodel A and Submodel B are lower than when solely retirement is an option (Figure 4-2). The difference is the lowest when Submodel B profit is the highest ($941/ha), which occurs under the growth of wheat with drainage water salinity of 4 dS/m, B_W: S4-W60. This scenario produces the exact results of the efficient solution (B_E: S4-W60).

The profits for Submodel A are reduced by about 47% with respect to A: W100 and about 35% with respect to A: W80, which is consistent with the idea that the marginal benefit of water increases as it becomes more scarce. Again we see that Submodel B's maximum profits are reduced by less, about 27% relative to B_W: S4-W100, and about 25% relative to B_W: S4-W80. Accordingly, the difference between Submodel B and Submodel A's profits are also decreased--Submodel B's results are about 83% of Submodel A's (Figure 4-4).

The IFDM crop scenarios again have full coverage of marginal land. Less water again decreases the need for evaporators. Again, *Brassica* results show a lower applied water level and a higher solar evaporator hectarage. The higher-valued crop mix is again consistent across the Submodel B scenarios. Some hectares shift from pistachios to lettuce.

Wheat is again not profitable with drainage salinity of 8 dS/m and 12 dS/m, therefore in B_W: S8-W60 and B_W: S12-W60, the solution and therefore profits ($797/ha) are equal to that of retirement (B_R: W60). Both B_B: S8-W60 and B_B: S12-W60 are equal to the efficient solution under their respective drainage salinity (again, we see no mixing of *Brassica*, wheat, and retirement in the efficient solutions) (Figure 4-2), producing $932/ha and $906/ha, respectively.

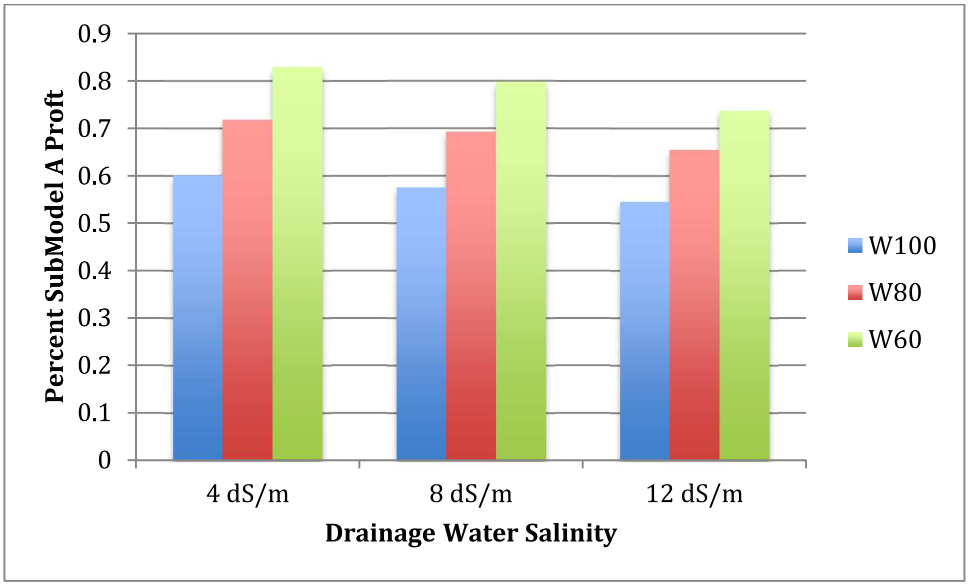
Figure 4- 3: 60% Water (54 cm) Profits/ha



4.4.4 Trends as water allocations decrease from 100% to 80% to 60%:

As described in the previous subsections, profits decrease. Max profit from Submodel B relative to the profit from Submodel A increases (Figure 4-4). With low water and low salinity of drainage water, Submodel B's profit reach over 80% of Submodel A's. As drainage water salinity increases, the relative profitability decreases, as IFDM yields decrease.

Figure 4- 4: Highest Submodel B Profit at Different Water Levels Relative to Submodel A Profit.



Land use and applied water change as water decreases. These changes are shown in spatial figures; Figure 4-5 represents Submodel A, Figure 4-6 represents the land retirement scenarios from Submodel B, Figure 4-7 represents the wheat scenarios, and Figure 4-8 represents the *Brassica* scenarios.[91]

Generally, we see as water decreases there is a shift to land uses that require less water, and less applied water. In Submodel A, land retirement increases. Applied water on each crop decreases. Hectares of almonds and pistachios decrease. Hectares of lettuce, a low water crop, are at their max

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[91] We have provided visual representations for the low salinity level only. The higher levels *Brassica* submodels show similar results (See Tables 4A-4 through 4A-10).

percentage and cannot increase, but respresent a higher percentage. Likewise, tomatoes and cotton[92], are at their minimum, so the changes seen are in their decreased applied water.

In the Submodel B retirement scenarios, fallowing remains constant. Solar evaporator hectarage decreases. Lettuce hectareage increases and pistachio hectarage decreases. Applied water decreases. In the wheat scenarios, wheat makes up a larger portion of the marginal land as compared to the evaporator . Lettuce hectareage increases and pistachio hectarage decreases. Applied water decreases. In the *Brassica* scenarios, *Brassica* makes up a larger portion of the marginal land as compared to the evaporator . Lettuce hectareage increases and pistachio hectarage decreases. Applied water decreases. Like cotton, Brassica has a lower relative water level than other crops. Precipitation provides about half of *Brassica's* water requirements, and as such, it does not require a high amount of water. This contributes to its growth capapbiities under salinie water.

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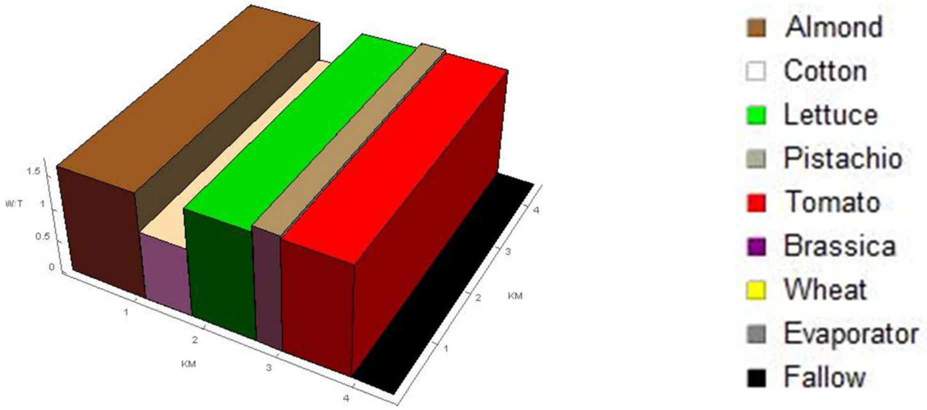
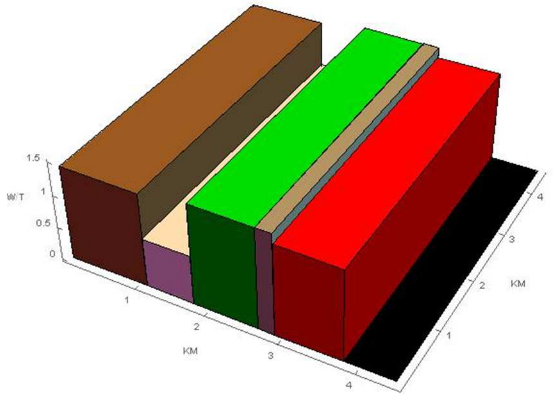
[92] Cotton consistently is provided with lower water amounts. It has a high water requirement, but remains profitable with lower amounts of water. Almonds are very profitable, and would take over the model if allowed, which is one reason ranges were installed (See Table 4-1).

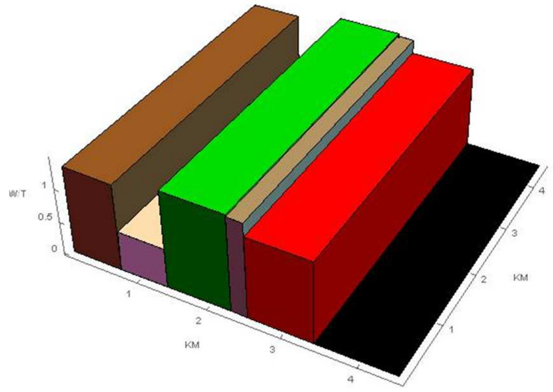
Figure 4- 5: Submodel A. Land Use & Applied Water.[93]



W100



W80



W60

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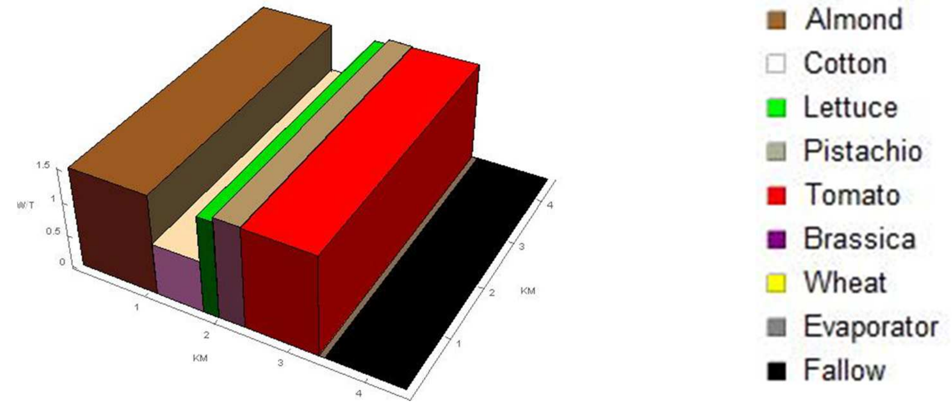
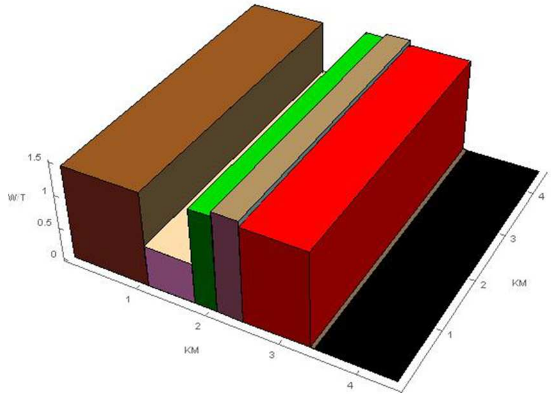
[93] The x-y plane represents the relative area of the farm. The z axis is the relative water applied (water divided by potential transpiration)

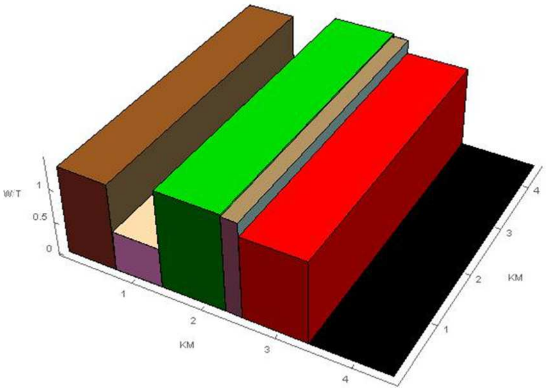
Figure 4- 6: Submodel B: Retirement. Land Use & Applied Water [94]



W100



W80



W60

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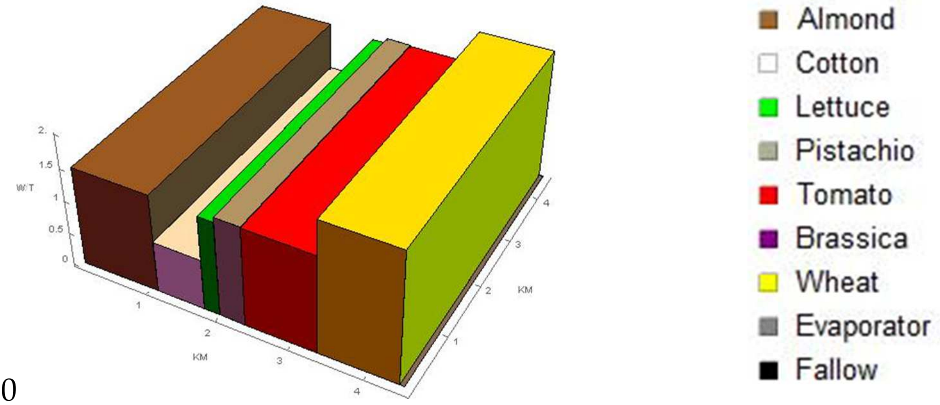
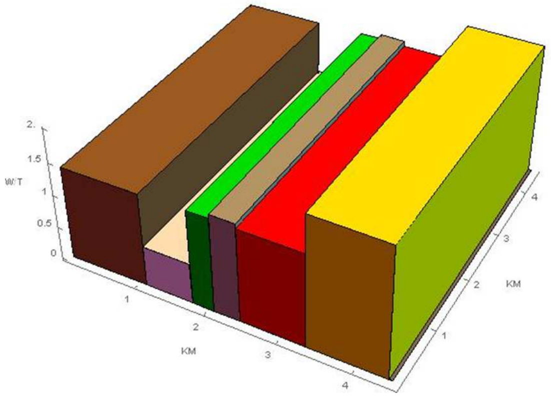
[94] The x-y plane represents the relative area of the farm. The z axis is the relative water applied (water divided by potential transpiration)

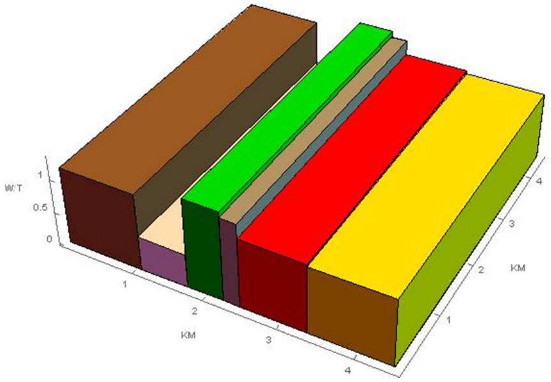
Figure 4- 7: Submodel B: Wheat. S: 4 dS/m. Land Use & Applied Water [95]



W100



W80



W60

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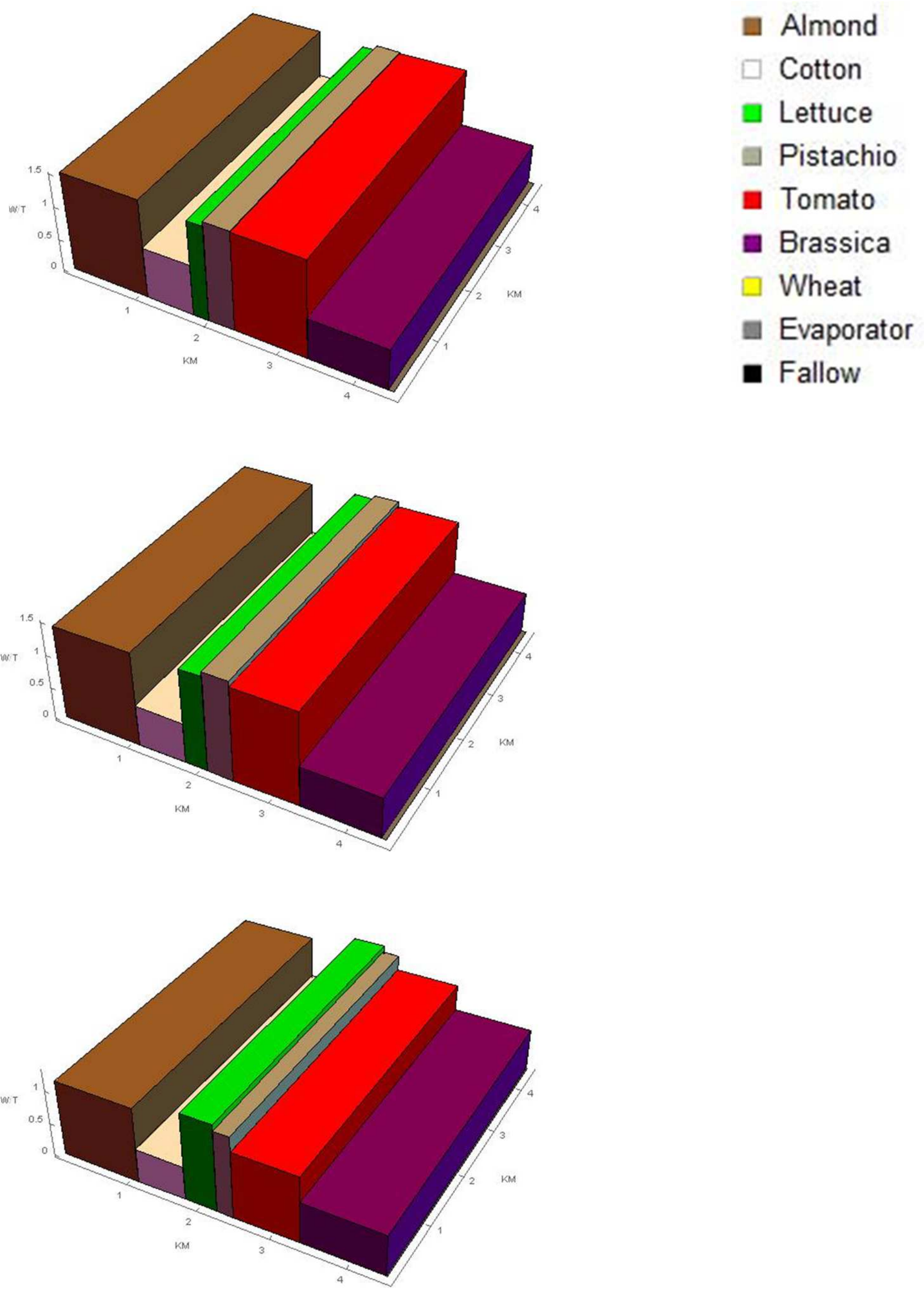
[95] The x-y plane represents the relative area of the farm. The z axis is the relative water applied (water divided by potential transpiration)

Figure 4- 8: Submodel B: *Brassica*. S: 4 dS/m. Land Use & Applied Water [96]



W100

W80

W60

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[96] The x-y plane represents the relative area of the farm. The z axis is the relative water applied (water divided by potential transpiration)

4.4.5 Carbon Dioxide Emissions and Biodiesel Production

Figure 4-9 shows farm-level CO_2 emissions for all the different scenarios. Submodel A has the highest carbon emissions, which is due to its increased total higher-valued crop area. Submodel B's emissions are highest with the growth of wheat, second highest with land retirement, and the lowest with the growth of *Brassica*.

As water decreases in Submodel A, emissions decrease because of the increased land retirement. This trend is reversed for Submodel B. Decreased water increases emissions. Lettuce area increases in Submodel B when water decreases. Lettuce happens to have the highest fuel requirement of all of the crops, which causes this.

Salinity appears to have a different effect on wheat than it does on *Brassica*, causing emissions to decrease for wheat and increase for *Brassica*. As described above, wheat is not profitable with salinity levels of 8 and 12 dS/m, which means its solutions are equal to that of retirement. For *Brassica*, increasing salinity causes an increase in CO_2 emissions, which is in line with *Brassica*'s reduced yield under higher salinity scenarios.

Emissions are linked to the amount of biofuel produced, which are shown in Figure 4-10. For a given salinity level, biodiesel production increases as water decreases. As water decreases, less land needs to be devoted to solar

Figure 4- 9: CO$_2$ Emissions

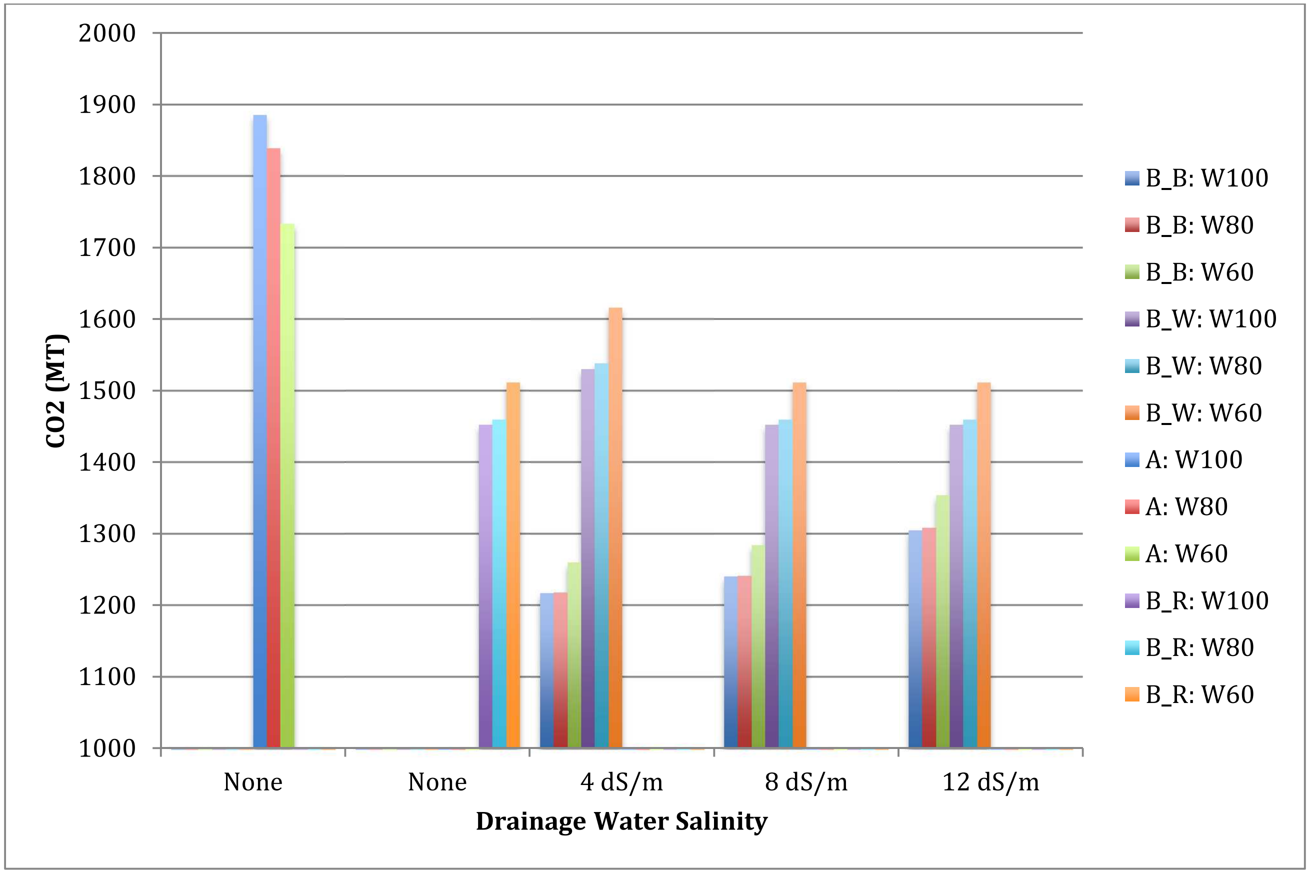
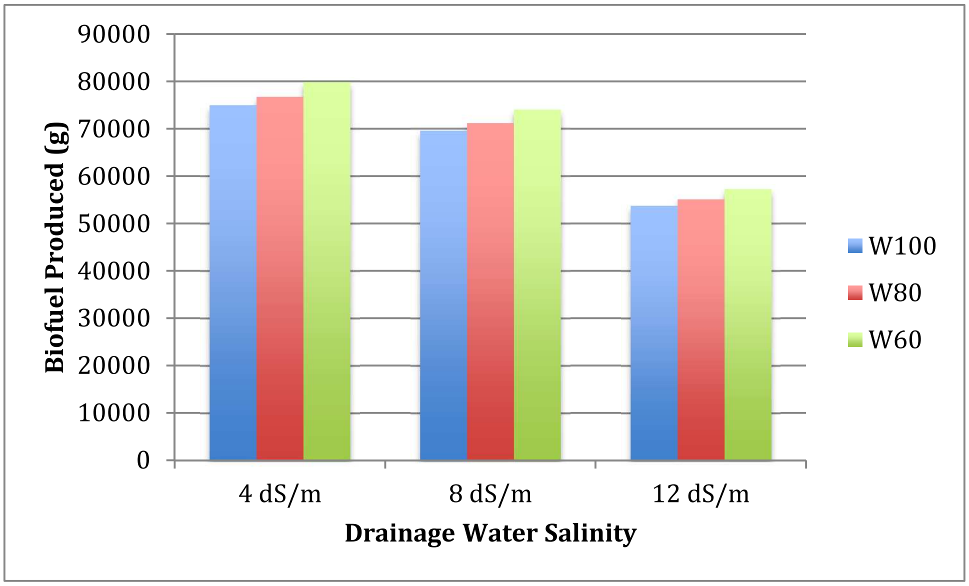
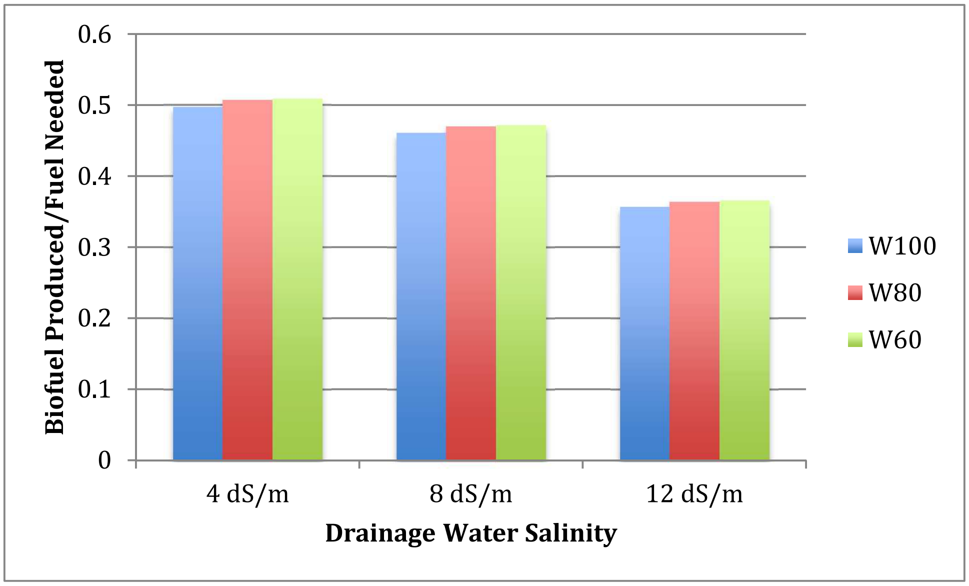


Figure 4- 10: Biodiesel Production



evaporators, which allows more land to be used for *Brassica*, which increases biofuel production. Because of land use change, particularly the increase in lettuce, the percentage of total fuel needed that is fulfilled by *Brassica*, does not follow exactly the total biofuel production, though it is close. This is shown in Figure 4-11. The percentage of fuel fulfilled at the lowest water level is proportionately lower than the biofuel production, shown in Figure 4-9.

Figure 4- 11: Percent of Total Required Fuel Need Met by Biodiesel



4.4.6 Fuel Price and Carbon Dioxide Tax Sensitivity Analysis

As biodiesel produced replaces fossil diesel on-farm, the cost of producing biodiesel affects the attractiveness of *Brassica*. In Figure 4-12, we show the cost to produce biodiesel under the different scenarios. If biodiesel were the only product from *Brassica*, the cost of production would be higher than the cost of diesel, which in the scenarios outlined above, we assume is $4/gal. But, *Brassica* also produces a co-product, seed meal, worth $2.08 per gal of biodiesel produced.[97] Once we account for the seed meal, the effective cost of biodiesel

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[97] We assume the seed meal price per kg is $0.40 ($350 dollars a short ton[US Canola 2014]). This is for regular, non-selenium enhanced seed meal, so it is a low estimate. It is likely that

decreases. Seed meal profits comprise a large percentage of total *Brassica* private benefits. As such, it is not unreasonable to predict that changing seed meal prices could significantly affect *Brassica*'s attractiveness. This may particularly be an issue if *Brassica* production were to increase to the point that seed meal prices dropped.

Also shown in Figure 4-12 is that as the drainage water salinity increases, the cost to produce each gallon of biodiesel increases (fixed costs remain the same, but biofuel production decreases). As water allocation falls, so does the cost of producing biodiesel, because of the decreased land use by solar evaporators (this effect is very small).

To further examine the effects fuel prices have on carbon dioxide emissions, fuel prices, and profits, we perform a sensitivity analysis of fuel prices and carbon taxes. We analyze *Brassica* scenarios with fuel prices of \$2, \$3, and \$4 per gallon, chosen from historical red diesel prices. We also include a carbon tax of \$0.05 and \$1.00 per gallon.

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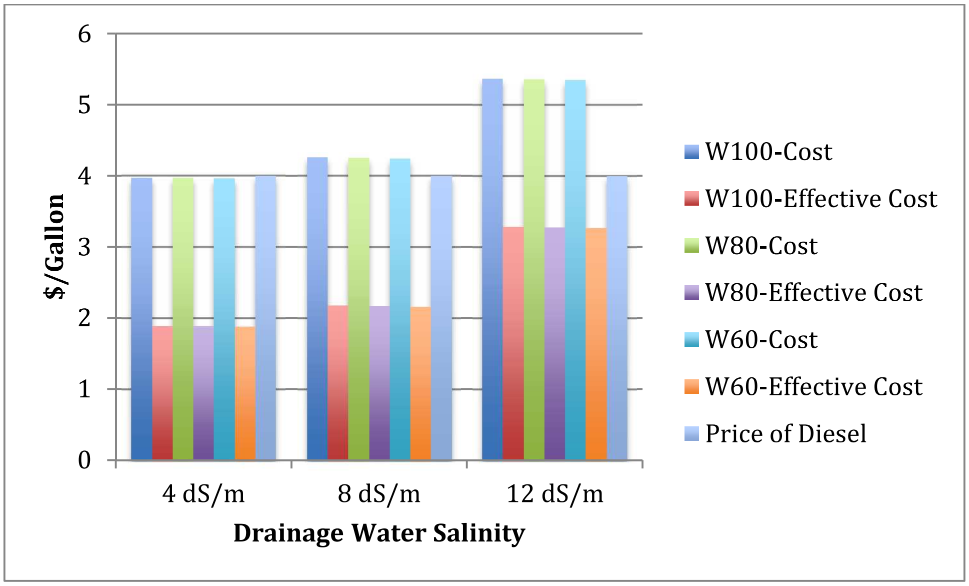
biofumigant prices would be higher, as well, but many biofumigant consumers would only want organically produced mustard meal, which we do not consider here. Each gallon of biodiesel is produced alongside about 5.4 kg of seed meal, worth \$2.08.

Figure 4- 12: Cost to Produce a Gallon of Biodiesel



Carbon emissions are relatively stable within water allocations (Figures 4-13 and 4-14). The exception is for the lowest water amount with the highest fuel price. In this situation, the model fallows 100 hectares of water, removing hectares from lettuce and tomatoes, two high-fuel requiring crops, which drops the carbon emissions.[98] *Brassica* hectares (Figures 4-15 and 4-16) and biofuel production (Figures 4-17 and 4-18) match the carbon emissions. Profits markedly decrease as water availability decreases, but do not vary as greatly as fuel prices differ within a water level (Figures 4-19 and 4-20), though they do decrease.

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[98] We ran this scenario alternatively, allowing *Brassica* to grow on the fallowed land. This produced higher profits and lower carbon emissions, but did not change any of the rankings--the profits, carbon dioxide emissions, etc, were still higher and lower than the same scenarios.

Carbon emissions per profit per hectare are given in Figures **4-**21 and **4-**22. These are, again, relatively stable across water allocations, increasing as carbon emissions decrease.

Overall, we find that water allocation has a larger effect on profits and *Brassica* production and therefore carbon emissions than fuel prices or carbon taxes.

Figure 4- 13: CO$_2$ with Carbon Tax = \$1.00/g

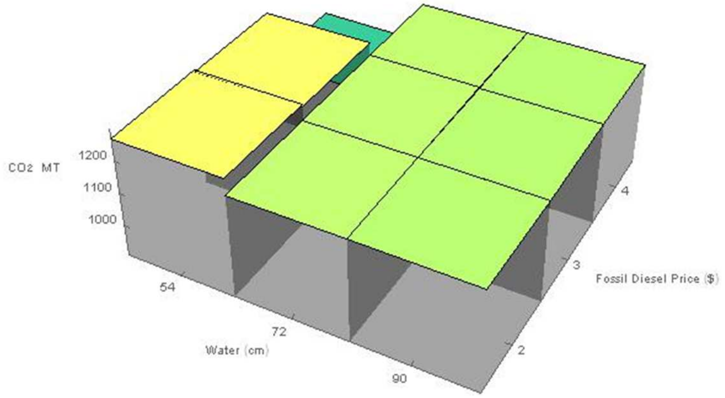


Figure 4- 14: CO$_2$ with Carbon Tax = \$0.05/g

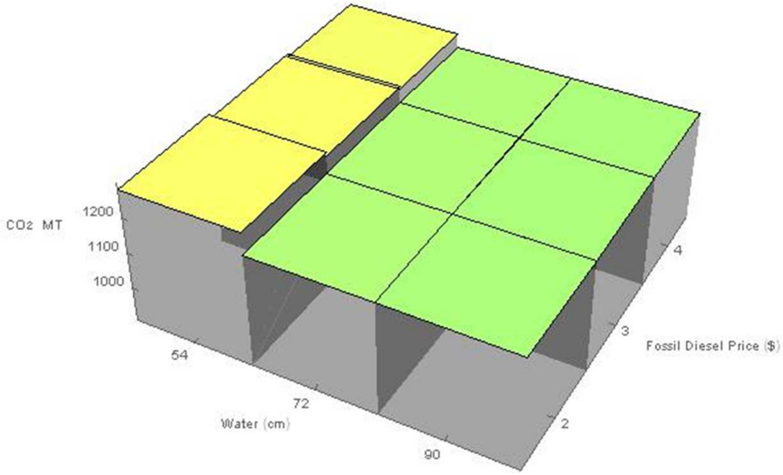


Figure 4- 15: Biodiesel Production: Carbon Tax = $1.00/g

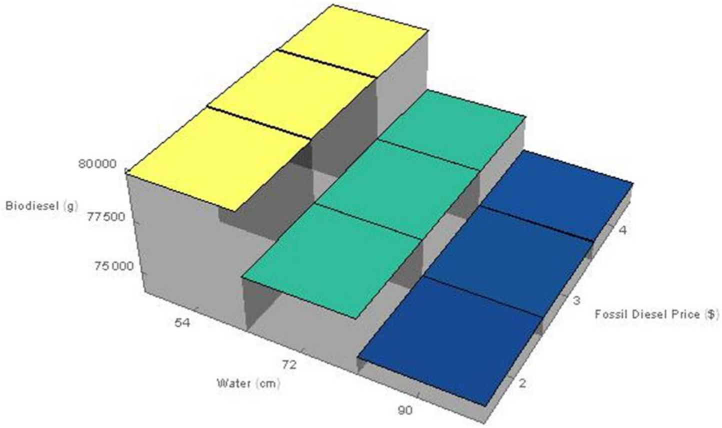


Figure 4- 16: Biodiesel Production: Carbon Tax = $0.05/g

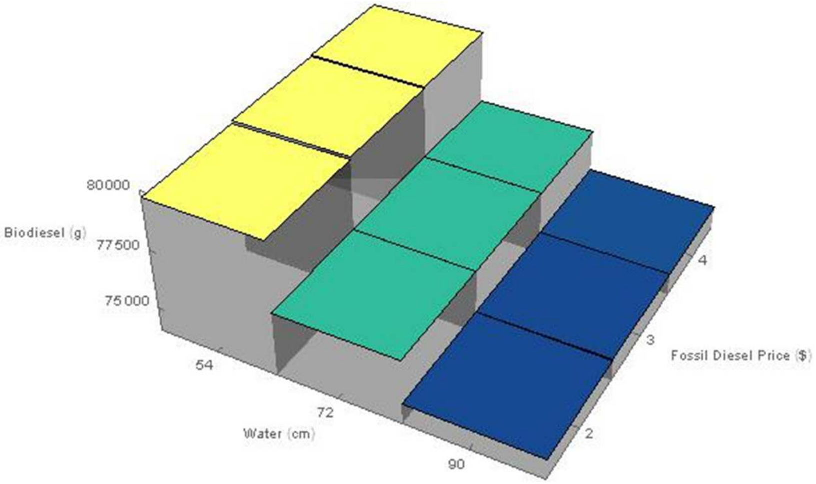


Figure 4- 17: Ha *Brassica* Carbon Tax = $1.00/g

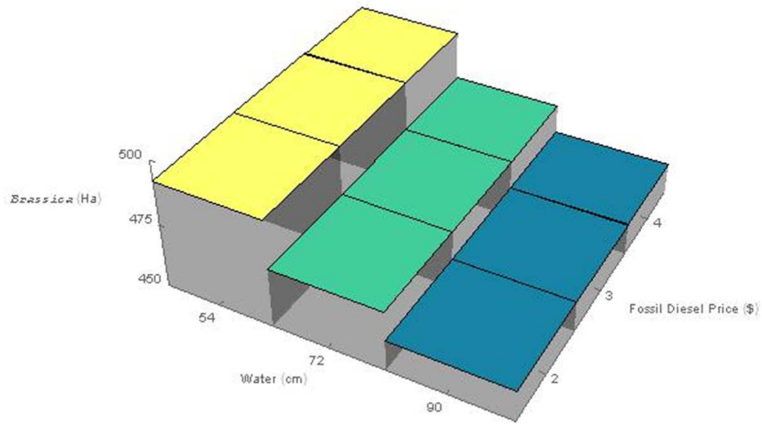


Figure 4- 18: Ha *Brassica* with Carbon Tax = $0.05/g

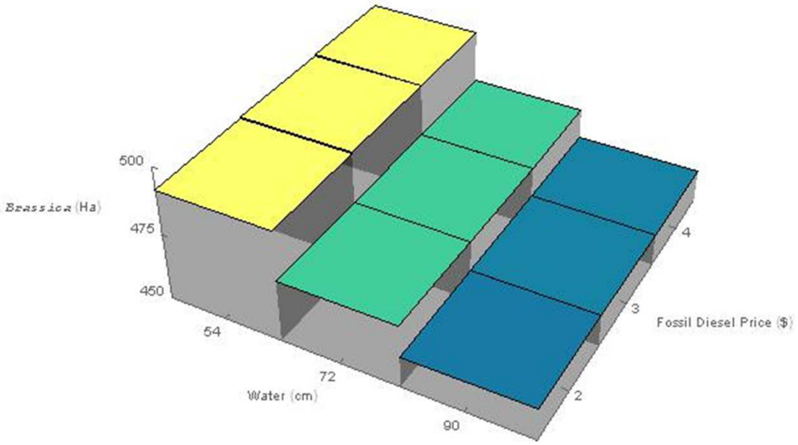


Figure 4- 19: Profit/Ha with Carbon Tax = $1.00/g

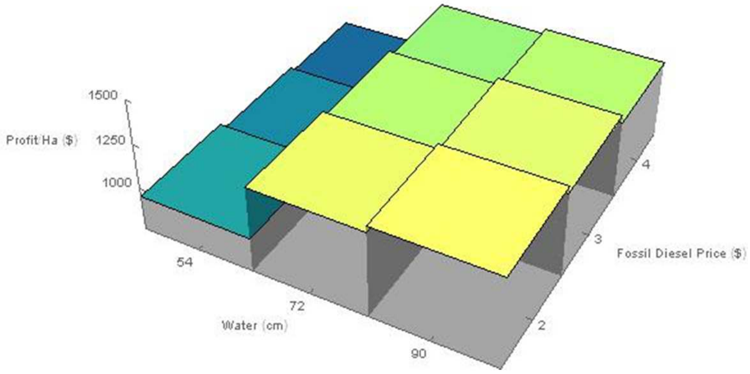


Figure 4- 20: Profit/Ha with Carbon Tax = $0.05/g

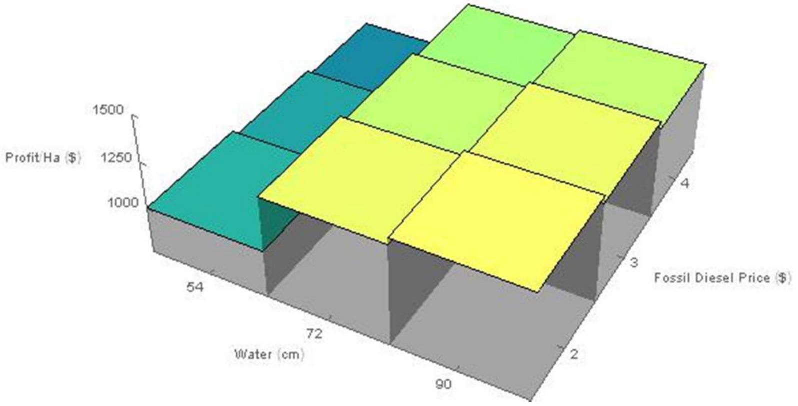


Figure 4- 21: Profit/MT CO_2 with Carbon Tax =$1.00/gal

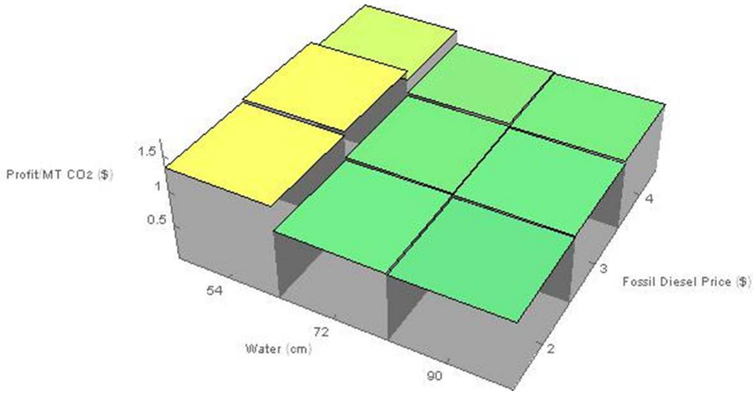
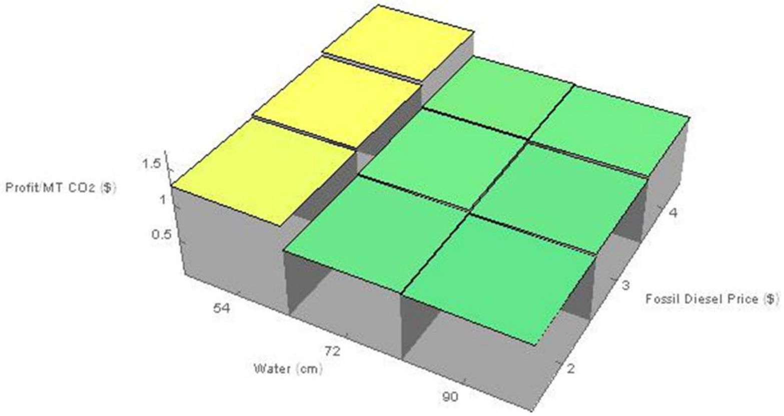


Figure 4- 22: Profit/MT CO_2 with Carbon Tax =$0.05/gal



Section 4.5: Conclusion

Arid regions throughout the world, including the SJV, have been battling the negative effects of salinization and drainage issues for decades (centuries, even). As water is brought into naturally dry areas, there are often not the biophysical infrastructure in place to handle it and its consequences. Even in times of drought, drainage is still of concern as groundwater can be used to supplement surface water supplies, and because of droughts' impermanence. IFDM is but one way that has been proposed to both improve environmental quality in drainage-impacted areas and keep land in production.

Both wheat's and *Brassica*'s inclusion in an IFDM system may be beneficial to the environment: wheat, simply by virtue of being an IFDM crop, and *Brassica* by both being an IFDM crop and by reducing carbon dioxide emissions. Of course, private growers are not likely to take into account environmental benefits when making their cropping decisions. But, they do not have to. They can choose the privately optimal choice, the IFDM crops, and still produce some public benefits. While wheat increases carbon dioxide emissions relative to retirement, it keeps land in production, which may have some regional labor benefits as compared to land retirement.[99]

IFDM is meant to link lower valued, saline tolerant crops with more saline water and land. An area that does not experience salinization and drainage-related issues would not implement IFDM, with which our results from Submodel A with 100% Water (A: W100) correspond. If the farm in question is in a drainage-impacted area and does have poor quality land that significantly impacts the growth of higher-valued crops, like in the west-side, then IFDM crops can be more profitable than not using the land at all, shown in Submodel B.

The private profitability of *Brassica* hinges on two components—the price of fossil diesel and the price of the co-product produced. The co-product price is significant, as over half of the yield of *Brassica* becomes seed meal. The social benefits of *Brassica* lie in the reduction of carbon dioxide emissions that biodiesel allows[100]. This benefit could be captured with either a carbon tax or a subsidy for biodiesel users. Varying carbon taxes have been proposed, and their potential

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[99] The growth of wheat requires about 2 to 3 percent more labor than land retirement. This may be important in impoverished areas like the SJV. It is unlikely that wheat, or Brassica, or any annual crop provides ecological benefits as compared to land retirement and establishment of perennial grasses and/or forbs (Levers and Kaffka, 2015).

[100] *Brassica* also uses less nitrogen than wheat. This may be another area of environmental benefit.

affects on Brassica's desirability seem to be very low. It is unknown how subsidies may alter results.

If because of subsidies or price mechanisms *Brassica* becomes more profitable than the higher-valued crops, there would be the very real concern of *Brassica* becoming a food vs. fuel biofuel. This may be particularly true during periods when available water is limited, for instance during a drought.

Many questions could be asked with this modeling framework regarding different crop mixes, different irrigation systems, climate change, subsidies, available water, varying salinity levels, nitrogen emissions, and labor effects.[101] This analysis has provided the mechanism by which these and many other questions about *Brassica's*, other biofuel crops', and non-biofuel crops' inclusion in an IFDM system can be asked.

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[101] We provide data regarding excess nitrogen into the system, which is simply applied nitrogen minus absorbed nitrogen. The N cycle is very complex, and we do not address this. The only thing we can show here is that as more nitrogen intensive crops are grown, more nitrogen is released into the environment. So, for instance, Wheat requires a lot of N, so scenarios involving it produce high levels of N pollution. As drainage water often contains fairly high levels of N, the required applied N for IFDM crops may very well be much lower than we assume here. This would reduce N's impact.

Chapter V: Conclusion

Salt tolerant biofuel crops like Bermuda grass and *Brassica* have potential to be grown on marginal land with drainage water, as part of an IFDM system in the San Joaquin Valley of California. In the process, crop growth may provide remediative effects on the land, in the form of increased soil quality and decreased selenium, benefits to wildlife, drainage water reuse, and carbon dioxide emission reductions.

Chapter Two provides background and preliminary information and arithmetic results. If all possible marginal land in the San Joaquin valley were used to produce Bermuda grass, upwards of 20 million mega-joules of energy could be produced.

In the pursuit of more detailed analytics, Chapter Three develops yield functions that extend the literature by including instantaneous yield reductions and climate data, which enable the functions to show yield differences between irrigation timing and methods and yearly data. Deep percolation functions are also generated that show differences in magnitude when different year's climate data and different irrigation timings are used as inputs. The results of model developed here are compared with that of Letey (2002) and Wang and

Baerenklau (2014). The models have different results, most generally that the Letey Model is less salt sensitive and more water sensitive. The Wang model produces higher relative yield values than the current model. The current model is capable of picking up on rather specific details that are missed by the Wang Model. As salinization and drainage concerns heighten, the capability of the model developed may prove useful when very specific irrigation methods and climate scenarios come into question.

In Chapter Four, using the functions developed in Chapter Three, it is shown that *Brassica*'s inclusion in an IFDM system may be beneficial to both the farmer and the environment. IFDM is meant to link lower valued, saline tolerant crops with more saline water and land. An area that does not experience salinization and drainage-related issues would not implement IFDM, which is also shown.

Many more questions could be asked with this modeling framework regarding different crop mixes, different irrigation systems, climate change, subsidies, available water, varying salinity levels, nitrogen emissions, and labor effects. This analysis has provided the mechanism by which these and many other questions about *Brassica's*, other biofuel crops', and non-biofuel crops' inclusion in an IFDM system can be addressed.

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APPENDICES

Appendix 2.A:

Table 2A- 1: Total applied water in acre-m for different crops and years.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Alfalfa-Hay	17,572	12,813	17,369	16,255	14,111	12,158	17,572	15,154	17,361	16,415	12,977
Alfalfa-Seed	11,775	2,924	1,928	444	1,474	3,293	2,492	2,729	2,087	4,299	4,231
Almonds	29,289	31,804	34,926	37,697	40,255	48,509	55,390	66,462	70,520	68,121	68,515
Apples	988	620	409	339	255	162	291	250	260	230	97
Apricots	526	521	457	466	412	457	424	390	430	484	488
Artichokes	39	32	33	-	-	-	9	63	-	-	-
Asparagus	660	499	511	472	352	447	553	580	573	416	136
Barley	3,132	6,908	3,490	3,291	2,554	5,501	2,582	2,333	4,838	1,690	2,396
Beans-Dry	843	449	833	723	626	431	390	290	510	2	235
Beans-Garbanzo	6,158	6,340	3,098	869	1,404	3,136	4,840	1,047	1,478	6,899	4,281
Beans-Green	1,045	527	324	210	1,213	601	132	197	2	-	25
Beans-Jojoba	-	-	-	8	8	8	8	8	8	8	8
Blueberries	-	-	-	-	-	2	37	160	242	92	104
Broccoli	1,654	2,328	3,325	3,462	4,978	4,945	4,187	1,176	868	1,158	1,085
Cabbage	43	264	62	-	-	-	42	8	-	-	-
Cantaloupes	11,090	8,550	8,693	10,188	10,797	11,876	9,498	10,100	10,034	7,546	9,224
Carrots-Bulk	400	345	49	366	447	947	390	771	711	341	440
Cauliflower	44	66	23	-	120	-	-	2	216	-	-
Cherries	87	101	150	178	168	274	305	230	209	368	272
Corn-Field	705	401	1,083	449	438	1,032	2,466	4,067	2,781	1,367	431
Corn-Sweet	4,308	3,679	5,338	6,026	5,991	5,512	5,870	6,355	5,709	5,626	7,796
Corn Nutes	182	147	163	-	-	-	-	-	-	-	-
Cotton-Lint-	137,267	74,946	77,195	92,852	77,908	56,935	33,655	19,287	4,650	1,247	3,200
Cotton-Lint-Pima	21,354	68,744	46,274	28,667	52,483	54,109	65,613	57,042	23,845	12,095	29,169
Cucumbers	190	181	420	420	383	345	271	290	71	-	348
Eucalyptus	52	47	45	45	21	86	21	-	-	-	-
Garlic	15,003	16,158	18,174	19,698	17,246	10,095	11,186	13,425	10,972	9,449	10,541
Grain-Hay	-	-	-	-	-	-	-	-	959	876	14,204
Grains-Sorghum	959	2,042	732	75	1,142	3,255	14,701	-	8,793	1,407	613
Grapefruit	29	29	29	29	29	29	52	23	82	15	-
Grapes-Juice	-	-	-	79	-	-	-	-	-	-	-
Grapes-Raisin	-	-	64	81	352	402	202	99	368	194	198
Grapes-Table	445	441	395	542	321	225	362	533	162	671	500
Grapes-Wine	3,852	3,999	3,635	2,980	2,952	4,137	5,011	5,241	5,543	5,238	5,140
Honeydew Melons	1,100	1,596	1,906	1,873	1,440	2,452	2,076	1,681	1,509	1,961	2,150
Jojoba	8	8	-	-	-	-	-	-	-	-	-
Lemons	-	-	-	-	-	-	-	76	76	76	76
Lettuce-Fall	12,680	11,247	12,769	12,639	11,598	15,505	13,681	7,613	13,634	8,192	8,999
Lettuce-Spring	16,692	16,960	18,201	16,437	17,755	17,799	19,285	19,099	6,030	9,676	11,237
Melons-Mixed	408	418	380	364	681	342	624	243	-	-	-
Mustard	-	36	151	136	234	77	-	88	58	-	-
Nectarines	32	-	-	91	225	360	427	384	384	321	375
Nursery	-	-	-	-	-	-	-	-	-	-	359
Oats	-	170	1,554	761	11	1,569	-	-	-	-	694
Olives	25	25	25	-	-	-	-	-	-	-	-
Onions-Dehy	17,554	14,496	17,269	-	-	18,568	22,794	16,803	12,333	10,533	10,573
Onions-Fresh	2,449	3,284	2,915	3,885	3,813	4,712	4,746	5,221	4,192	5,020	5,466
Oranges	149	149	718	149	149	546	778	1,069	1,134	1,116	986
Parsley	428	419	322	721	463	161	933	1,078	577	619	890
Pasture	1,895	2,120	1,902	2,049	682	2,874	1,252	1,447	1,352	350	430
Peaches	212	210	913	1,065	1,479	1,041	1,110	1,084	1,110	1,157	1,050
Peas	-	-	-	-	-	4	-	-	-	91	85
Peppers-Misc.	2,662	2,728	1,850	2,405	3,501	3,031	3,240	3,165	1,823	1,128	1,237

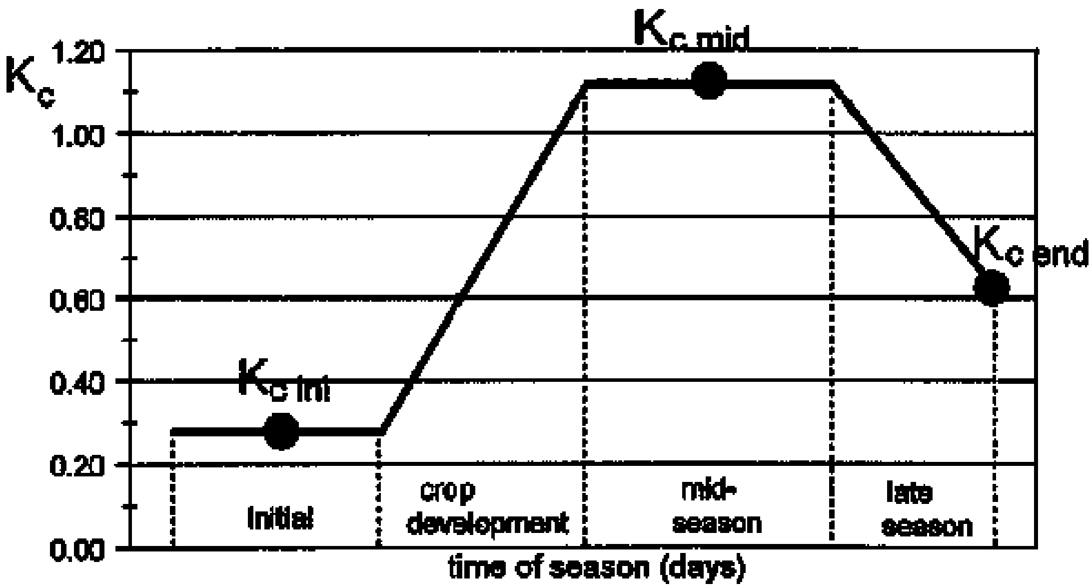
Table 2A-1 Continued.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Pistachios	5,844	10,630	12,976	12,708	11,239	13,531	17,232	19,173	24,046	19,813	21,983
Plums	-	-	302	149	273	354	380	285	296	324	418
Pluots	-	-	-	-	-	87	17	166	166	124	-
Pomegranates	1,239	1,298	1,443	1,557	1,738	1,829	1,908	2,646	3,148	3,575	3,533
Potatoes	17	-	-	-	-	-	-	-	-	-	-
Prunes	154	237	154	154	231	231	227	231	307	153	153
Pumpkins	47	-	5	-	-	-	-	3	-	15	8
Radicchio	3	17	-	48	-	-	-	-	-	-	-
Safflower	1,347	2,688	2,412	1,363	122	805	1,563	4,731	23,642	800	639
Seed Crop-Misc	1,449	1,821	1,494	1,042	1,837	815	1,462	789	945	276	626
Spinach	-	40	40	163	134	32	150	134	97	212	148
Squash	-	-	-	-	20	41	-	15	-	38	77
Stevia	-	-	-	-	-	-	-	-	-	48	4
Sugar Beets	18,227	10,683	10,845	10,634	10,068	10,169	9,021	11,899	6,467	-	-
Sunflower	-	-	-	-	-	-	-	44	-	-	-
Tangerines	39	39	39	39	143	143	143	143	39	69	474
Tomatoes-Fresh	2,958	2,934	2,574	4,140	2,976	4,293	5,333	5,171	3,196	2,761	3,179
Tomatoes-Proc.	101,327	87,385	96,396	93,930	98,567	86,242	93,258	101,901	91,757	83,429	80,501
Walnuts	461	357	358	413	409	407	409	409	358	298	449
Watermelons	1,706	1,773	1,604	2,085	2,688	2,176	2,157	2,492	1,556	3,141	4,579
Wheat	14,445	17,856	17,360	29,385	22,039	24,684	17,799	17,987	32,871	27,304	38,979

APPENDIX 2. B

Crop evapotranspiration or ETc is equal to Kc(ETo), where Kc is the crop specific coefficient and ETo is the reference ET. During a plant's growth cycle, it has several different Kc values, an initial Kc, a mid Kc, and an ending Kc, as illustrated in the following diagram, Figure 2.B.1.

Figure 2B- 1: Kc over a season.



These values are available from FAO. For crops that did not have a published value, a substitute value was used as shown in Table 2B.1.

Table 2B- 1: Crops with unpublished Kc stage values and the substitutes that were used.

Crop	Substitute
Beans-Jojoba	Beans-Dry
Cantaloupes	Melons
Corn Nuts	Sweet Corn
Eucalyptus	Almond
Grapes-Juice	Wine Grapes
Honeydew	Melons
Jojoba	Beans-Dry
Mustard	Rapeseed
Nursery	Mean
Parsley	Spinach
Pomegranates	Apples
Radicchio	Small Veg.
Seed Crop-Misc	Mean
Stevia	Mean
Vetch	Small Veg.

ETo was calculated using the monthly average ETo values from CIMIS. The initial period was assumed to have begun on the first day of the planting month indicated. Up to the first 30 days of the initial period was assigned 1/30 of the first month's value. The next 30 days were assigned 1/30 of the value of the second month, etc. The ETo of the mid stage was calculated similarly. The development and late stages were found by finding the average between the initial value and mid value and the mid and late value, respectively. Please see the following example of a cruciferous friend for clarification.

Example: Broccoli, Planting Month: September; Year: 2003

Table 2B- 2: Crop Coeffiencts

	Initial	Dev	Mid	Late
Kc	0.7		1.05	0.95
Days	35	45	40	15

Table 2B- 3: ET$_0$

Month	1	2	3	4	5	6	7	8	9	10	11	12
ETo	14.44	51.94	116.59	130.75	196.6	227.75	232.3	204.31	171.05	124.69	52.43	31.39

Initial Stage ETc = 0.7*171.05*(30/30)+124.69*(5/30)= 139.7

Development ETc = 0.5*(0.7+1.05)*171.05*(45/30) =224.5

Mid ETc =1.05*(40/30)*0.5(52.43+31.39)=58.67

Late ETc =0.5*(0.95+1.05)*(15/30)*14.44 = 7.22

Total 2003 Seasonal Broccoli ETc = 430.1 mm

Appendix 3.A: Model Specifics

Kan et al. (2002)

For variable definitions, see Tables 3A-1 and 3A-2. Seasonal yield is defined as a function of actual seasonal evapotranspiration and minimum seasonal evapotranspiration:

$$[3A.1]\ y^s = \psi 1 \ \ [e^s - \underline{e}] + \psi_2[e^s - \underline{e}]^2.$$

Seasonal evapotranspiration is substituted for water uptake. Osmotic pressure is assumed to be a scalar multiple of the salinity concentration of the irrigation water. Matric pressure head is assumed to be an exponential function of applied water. These assumptions and substitutions allow seasonal evaporation to be written as:

$$[3A.2]\ e^s = \frac{\bar{e}}{1+\alpha_1(c+\alpha_2 w^{\alpha_3})^{\alpha_4}}$$

The authors used van Genuchten and Hoffman's S-shaped stress relationship in to generate [A3]:

$$[3A.3]\ w^a = \frac{\bar{e}}{1+\left(\frac{\alpha h_m + h_c}{h_{50}}\right)^b}$$

The authors used data generated from their steady-state model to run regressions on equations [A1] and [A2] to generate parameters.

In their steady-state model, the authors use seasonal evapotranspiration, given as the min function:

$$[3A.4]\ e^s = min[w, \overline{e}]\ e^r,$$

Maas and Hoffman(1984)'s crop specific relationships between soil salinity and yield, an assumed linear relationship between evapotranspiration and yield, and Hoffman and van Genuchten (1983)'s soil salinity function, that is dependent on water uptake, water salinity, and evapotranspiration, and an assumption of marketable yield equating to vegetative yield.

The authors assume a spatial distribution function of applied water over the field, which accounts for nonuniformity. Using published parameter rates, this steady-state model generates sets of data comprising of applied water, salinity of irrigation water, actual evapotranspiration, and yield.

Wang and Baerenklau (2014):

For variable definitions, see Tables 3A-1 and 3A-3. Wang and Baerenklau (2014) also employ a two-step process fitting generated data to analytical functions. Seasonal yield is given as:

$$[3A.5]\ y^s = R\overline{y}$$

Relative yield is defined following the Mitscherlich-Baule form and is:

$$[3A.6]\ R = \prod_{j=\{w,n,s\}} 1 - e^{-\beta_j^1\left(j-\beta_j^2\right)}$$

Wang and Baerenklau (2014) found thattheresimulated data was bell shaped, which did not fit this functional form. To account for this shape, she introduced a water parameter, which is based on the logistic probability function, which allowed for relative yield of each salinity level to be modified as:

$$[3A.7]\ R = (1 - e^{-\beta_w^1(\varphi w-\beta_w^2)})\left(1 - e^{-\beta_n^1(n-\beta_n^2)}\right)$$

with a resulting water parameter as:

$$[3A.8]\ \varphi = \frac{4e^{\gamma_1 w+\gamma_2}}{(1+e^{\gamma_1 w+\gamma_2})^2} + \gamma_3$$

By effectively removing salinity from the function, all of the coefficients are estimated as multinomial functions of salinity of the form:

$$[3A.9]\ Coefficient\ =\ \mathrm{B}_0 +\ \mathrm{B}_1 s + \mathrm{B}_2 s^2 \ldots$$

To generate data to fit to these functions, Wang and Baerenklau (2014) use HYDRUS-1D. HYDRUS contains a salinity module that can use van Genuchten and Hoffman's S-shaped stress function to estimate water uptake reduction by specific crops. HYDRUS can also specify solute uptake, which is used here to estimate nitrogen uptake. The authors then use Pang and Letey’s (1998) relative yield definition:

$$[3A.10] \qquad R = min\left[\frac{w^a}{w^p}, \phi\left(\frac{n^a}{n^p}\right)\right]$$

For varying levels of applied water, applied nitrogen, and salinity,[102] the authors use HYDRUS to estimate actual water uptake and actual nitrogen uptake over the season. They then compare these values to potential rates and determine estimated relative yield. These values are used to fit the above equations and coefficients are generated.

Current Analysis:

For variable definitions, see Tables 3A-1 and 3A-4. The methodology presented here follows that of Wang and Baerenklau (2014), with the following differences:

1) The Mitscherlich-Baule form is not modified to include a water coefficient.

2) The coefficients are solved for and different values are used for varying levels of applied water salinity. This keeps the fit higher, but requires HYDRUS be run for specific desired levels of salinity.

3) Pang and Letey (1998)'s relative yield form is used, but the nitrogen coefficient, ϕ is assumed to be one.[103]

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[102] Applied water levels were twenty-five to two hundred percent of seasonal evapotranspiration. Nitrogen was likewise twenty-five percent to two hundred percent potential nitrogen uptake. Salinity was zero to one hundred percent of $\overline{EC}$, which is that point at which yield goes to zero (from Maas and Hoffman).

[103] Per personal communications with Jirka Simunek (2013).

4) Evapotranspiration is split into transpiration and soil evaporation via FAO guidelines.

5) Instead of seasonal yield reductions, instantaneous yield reductions throughout the growing season are used. HYDRUS was modified by Jirka Simunek to make this possible. This allows intra-seasonal affects to be included in the analysis. Relative yield, then, is:

$$[3A.11] \qquad R = \int 1 - yr(t)$$

where yield reduction at time t is:

$$[3A.12] \qquad yr(t) = max\left[\frac{\tau^p(t)-\tau^a(t)}{w^p}, \frac{n^p(t)-n^a(t)}{n^p}\right]$$

This means that throughout the growing season, nitrogen or water, whichever is the limiting factor, will reduce the potential relative yield accordingly. This is a more accurate representation of how plants grow. As an example, a plant given a certain amount of water all in the last day of its growing season cannot possibly obtain the same relative yield as a plant given the same amount of water spread throughout the season. This additional specificity opens the analysis up to include varying irrigation systems and climate data.

Table 3A- 1: Shared Variables

Variable	Description	Units
e^s	Seasonal actual evapotranspiration	cm
$\underline{e}$	Minimum seasonal evapotranspiration required for any yield	cm
$\overline{e}$	Potential (maximum) evapotranspiration	cm
n^a	Actual nitrogen uptake	kg/ha
n^p	Potential nitrogen uptake	kg/ha
n	Applied nitrogen	kg/ha
R	Relative yield (actual yield over maximum yield)	-
s	Salinity of irrigation water	dS/m
w^a	Actual seasonal water uptake	cm
w^p	Potential seasonal water uptake	cm
w	Applied water	cm
y^s	Seasonal actual yield	kg/ha
$\overline{y}$	Maximum yield	kg/ha

Table 3A- 2: Kan et al. (2002) Variables

Variable	Description	Units
a	Scalar	-
b	Scalar	-
h_m	Matric potential	cm
h_c	Osmotic pressure	cm
h_{50}	Stress at which yield is reduced 50%	cm
ψ	Scalar	-
$\alpha_i;\ i = \{1..4\}$	Coefficients	-
e^r	Proportionate reduction in evapotranspiration due to salinity	-

Table 3A- 3: Wang and Baerenklau (2014) Variables

Variable	Description	Units
ϕ	$\phi(x) = 1.7x - 0.7x^2$	-
$\beta_{\{n,s\}}^{\{1.2\}}$	Nitrogen and Salinity coefficients	-
$\gamma_{\{1,2,3\}}$	Water coefficients	-

Table 3A- 4: Current Analysis Variables

Variable	Description	Units
$n^a(t)$	Actual nitrogen uptake at time t	kg/ha
$n^p(t)$	Potential nitrogen uptake at time t	kg/ha
$\tau^a(t)$	Actual transpiration at time t	cm/d
$\tau^p(t)$	Potential transpiration at time t	cm/d
$yr(t)$	Instantaneous yield reduction at time t	-

Appendix 3.B: Deep Percolation

Deep percolation (D) is the amount of water (either applied, w, or from precipitation, P) that neither transpires nor evaporates (or runs off, for that matter).

$$[3B.1]\ D = P + w - e^{s}$$

where e^s is actual seasonal evapotranspiration that includes both transpiration, T, and evaporation, e. Actual seasonal evapotranspiration is

$$[3B.2]\ e^{s} = RW(T + e)$$

where RW is relative yield HYDRUS provides data on both actual evaporation and water uptake. These data can be pulled from the output files and fit to functions, the functional form of which varies depending on the particular data set as the amount of water actually transpired/evaporated is a function of precipitation (the plant may grow without any irrigation), as well as climate variables, soil characteristics, and crop-specific variables. Relative water uptake is not affected by nitrogen levels, nor is evaporation. The curves took on several different forms, variations of exponential growth and decay including:

[3B.3] RW= α+β/(1+e $RW = \alpha + \beta/(1 + e^{\gamma w})$,

$$[3B.4]\ RW = \alpha + w^{\beta},$$

and [3B.5] e= $\alpha + \beta/(1 - e^{\gamma w})$.

Depending on the crop and salinity levels, more or less parameters may be needed for good fit. Once an appropriate functional form was determined, parameters were fit and RW and e functions were generated. These were then used to estimate deep percolation.

Table 3B- 1: Deep Percolation Variables

Variable	Description	Units
D	Seasonal deep percolation	cm
P	Seasonal precipitation	cm
w	Seasonal applied water	cm
e^s	Seasonal evapotranspiration	cm
RW	Relative water uptake	-
T	Actual water uptake	cm
e	Actual evaporation	cm
α	Crop-system specific parameter	-
β	Crop-system specific parameter	-
γ	Crop-system specific parameter	-

Appendix 4.A: Results

Table 4A- 1: Submodel A Results

Submodel A: No Marginal Land. External Drainage.			
	A:W100	A:W80	A: W60
	100% Water	80% Water	60% Water
Profits (2015 $)			
Profit	4288637	3469353	2269779
Profit/Ha	2144	1735	1135
Fuel (g)			
Fuel Used	185730	181170	170680
High Value Crops (ha)			
Almonds	500	500	321.42
Cotton	300	300	300
Lettuce	400	400	400
Pistachios	160	100	100
Tomatoes	400	400	400
Fallow	240	300	478.58
Emissions			
GHG (CO2 MT)	1885	1839	1733
Nitrogen (MT)	419	422	389

Table 4A- 2: Results with 100% Water Allocation and 4 dS/m Salinity

Submodel B: 90 cm Water (100%-1800 ha-m total). Drainage Salinity is 4 dS/m.					
	B_R:S4-W100	B_B:S4-W100	B_W:S4-W100	B_E: S4-W100	A:W100
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Wheat	
Profits (2015 $)					
Profit	2264907	2517379	2575847	2575847	4288637
Profit/Ha	1132	1259	1288	1288	2144
Fuel (g)					
Fuel Used	143057	150636	150719	150719	185730
Fuel Produced	0	74955	0	0	0
Fuel Needed	143057	75681	150719	150719	185730
High Value Crops (ha)					
Almonds	500	500	500	500	500
Cotton	300	300	300	300	300
Lettuce	100	100	100	100	400
Pistachios	160	160	160	160	160
Tomatoes	440	440	440	440	400
IFDM (ha)					
Brassica	N/A	462.17	N/A	N/A	0
Wheat	N/A	N/A	467.24	467.24	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	41.51	37.83	32.76	32.76	N/A
Fallow	458.49	0	0	0	240
Emissions					
GHG (CO2 MT)	1452	1217	1530	1530	1885
Nitrogen (MT)	353	405	545	545	419

Table 4A- 3: Results with 80% Water Allocation and 4 dS/m Salinity

Submodel B: 72 cm Water (80%-1440 ha-m total). Drainage Salinity is 4 dS/m.

	B_R:S4-W80	B_B:S4-W80	B_W:S4-W80		A:W80
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Wheat	
Profits (2015 $)					
Profit	2193814	2452908	2496343	2496343	3469353
Profit/Ha	1097	1226	1248	1248	1735
Fuel (g)					
Fuel Used	143693	151454	151538	151538	181170
Fuel Produced	0	76749	0	0	0
Fuel Needed	143693	74705	151538	151538	181170
High Value Crops (ha)					
Almonds	500	500	500	500	500
Cotton	300	300	300	300	300
Lettuce	140	140	140	140	400
Pistachios	160	160	160	160	100
Tomatoes	400	400	400	400	400
IFDM (ha)					
Brassica	N/A	473.23	N/A	N/A	0
Wheat	N/A	N/A	478.32	478.32	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	29.87	26.77	21.68	21.68	N/A
Fallow	470.13	0	0	0	300
Emissions					
GHG (CO2 MT)	1459	1218	1538	1538	1839
Nitrogen (MT)	364	417	561	561	422

Table 4A- 4: Results with 60% Water Allocation and 4 dS/m Salinity

Submodel B: 54 cm Water (60%-1080 ha-m total). Drainage Salinity is 4 dS/m.					
	B_R:S4-W60	B_B:S4-W60	B_W:S4-W60		A:W80
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Wheat	
Profits (2015 $)					
Profit	1593962	1864224	1882699	1882699	2269779
Profit/Ha	797	932	941	941	1135
Fuel (g)					
Fuel Used	148834	156910	159189	159189	170680
Fuel Produced	0	79862	0	0	0
Fuel Needed	148834	77048	159189	159189	170680
High Value Crops (ha)					
Almonds	500	500	478.39	478.39	321.42
Cotton	300	300	300	300	300
Lettuce	200	200	221.61	221.61	400
Pistachios	100	100	100	100	100
Tomatoes	400	400	400	400	400
IFDM (ha)					
Brassica	N/A	492.43	N/A	N/A	0
Wheat	N/A	N/A	495.77	495.77	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	10.79	7.57	4.23	4.23	N/A
Fallow	478.42	0	0	0	478.58
Emissions					
GHG (CO2 MT)	1511	1260	1616	1616	1733
Nitrogen (MT)	389	445	592	592	389

Table 4A- 5: Results with 100% Water Allocation and 8 dS/m Salinity

Submodel B: 90 cm Water (100%-1800 ha-m total). Drainage Salinity is 8 dS/m.					
	B_R:S4-W100	B_B:S4-W100	B_W:S4-W100	B_E: S4-W100	A:W100
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Brassica	
Profits (2015 $)				0	
Profit	2264907	2468724	2264907	2468724	4288637
Profit/Ha	1132	1234	1132	1234	2144
Fuel (g)				0	
Fuel Used	143057	150625	143057	150625	185730
Fuel Produced	0	69526	0	69526	0
Fuel Needed	143057	81099	143057	81099	185730
High Value Crops (ha)				0	
Almonds	500	500	500	500	500
Cotton	300	300	300	300	300
Lettuce	100	100	100	100	400
Pistachios	160	160	160	160	160
Tomatoes	440	440	440	440	400
IFDM (ha)				0	
Brassica	N/A	461.5	N/A	461.5	0
Wheat	N/A	N/A	0	N/A	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	41.51	38.5	41.51	38.5	N/A
Fallow	458.49	0	458.49	0	240
Emissions				0	
GHG (CO2 MT)	1452	1240	1452	1240	1885
Nitrogen (MT)	353	408	353	408	419

Table 4A- 6: Results with 80% Water Allocation and 8 dS/m

Submodel B: 72 cm Water (80%-1440 ha-m total). Drainage Salinity is 8 dS/m.					
	B_R:S4-W80	B_B:S4-W80	B_W:S4-W80		A:W80
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Brassica	
Profits (2015 $)					
Profit	2193814	2403082	2193814	2403082	3469353
Profit/Ha	1097	1202	1097	1202	1735
Fuel (g)					
Fuel Used	143693	151445	143693	151445	181170
Fuel Produced	0	71208	0	71208	0
Fuel Needed	143693	80237	143693	80237	181170
High Value Crops (ha)					
Almonds	500	500	500	500	500
Cotton	300	300	300	300	300
Lettuce	140	140	140	140	400
Pistachios	160	160	160	160	100
Tomatoes	400	400	400	400	400
IFDM (ha)					
Brassica	N/A	472.66	N/A	472.66	0
Wheat	N/A	N/A	0	N/A	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	29.87	27.34	29.87	27.34	N/A
Fallow	470.13	0	470.13	0	300
Emissions					
GHG (CO2 MT)	1459	1241	1459	1241	1839
Nitrogen (MT)	364	420	364	420	422

Table 4A- 7: Results with 60% Water Allocation and 8 dS/m Salinity

Submodel B: 54 cm Water (60%-1080 ha-m total). Drainage Salinity is 8 dS/m.					
	B_R:S4-W60	B_B:S4-W60	B_W:S4-W60		A:W80
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Brassica	
Profits (2015 $)					
Profit	1593962	1812376	1593962	1812376	2269779
Profit/Ha	797	906	797	906	1135
Fuel (g)					
Fuel Used	148834	156900	148834	156900	170680
Fuel Produced	0	74097	0	74097	0
Fuel Needed	148834	82803	148834	82803	170680
High Value Crops (ha)					
Almonds	500	500	500	500	321.42
Cotton	300	300	300	300	300
Lettuce	200	200	200	200	400
Pistachios	100	100	100	100	100
Tomatoes	400	400	400	400	400
IFDM (ha)					
Brassica	N/A	491.84	N/A	491.84	0
Wheat	N/A	N/A	0	N/A	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	10.79	8.16	10.79	8.16	N/A
Fallow	478.42	0	478.42	0	478.58
Emissions					
GHG (CO2 MT)	1511	1284	1511	1284	1733
Nitrogen (MT)	389	448	389	448	389

Table 4A- 8: Results with 100% Water Allocation and 12 dS/m Salinity

Submodel B: 90 cm Water (100%-1800 ha-m total). Drainage Salinity is 8 dS/m.

	B_R:S4-W100	B_B:S4-W100	B_W:S4-W100	B_E: S4-W100	A:W100
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Brassica	
Profits (2015 $)				0	
Profit	2264907	2341165	2264907	2341165	4288637
Profit/Ha	1132	1171	1132	1171	2144
Fuel (g)				0	
Fuel Used	143057	150600	143057	150600	185730
Fuel Produced	0	53763	0	53763	0
Fuel Needed	143057	96837	143057	96837	185730
High Value Crops (ha)				0	
Almonds	500	500	500	500	500
Cotton	300	300	300	300	300
Lettuce	100	100	100	100	400
Pistachios	160	160	160	160	160
Tomatoes	440	440	440	440	400
IFDM (ha)				0	
Brassica	N/A	459.93	N/A	459.93	0
Wheat	N/A	N/A	0	N/A	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	41.51	40.07	41.51	40.07	N/A
Fallow	458.49	0	458.49	0	240
Emissions				0	
GHG (CO2 MT)	1452	1305	1452	1305	1885
Nitrogen (MT)	353	412	353	412	419

Table 4A- 9: Results with 80% Water Allocation and 12 dS/m Salinity

Submodel B: 72 cm Water (80%-1440 ha-m total). Drainage Salinity is 8 dS/m.					
	B_R:S4-W80	B_B:S4-W80	B_W:S4-W80		A:W80
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Brassica	
Profits (2015 $)					
Profit	2193814	2272393	2193814	2272393	3469353
Profit/Ha	1097	1136	1097	1136	1735
Fuel (g)					
Fuel Used	143693	151424	143693	151424	181170
Fuel Produced	0	55100	0	55100	0
Fuel Needed	143693	96324	143693	96324	181170
High Value Crops (ha)					
Almonds	500	500	500	500	500
Cotton	300	300	300	300	300
Lettuce	140	140	140	140	400
Pistachios	160	160	160	160	100
Tomatoes	400	400	400	400	400
IFDM (ha)					
Brassica	N/A	471.38	N/A	471.38	0
Wheat	N/A	N/A	0	N/A	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	29.87	28.62	29.87	28.62	N/A
Fallow	470.13	0	470.13	0	300
Emissions					
GHG (CO2 MT)	1459	1308	1459	1308	1839
Nitrogen (MT)	364	425	364	425	422

Table 4A- 10: Results with Water Allocations and 12 dS/m Salinity

Submodel B: 54 cm Water (60%-1080 ha-m total). Drainage Salinity is 8 dS/m.					
	B_R:S4-W60	B_B:S4-W60	B_W:S4-W60		A:W80
	No IFDM	*Brassica*	Wheat	Efficiency	SubModel A
				Brassica	
Profits (2015 $)					
Profit	1593962	1676384	1593962	1676384	2269779
Profit/Ha	797	838	797	838	1135
Fuel (g)					
Fuel Used	148834	156878	148834	156878	170680
Fuel Produced	0	57336	0	57336	0
Fuel Needed	148834	99542	148834	99542	170680
High Value Crops (ha)					
Almonds	500	500	500	500	321.42
Cotton	300	300	300	300	300
Lettuce	200	200	200	200	400
Pistachios	100	100	100	100	100
Tomatoes	400	400	400	400	400
IFDM (ha)					
Brassica	N/A	490.5	N/A	490.5	0
Wheat	N/A	N/A	0	N/A	0
Evaporation Pond	0	0	0	0	N/A
Solar Evaporator	10.79	9.5	10.79	9.5	N/A
Fallow	478.42	0	478.42	0	478.58
Emissions					
GHG (CO2 MT)	1511	1354	1511	1354	1733
Nitrogen (MT)	389	453	389	453	389

Table 4A- 11: Sensitivity Analysis. Low Carbon Tax and High Water

90 cm Water. 4 dS/m. C=$0.05			
	P=$2	P=$3	P=$4
Profits (2015 $)			
Profit	2662794	2587077	2511384
Profit/Ha	1331	1294	1256
Fuel (g)			
Fuel Used	150631	150634	150636
Fuel Produced	74902	74929	74955
Fuel Needed	75729	75705	75681
High Value Crops (ha)			
Almonds	500	500	500
Cotton	300	300	300
Lettuce	100	100	100
Pistachios	160	160	160
Tomatoes	440	440	440
IFDM (ha)			
Brassica	461.84	462.01	462.17
Solar Evaporator	38.16	37.99	37.83
Emissions			
GHG (CO2 MT)	1217	1217	1217
Nitrogen (MT)	405	405	405

Table 4A- 12: Sensitivity Analysis. High Carbon Tax and High Water Allocation

90 cm Water. 4 dS/m. C=$1.00			
	P=$2	P=$3	P=$4
Profits (2015 $)			
Profit	2548870	2473161	2397476
Profit/Ha	1274	1237	1199
Fuel (g)			
Fuel Used	150632	150635	150637
Fuel Produced	74911	74937	74964
Fuel Needed	75721	75698	75673
High Value Crops (ha)			
Almonds	500	500	500
Cotton	300	300	300
Lettuce	100	100	100
Pistachios	160	160	160
Tomatoes	440	440	440
IFDM (ha)			
Brassica	461.9	462.06	462.23
Solar Evaporator	38.1	37.94	37.77
Emissions			
GHG (CO2 MT)	1217	1217	1217
Nitrogen (MT)	405	405	405

Table 4A- 13: Sensitivity Analysis. Low Carbon Tax and Med Water Allocation

72 cm Water. 4 dS/m. C=$0.05			
	B_R:S4-W80	B_B:S4-W80	B_W:S4-W80
	P=$2	P=$3	P=$4
Profits (2015 $)			
Profit	2596489	2521781	2447074
Profit/Ha	1298	1261	1224
Fuel (g)			
Fuel Used	151454	151454	151454
Fuel Produced	76746	76747	76747
Fuel Needed	74708	74707	74707
High Value Crops (ha)			
Almonds	500	500	500
Cotton	300	300	300
Lettuce	140	140	140
Pistachios	160	160	160
Tomatoes	400	400	400
IFDM (ha)			
Brassica	473.22	473.22	473.22
Solar Evaporator	26.78	26.78	26.78
Emissions			
GHG (CO2 MT)	1218	1218	1218
Nitrogen (MT)	417	417	417

Table 4A- 14: Sensitivity Analysis. High Carbon Tax and Med Water Allocation

72 cm Water. 4 dS/m. C=$1.00			
	P=$2	P=$3	P=$4
<u>Profits (2015 $)</u>			
Profit	2482500	2407793	2333086
Profit/Ha	1241	1204	1167
<u>Fuel (g)</u>			
Fuel Used	151454	151454	151454
Fuel Produced	76746	76747	76747
Fuel Needed	74708	74707	74707
<u>High Value Crops (ha)</u>			
Almonds	500	500	500
Cotton	300	300	300
Lettuce	140	140	140
Pistachios	160	160	160
Tomatoes	400	400	400
<u>IFDM (ha)</u>			
Brassica	473.22	473.22	473.22
Solar Evaporator	26.78	26.78	26.78
<u>Emissions</u>			
GHG (CO2 MT)	1218	1218	1218
Nitrogen (MT)	417	417	417

Table 4A- 15: Sensitivity Analysis. Low Carbon Tax and Low Water Allocation

54 cm Water. 4 dS/m. C=$0.05			
	P=$2	P=$3	P=$4
Profits (2015 $)			
Profit	2013282	1935154	1858016
Profit/Ha	1007	968	929
Fuel (g)			
Fuel Used	158470	157345	156910
Fuel Produced	79733	79827	79862
Fuel Needed	78737	77518	77048
High Value Crops (ha)			
Almonds	484.72	495.74	500
Cotton	300	300	300
Lettuce	215.28	204.26	200
Pistachios	100	100	100
Tomatoes	400	400	400
IFDM (ha)			
Brassica	491.63	492.21	492.43
Solar Evaporator	8.37	7.79	7.57
Emissions			
GHG (CO2 MT)	1277	1265	1260
Nitrogen (MT)	444	444	445

Table 4A- 16: Sensitivity Analysis. High Carbon Tax and Low Water Allocation

54 cm Water. 4 dS/m. C=$1.00			
	P=$2	P=$3	P=$4
Profits (2015 $)			
Profit	1894292	1817105	1750421
Profit/Ha	947	909	875
Fuel (g)			
Fuel Used	157450	156910	140738
Fuel Produced	79818	79862	79828
Fuel Needed	77632	77048	60910
High Value Crops (ha)			
Almonds	494.71	500	500
Cotton	300	300	300
Lettuce	205.29	200	100
Pistachios	100	100	100
Tomatoes	400	400	400
IFDM (ha)			
Brassica	492.16	492.43	492.22
Solar Evaporator	7.84	7.57	7.78
Emissions			
GHG (CO2 MT)	1266	1260	1096
Nitrogen (MT)	444	445	416

Appendix 4.B: Hydrus and Relative Yield

Pang and Letey (1998)'s relative yield definition on a seasonal basis is:

$$[4B.1]\quad RY^{L} = \min\left[\frac{w^{a}}{w^{p}}, \frac{n^{a}}{n^{p}}\right],$$

where w^a is actual water uptake, w^p is potential water uptake, n^a is potential nitrogen uptake, n^p is potential nitrogen uptake.

Simulated relative yield is:

$$[4B.2]\quad RY^{s} = 1 - \int yr(t),$$

$$[4B.3]\quad yr(t) = \max\left[\frac{T^{p} - T^{a}}{w^{p}}, \frac{R^{p} - R^{a}}{n^{p}}\right],$$

where T^a is actual transpiration at time t, T^p is potential transpiration at time t, R^a is actual nitrogen uptake at time t, R^p is potential nitrogen demand at time t, and yr(t) is yield reduction at time t.

To generate simulated relative yield for one run of a crop, irrigation system, season, and water/nitrogen application, the user specifies length of a growth season, soil hydraulic and plant properties, and number of inputs, generally two per day[104]. For each input time, the user specifies precipitation

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[104] The inputs are the number of divisions made in a growing season. For example, if a growing season is 180 days, we select 360 inputs. This means the growing season is divided into 360 twelve hour segments. Two inputs are chosen per day so that precipitation and applied water can be assigned different salinity and nitrogen concentrations.

(either actual or irrigation), potential evaporation, potential transpiration, concentration of salinity in precipitation/irrigation water, concentration of nitrogen in precipitation/irrigation water, and potential nitrogen plant uptake.

Hydrus sums the potential transpira to determine total potential transpiration, synonymous with Σw^p, While transpiration and water uptake are not the same, they are often equated with one another as the transpiration ratio—the ratio of water transpired to weight of dry matter produced—of most crop plants have an order of magnitude equal to two as illustrated in Ward and Trimble (2003). Similarly, the potential solute uptake is summed to determine cumulative potential nitrogen demand, Σn^p.

To calculate instantaneous yield reduction at each time step, Hydrus applies the simulated relative yield equation, [4.B2] and [4.B3]. In order to estimate a yield function for a specific crop, season, and irrigation scheme that is dependent on water, salinity, and nitrogen, data is inputted for at least five levels of applied water (ΣT^p[0.25, 0.5, 1, 1.5, 2]), five levels of applied nitrogen (ΣR^p [0.25, 0.5, 1, 1.5, 2]), and six levels of salinity ($\bar{E}C$ [0, 0.2, 0.4, 0.6, 0.8, 1]) , where $\bar{E}C$ is the level of salinity at which relative yield decreases to zero. This makes for 150 runs of Hydrus for each set of inputs.

Appendix 4.C: Mathematica and Relative Yield

Wang and Baerenklau (2014)'s general relative yield equation does not fit our data well. This is likely because Wang's results were bell shaped and ours continue to increase as water and nitrogen increase. This difference is likely due to our inclusion of evaporation. We use the relative yield definition of MB:

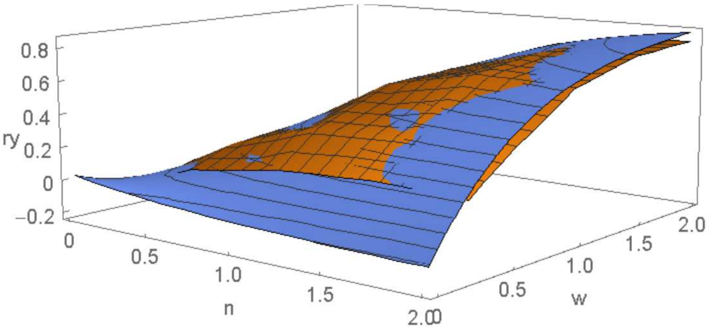
$$[4C.1]\ RY = (1-EXP(-b_n^1(n-b_n^2)))\ (1-EXP(-b_s^1(s-b_s^2)))\ (1-EXP(-b_w^1(w-b_w^2))),$$

where w is applied water depth, n is applied nitrogen, s is salinity. The remaining parameters are estimated with Mathematica.

If an entire data set is used, functions are generated with adjusted R-squared values of approximately 0.75. However, if sets specific to certain levels of salinity are generated, we find R-squared values of approximately 0.99 (Figure C1).

For higher accuracy, we separate the data into groupings by salinity ([0, 0.2, 0.4, 0.6, 0.8, 1.0]*ECmax), then we estimate parameters for the each set of values.

Figure 4C- 1: Hydrus Simulated Data from Tomatoes (Orange) vs. Mathematica Fitted Data (Blue). Adj. R^2=0.992213. Salinity is zero.



Since the amount of water actually transpired is a function of precipitation (the plant may grow without any irrigation), we used multiple different functions for different levels of salinity. Each set of applied water and relative water uptake (T^p/T^a) values had to be examined, then a function was chosen and nonlinear regression was performed in Mathematica to fit the data. As an example, *Brassica* in the 2011 season with furrow irrigation and a salinity level of 0.2 times its EC max had a fitted relative water uptake of:

$$[4C.2]\ RW = a_{0.2} + b_{0.2} /(1+e\text{^}(c_{0.2}*w_{ij})),$$

where $a_{0.2}$, $b_{0.2}$, and $c_{0.2}$ are parameters estimated my Mathematica. With the same inputs, but a salinity level of 0.4 times EC max,

$$[4C.3] \quad RW = a_{0.4} + w_{ij} \hat{} b_{0.4}.$$

This is an interesting area, and future analyses may include the investigation of a functional form that can be used throughout salinity levels.

Appendix 4.D: Hydrus Loop using Matlab

Hydrus inputs are stored in text files. The ATMOPH.IN file stores the Time Variable Boundary Conditions, which is where the evaporation, transpiration, irrigation, precipitation, applied water, salinity, and applied nitrogen are inputted. Instantaneous yield reduction and cumulative relative yield are outputted into the PROFILE.OUT file.

To simulate a particular crop/irrigation scheme/season, first we input the correct crop and soil specific into Hydrus. Then, we run Matlab code that we wrote to run Hydrus on a loop to complete the 150 iterations necessary.

The Matlab code does the following:

1. Calls the correct crop/irrigation/season file.
2. Creates a shell file to contain the relative yield output.
3. Creates an empty matrix to contain the relative yield data.
4. Recreates the contents of ATMOSPH.IN.
5. Generates a 150 cycle loop.
    a. Opens ATMOSPH.IN.
    b. Writes to ATMOSPH.IN, pulling the correct applied water/salinity/nitrogen data (seasonal data does not change).
    c. Runs Hydrus.

d. Opens and reads PROFILE.OUT, pulling the cumulative relative yield value.

e. Places relative yield in the matrix created above.

6. Outputs the matrix to the shell file.

Appendix 4. E: Evapotranspiration

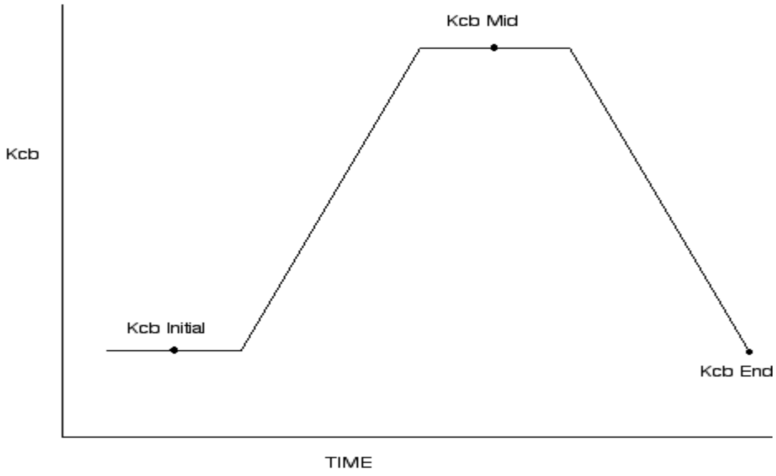
To increase accuracy in the evaporation/transpiration division, the FAO has published a procedure for splitting K_c into its components, K_{cb}, the transpiration coefficient, and K_e, the soil evaporation coefficient (Crop, 1998) . As a crop grows throughout the season, it goes through different stages, which have varying levels of K_{cb}. The FAO has broken these stages down into the initial stage, the development stage, the middle stage, and the end stage. $K_{cb(tab)}$, estimates of K_{cb} values for the initial stage, the middle stage, and the end are published on FAO's website, along with the lengths of the stages for different crops in different areas. The initial stage's $K_{cb(tab)}$ does not need to be modified, but the mid and end stages do since the climate varies:

$$[4E.1] \quad K_{cb} = K_{cb(tab)} + [0.04(u-2) - 0.004(RH_{min} - 45)](\frac{h}{3})^{0.3},$$

where K_{cb} is the calculated value, $K_{cb(tab)}$ is the FAO, unmodified value, u is wind speed (m/s), h is plant height in meters, and RH_{min} is the minimum daily relative humidity (%). The K_{cb} values for the development and end stages are extrapolated from the three points discovered above. See Figure (4E-1).

Crop transpiration can then be calculated by multiplying the respective K_{cb} values by the ET_0 for each day in the plant's growing season. These values are then entered into Hydrus and do not vary for different irrigation schemes.

Figure 4E- 1: K_{cb} over Time



Since Hydrus allows daily data inputs, very specific irrigation schemes can be inputted. Each of these will have different daily K_e values. When the topsoil has just been wetted, K_e is at its maximum. However, K_e can never exceed a maximum value, K_{cmax}. When the topsoil is dry, K_e is very small, possibly zero. K_e is expressed as:

$$[4E.2] \qquad K_e = \min(K_r(K_{c\max} - K_{cb}), f_{ew}K_{c\max}),$$

where K_r is a dimensionless evaporation coefficient dependent on the cumulative depth of water depleted from the topsoil, and f_{ew} is the fraction of the soil that is wetted and exposed and is dependent on the irrigation method and the crops. Following wetting, K_r is 1. As the soil dries, K_r reduces and becomes zero when all the water is gone. K_r estimation requires a daily water balance computation.

Once daily K_e is estimated, K_e can be multiplied by ET_0 to determine daily crop evaporation. These values can then be inputted into Hydrus.

Appendix 4.F: Model Parameters

Table 4F- 1: Crop Parameters[105][106]

	Prices ($/kg)	**Max Nitrogen (kg)**	**Production Costs ($/ha)**
Almonds	8.00	200	7364
Tomatoes	0.11	165	3528
Cotton	2.00	200	1372
Wheat	0.26	280	788
Lettuce	0.85	225	6531
Pistachios	6.06	150	7054
Brassica	0.40 (meal)	100	357

	Potential Yield (MT)	**Production Labor (hrs/ha)**	**Harvest Labor (hrs/kg)**
Almonds	2.5	68.18	N/A
Tomatoes	85	16.76	0.0003
Cotton	3.0	23.56	0.0029
Wheat	10	2.03	0.0004
Lettuce	35	50.00	N/A
Pistachios	2.8	33.00	N/A
Brassica	2.0	2.47	0.0004

	Fuel (g/ha)	**Irrigation ($/ha)**	**Irrigation Fuel (g/ha)**
Almonds	58.74	342	N/A
Tomatoes	143.5	247.9	2.30
Cotton	67.8	22.9	2.93
Wheat	13.4	0	N/A
Lettuce	125.0	111.4	36.68
Pistachios	74.0	95	2.00
Brassica	13.4	0	N/A

	Harvest Cost ($/kg)	**Irrigation Labor (hr)**
Almonds	0.330	8.60
Tomatoes	0.005	27.1
Cotton	0.119	10.3
Wheat	0.010	0.75
Lettuce	0.516	39.75
Pistachios	0.349	12.9
Brassica	0.023	0.75

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[105] Values were calculated from UC Davis Cost and Return Studies. Almonds, Lettuce, and Pistachios were assumed to hire out crews to harvest. Data on hours were not available. These costs were transferred into the production category. Fuel values were not given for Almond, Wheat, or Brassica irrigation. These costs were absorbed by the fixed irrigation and production costs. Likewise, values were not provided for Wheat or Brassica irrigation fixed costs.

[106] Potential yields were determined by calculating relative yield for the irrigation system, timing, and water levels given in the Cost and Return Studies, then matching the values.

Table 4F- 2: Model Scalars

Costs	**Values**	**Units**
Evap Pond Pumping	0.1531106	$/cm-ha
Solar Evap Pumping	6.18	$/cm-ha
Water	3.34	cm-ha
Labor	12	$/hour
Seed Press	200074	$
Energy		$/kwh
Solar Evap	23743	$/ha
Evap Pond	411.95	$/ha
Habitat	5278.7	$/ha
Rates		
Evap Pond	162.15	cm water/ha
Solar Evap	1243	cm water/ha
Energy/cycle press	1000	kwh
Labor/cycle press	50	hours
Seed processing	18144	kg/cycle
Mass of gal of oil	3.48	kg
Press Efficiency	0.8	
Interest	0.05	
Lifespans		
Seed Press	20	yrs
Solar Evaporator	20	yrs
Almonds	24	yrs
Pistachios	24	yrs