IMPLICATIONS OF THE WATER-ENERGY-FOOD NEXUS ON COASTAL GROUNDWATER MANAGEMENT, PAJARO VALLEY, CA

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CERTIFICATION OF APPROVAL

I certify that I have read *Implications of the Water-Energy-Food Nexus on coastal groundwater management, Pajaro Valley, CA* by Lauren Rachael Finkelstein, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Geosciences at San Francisco State University.

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In the Pajaro Valley in central California USA, intensive groundwater use for agricultural development has led to a 12,000 acre-foot per year groundwater overdraft and seawater intrusion since the 1950s. Consequently, the Pajaro Valley is considered a high priority basin under California's new (2014) Sustainable Groundwater Management Act (SGMA). Groundwater extractions for agriculture can come with significant energy costs; therefore, the Water-Energy-Food (WEF) Nexus theoretical concepts can provide additional information to support evaluation of SGMA requirements and the sustainable use of natural resources. In this study, I explore the implications of applying a WEF Nexus approach to coastal groundwater management and policy in the Pajaro Valley in the context of SGMA regulations. Using results from a regional hydrologic model of the Pajaro Valley, I quantify relationships and linkages (i.e., synergies, alterations, and trade-offs) within the water-for-food and energy-for-water Nexus of the Pajaro Valley. I also explore how these relationships respond to temporal trends in cropping patterns and irrigation demand. I present results that illustrate how understanding the Nexus relationships surrounding water use and availability, energy consumption for groundwater pumping, and food production can provide stakeholders with useful guidelines for optimal farming practices to mitigate seawater intrusion and other trade-offs associated with intensive groundwater use. Findings presented here have important implications for resource managers and policy makers toward developing sustainable groundwater management plans in coastal aquifers.

I certify that the abstract is a correct representation of the content of this thesis.

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PREFACE AND/OR ACKNOWLEDGEMENTS

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1. Introduction

Water, energy, and food are among the most critically important resources for humans and society. However, due to socioeconomic changes (i.e., population growth, globalization, economic growth, urbanization) and climate change, the demand for these resources in California and globally is projected to increase (Hoff, 2011; National Intelligence Council (U.S.), 2012; Endo et al., 2015; Taniguchi et al., 2017b, 2017a; Gurdak, 2017; Al-Saidi and Elagib, 2017; Li et al., 2019). By 2030, the global demand for water, energy, and food is estimated to increase by 40%, 50%, and 35%, respectively (National Intelligence Council (U.S.), 2012). These increased pressures will likely lead to a growing number of trade-offs and potential conflicts among the three resources (Al-Saidi and Elagib, 2017; Endo et al., 2015). Recent advances in science and policy research have demonstrated the benefits of approaching these challenges from the perspective of the inextricable linkages among the three resources and sectors as opposed to using a one-sector view (Al-Saidi and Elagib, 2017). Hence, the Water-Energy-Food (WEF) Nexus concept has recently received broad attention in the scientific literature and emerged in the international community as a new development paradigm (Al-Saidi and Elagib, 2017; Endo et al., 2015; Hoff, 2011; Leck et al., 2015; Li et al., 2019).

The WEF Nexus conceptual Framework (Figure 1) includes water-energy (water for energy and energy for water), water-food (water for food), and energy-food (energy for food and food for energy) relationships, as well as closer cooperation between water, energy, and food sectors (Endo et al., 2015). Within this framework, human and environmental security hinge on a healthy and sustainable WEF Nexus. Examples of water for energy relationships include water used for hydroelectric power, powerplant cooling, and hydraulic fracturing. Examples of energy for water relationships include energy used for groundwater pumping, transporting water, and heating water. Examples of water for food relationships include water used for irrigated agriculture, rainwater harvesting, and aquaculture. Examples of energy for food relationships include energy used in the production, processing, and transportation of food. The relationship of food used for energy includes crops grown for biofuels (Gurdak, 2017). Drivers that influence changes within these relationships and often increase the demand for these resources include socioeconomic changes (Gurdak, 2017) and climate variability and change (CA DWR, 2017).

The inherent complex and interdisciplinary nature of water, energy, and food systems and sectors can be framed by various types of linkages that characterize relationships between the consumption, use, alteration, or production of water, energy, and food (Figure 1). Linkages describe, qualitatively and quantitatively, the synergies, alterations, and trade-offs within the WEF nexus of a given system. Here, I define synergies as relationships where no resource is consumed or degraded in using or producing another resource, or where there exists a mutual benefit or co-production of resources. Alterations are relationships where one resource is altered or degraded, but not consumed, as a result of producing another resource. Trade-offs occur when one resource is produced at the expense of another. Trade-offs often represent the primary source of conflict and disagreement among stakeholders (Gurdak, 2017). A better understanding of WEF Nexus linkages can provide a framework for addressing resource competition and enhancing resource use efficiency as well as cooperation and policy coherence among the three sectors (Golam Rasul and Sharma, Bikash, 2015).

The Nexus conceptualizes that use and production and thus availability and sustainability of water, energy, and food resources have complex interactions across multiple temporal and spatial scales (Gurdak, 2017; Leck et al., 2015). A Nexus approach recognizes the inherent interdisciplinary nature of water, energy, and food systems and sectors and potential strategies for integrated and effective resource management by optimizing Nexus trade-offs and synergies (Golam Rasul and Sharma, Bikash, 2015). Thus, a Nexus approach for the collective management of water, energy, and food resources may help avoid the negative consequences of more siloed management of the three resources (Gurdak, 2017; Mroue et al., 2019) by focusing on system efficiency rather than an individual sector's productivity (Golam Rasul and Sharma, Bikash, 2015). Historically, inadequate consideration or coordination of cross-sectoral interactions has often result in increased vulnerability and decreased resilience of natural resources (Golam Rasul and Sharma, Bikash, 2015). Additionally, in recent years, water and food crises have emerged in relation to drought and heat waves around the globe (Al-Saidi and Elagib, 2017). This type of siloed approach coupled with droughts has led to overdraft of groundwater resources, seawater intrusion (SWI) in coastal systems, groundwater quality degradation, land subsidence and associated infrastructure damage, and loss of aquifer storage (Gurdak, 2017).

Evaluating WEF Nexus relationships requires not only an understanding of the decision-making and human engineered systems of the Nexus, but also an analysis of the biophysical and earth systems (Taniguchi et al., 2013; Vanham, 2015). Here I focus on the coupled human-natural groundwater systems because they are integral resources for energy and food security, ecosystem health, drinking water, and industry needs (Gleeson et al., 2015; Gurdak, 2017), and because groundwater provides a critical buffer to stressors within the WEF Nexus, particularly during droughts. Yet, many of the world's aquifers, especially in semi-arid and arid regions, are pumped at rates far greater than they are recharged. Furthermore, many of these over-drafted aquifers currently sustain some of the world's most productive agricultural regions (Famiglietti, 2014).This poses major implications on the sustainability of global freshwater resources, local WEF Nexus systems, and food security. In the context of groundwater sustainability in California and elsewhere, the management of these groundwater resources from the perspective of the WEF Nexus would allow for the breakdown of silos and a more comprehensive analysis of sustainability.

The environmental consequences of groundwater depletion to support irrigated agriculture extend beyond decreasing freshwater availability. Groundwater depletion also results in various unintended consequences, such as land surface subsidence, streamflow depletion, loss of springs, wetland and ecological damages (Famiglietti, 2014; Konikow and Kendy, 2005), and regional climate feedbacks (Famiglietti, 2014). Furthermore, as water table levels drop, wells may run dry and need to be drilled to deeper depths. Drilling deeper wells is costly and can often result in poor groundwater quality and the need for increased energy consumption to lift groundwater from deeper depths to land surface (Famiglietti, 2014; Konikow and Kendy, 2005), which further drives greenhouse gas emissions, especially when fossil energy is used (Liu, 2017). Another consequence occurs in coastal areas, which often house some of the world's largest cities; coastal aquifers experiencing head declines face the additional threat of SWI and up-coning, leading to a reduction in the available volume and quality of freshwater to meet food and energy system needs (Konikow and Kendy, 2005).

California is a hotspot of global groundwater depletion because of extensive agriculture that requires vast amounts of water and energy (Famiglietti, 2014). A major portion of the state's $45 billion agriculture industry and over 6 million people rely on groundwater (CDFA, 2016), which comprises 30-60% of California's annual water use and provides critical water resources during dry years when surface water is scarce (Liu, 2017). This demand coupled with excessive water extraction has led to rapid decline in water levels and substantial loss of storage, as well as SWI in many of California's coastal aquifers. The importance of groundwater coupled with overdraft conditions and the recent (2012 – 2016) historic drought across California are among the catalysts that led to the implementation of the Sustainable Groundwater Management Act (SGMA) in 2014 (Gurdak, 2017).

SGMA established regulations and a timeline to achieve groundwater sustainability and prioritizes basins with overdraft conditions (Figure 2). Under SGMA, high and medium priority basins are required to form a Groundwater Sustainability Agency (GSA) by 2017 and to develop a Groundwater Sustainability Plan (GSP) by 2020 for critically over-drafted basins and by 2022 for all remaining basins. The GSP will be implemented to achieve groundwater sustainability in critically over-drafted basins by 2040 and for all other remaining basins by 2042 (California Department of Water Resources, 2015).

Although not mentioned by name in the California Department of Water Resources' (DWR) SGMA regulations, theoretical concepts from the WEF Nexus complement many SGMA requirements (Gurdak, 2017). Gurdak (2017) characterized a two-way relationship (i.e., impacts and feedbacks) between the WEF Nexus and SGMA: (1) WEF Nexus thinking may directly impact local managers and the public tasked with designing optimal GSPs to better meet the interests of diverse stakeholders in groundwater resources, and in turn, (2) implementation of SGMA and future sustainable groundwater resources will have positive feedbacks toward a more resilient WEF Nexus across California (Figure 3).

1.1 Knowledge gaps

The WEF Nexus has recently received broad attention in the scientific literature and worldwide (Al-Saidi and Elagib, 2017; Li et al., 2019). Numerous articles have emphasized the importance and theoretical framing of the WEF Nexus (Taniguchi et al., 2017a). However, the literature is in its infancy regarding the practical aspects of science, management, and policy approaches and methods to address the Nexus (Dargin et al., 2019; Li et al., 2019; Taniguchi et al., 2017a). Specifically, a very limited number of studies that quantify the WEF nexus to address resource management of water and energy for agriculture have been reported (Li et al., 2019). To advance the theoretical and applied aspects of the Nexus, further disciplinary and broad interdisciplinary science is required, including collaborative advances from the natural and social sciences and engineering (Taniguchi et al., 2017a). Bridging these knowledge gaps using a WEF Nexus approach requires a better understanding of the inherent relationships and linkages (i.e., synergies, alterations, and tradeoffs) within the WEF Nexus and in the context of groundwater sustainability, as well as case-study based recommendations (Al-Saidi and Elagib, 2017).

1.2 Study objectives

In this thesis, I explore the implications of applying a hydrologic science-based WEF Nexus approach in the context of SGMA to coastal groundwater management and policy in the Pajaro Valley, which is one of the most productive and valuable agricultural regions in California. Specifically, I characterize and quantify relationships and linkages (i.e., synergies, alterations, and trade-offs) of the water-for-food (W-F) (i.e., water for irrigated agriculture) and energy-for-water (E-W) (i.e., energy for groundwater pumping) Nexus relationships in the Pajaro Valley under historical (1960s) to present availability. I then compare and evaluate these relationships surrounding water use and availability, energy consumption, and food production.

By characterizing and quantifying Nexus relationships and linkages, I am able to address the following research questions: (1) What are the significant drivers of trade-offs and alterations and the opportunities for synergies within the W-F and E-W Nexus of the Pajaro Valley? (2) Could modest changes to land-use and farming practices help contribute to an overall reduction of trade-offs and alterations and increase synergies within the W-F and E-W Nexus of the Pajaro Valley? (3) By evaluating research questions (1) and (2), is it possible to substantially reduce SWI while having a minimal effect on the agricultural economy of the Pajaro Valley?

This study is novel and significant because, for the first time, groundwater sustainability in a coastal aquifer is addressed to reduce SWI using a Nexus-based approach. Findings are transferrable to other coastal aquifer systems in California and elsewhere, including practical guidelines on how WEF Nexus concepts can be used to develop effective GSPs. On a global-scale, this project highlights the importance of approaching issues of sustainability and human and environmental security from a WEF Nexus perspective when implementing policy and management decisions.

1.3 Study area

1.3.1 Physiography and Land Use

The Pajaro Valley (Figure 4) comprises the 237 mi^2 coastal part of the Pajaro River watershed adjacent to Monterey Bay, within the Pajaro Valley Water Management Agency (PV Water) boundary in the southern part of Santa Cruz County and the northern part of Monterey County (Hanson et al., 2014). Since the late 1800s, the valley has been developed predominantly for agriculture, though it also contains the city of Watsonville and other small towns and suburban areas (Hanson et al., 2014). Of the approximately 70,000 acres within the PV Water service area, about 40% is agricultural land, 47% is natural vegetation, and 13% is primarily urban land (Hanson et al., 2014).

The Pajaro Valley is one of the most productive and valuable agricultural regions in California and the world (Hanson et al., 2014), with crop value estimated at over $900 million annually (PV Water, 2014). Nearly 100% of irrigated agriculture in the Pajaro Valley is supported by groundwater from the local coastal aquifer system (PV Water, 2014). The demand for limited, available water supplies in the valley (groundwater, captured surface water, and recycled water) has increased over time due to increases in population, agricultural development (such as increased cultivation and shifts to more water-intensive crops), and climate variability (Hanson et al., 2014). Climate variability has been shown to significantly affect inflows, outflows, and water use in the valley (Hanson et al., 2014), influencing an increased demand for groundwater during dry years due to decreased precipitation and recharge. Intensive agricultural pumping to meet these demands has resulted in a 12,000 acre-foot per year (acre-ft/yr) groundwater overdraft (PV Water, 2014) and SWI since the 1950s (Hanson et al., 2014; PV Water, 2014).

To mitigate groundwater overdraft, halt SWI, and improve and protect water quality, all of which threaten the agricultural productivity and economic conditions of the valley, PV Water has worked with local stakeholders to develop a Basin Management Plan (BMP) (PV Water, 2014). The BMP was originally adopted in 1994, revised in 2002, and updated in 2014. Per the 2002 revision and as of 2014, three projects had been completed, including (1) the Harkins Slough Recharge Facilities, (2) the Recycled Water Facility, and (3) a significant portion of the Coastal Distribution System (CDS) (PV Water, 2014). The CDS (see Figure 2-14, PVWMA, 2014) is a pipeline network that distributes blended recycled water (from the Watsonville Recycled Water Facility and blend wells) and recovered Harkins Slough water (from the Harkins Slough Recharge Facilities) for agricultural use in coastal areas most impacted by SWI to reduce groundwater pumping near the coast (PV Water, 2014).

Hydrologic modeling of future simulations (Hanson et al., 2014) showed that these projects reduced, but did not solve, the SWI and overdraft (PV Water, 2014). Hence, the 2014 BMP Update (PV Water, 2014) was created to identify projects and programs to bring the basin back into hydrologic balance and replace previous BMPs. The 2014 BMP updates (PV Water, 2014) include seven programs and projects that consist of three main components: (1) conservation measures (i.e., water use efficiency and water demand reduction alternatives to reduce basin demand), (2) the optimization of existing supplies (i.e., improvements to existing infrastructure to increase water supply including recycled water storage, water deliveries, and Harkins Slough recharge facilities), and (3) new supply projects (i.e., to provide new sources of water to replace groundwater pumping). The seven projects are projected to increase the Pajaro Valley groundwater basin's water supply by 12,100 acre-ft/yr and are estimated to solve 90% of the SWI and 100% of the basin overdraft problems. In addition, seven supplemental future projects have been proposed in case the first seven projects do not meet expectations (PV Water, 2014).

Data analyses in this study reflect the 2002 BMP Revision projects and programs. The 2014 BMP Update is still described here because this WEF Nexus analysis can provide support and guidance as these new projects and programs are developed and implemented. For example, of these seven 2014 projects and programs, irrigation efficiency alone is anticipated to provide 40% of the reduced groundwater pumping needed to bring the basin back into hydrologic balance (PV Water, 2014). Analyzing a basin's hydrologic system using a WEF Nexus approach provides a framework to assess agricultural water-use efficiency and identify opportunities for farmers to profitably use less water (Smidt et al., 2016). Thus, the Pajaro Valley could benefit from examining groundwater sustainability in the context of a comprehensive WEF Nexus approach. As part of this WEF Nexus study in the Pajaro Valley, I analyze the impacts of the CDS system supplemental water supply, climate and market drivers on the Pajaro Valley agricultural WEF Nexus, and three of the valley's major crop types to make basin-wide suggestions for farmers to profitably improve agricultural water use efficiency (WUE).

1.3.2 Geohydrologic framework

I follow the same hydrogeologic framework of the Pajaro Valley as presented by Hanson et al. (2014). The framework includes (1) two layers of the alluvial deposits, which represent an alluvial deposit layer and a basal fine-grained confining unit, (2) three layers of the Aromas Sand, which represent the upper Aromas, an upper Aromas basal fine-grained confining unit, and a lower Aromas unit, and (3) one layer, which represents a combination of the Purisma Formation and other minor pre-Pliocene bedrock units (Hanson et al., 2014).

1.3.3 Conceptual model of the hydrologic system

The Pajaro Valley watershed lies along Monterey Bay. Its aquifers extend offshore, where they crop out along the seafloor and the Monterey submarine canyon walls (Hanson et al., 2014). Thus, the aquifers are susceptible to SWI, which occurs when total outflows (including pumpage) exceed total inflows of freshwater for extended periods of time, resulting in groundwater overdraft (Hanson et al., 2014).

Simulations of inflows and outflows into the basin indicate an average groundwater overdraft of about 12,950 acre-ft/yr from 1964–2009, over which time total pumpage for water supply grew from about 6,000 acre-ft/yr to 11,000–12,000 acre-ft/yr, with variations between wet and dry periods (Hanson et al., 2014). From 1999–2009, groundwater pumpage included 79 percent agricultural supply, 18 percent municipal water supply, and 3 percent domestic use, with variations in agricultural pumpage by as much as 18 percent between consecutive wet and dry years (Hanson et al., 2014); this variation is similar to the 20 percent variation reported for other coastal agricultural basins in California (Hanson et al., 2009). By 2009, over 2700 wells had been constructed and put into use in the Pajaro Valley, including over 1,695 domestic wells, 32 municipal-supply wells, and approximately 1,026 irrigation wells (Hanson et al., 2014).

Prior to development in the Pajaro Valley, groundwater flowed from the foothills of the Santa Cruz Mountains on the east side of the basin to the Pacific Ocean on the west side. Decades of withdrawals in excess of recharge have resulted in onshore flow of seawater and regional cones of depression in the center of the valley. These depressions have superimposed seasonal declines in groundwater levels due to increased agricultural and municipal pumpage during summer (Hanson et al., 2014). As a result of overdraft conditions, chloride contamination of groundwater wells has been detected up to three miles inland in the valley (PV Water, 2014).

The valley is drained by the Pajaro River and its tributaries. Streamflow originates as runoff outside the Pajaro Valley and then enters through the Pajaro River. Runoff from within the valley moves towards small tributaries of the local stream networks and then to the Pajaro River (Hanson et al., 2014). Inflows and outflows in the valley include both natural processes and man-made supply and demand components of water use (Hanson et al., 2014).

1.3.4 Regional climate

The Monterey Bay region climate is Mediterranean, with mild summers and wet, cool winters (Hanson et al., 2014). Mean precipitation in the Pajaro Valley ranges from 406 millimeters near the coast to over 1016 millimeters in the foothills of the Santa Cruz Mountains on the east side of the basin, where most of the annual precipitation volume falls (Hanson et al., 2014). Average annual reference evapotranspiration values show orographic effects similar to precipitation (Hanson et al., 2014).

Long term precipitation and stream flow records suggest a significant influence in climate variability associated with El Niño-Southern Oscillation (ENSO), the North American Monsoon-Pineapple Express (NAMS/PE), and the Pacific Decadal Oscillation (PDO) (Hanson et al., 2014; Velasco et al., 2015). Interannual climate variability has also been shown to significantly affect inflows, outflows, and water use between wet and dry years, by as much as 50% (Hanson et al., 2014). Hanson et al. (2014) and Earll et al. (in prep) characterize relatively wet periods as 1967–70, 1973–74, 1978–83, 1994–2001 (except 1997, which is classified as dry), 2006–07, and 2010–11, and relatively dry periods as 1963–66, 1971–72, 1975–77, 1984–93, 2002–05, 2008–09, and 2012–14. In this study, I assess the impacts of these wet and dry periods on the Pajaro Valley WEF Nexus relationships.

2. Methods

In this study, I characterize and quantify the agricultural WEF Nexus relationships and linkages within the Pajaro Valley coastal aquifer to address issues of groundwater overdraft and SWI. I use a WEF Nexus analysis that is based primarily on the output from a numerical groundwater flow model called the Pajaro Valley Hydrologic Model (PVHM) (Hanson et al., 2014), which has been updated through 2014 (Earll et al., in prep). I also use data from other public sources such as the County of Santa Cruz, the Pajaro Valley Water Management Agency (PV Water) and Pacific Gas and Electric Company (PG&E). The specified methods are described next.

2.1 The Pajaro Valley Hydrologic Model (PVHM)

The Pajaro Valley Hydrologic Model (PVHM) is an existing, calibrated, and integrated model that provides a representation of the regional flow system as well as the conjunctive use and movement of water throughout the Pajaro Valley (Hanson et al., 2014). The PVHM (Hanson et al., 2014) was originally built using MODFLOW 2005 with the Farm Process version 2 (MF2005-FMP2) (Schmid and Hanson, 2009) and spanned the years 1964–2009. An updated version of the PVHM (Earll et al., in prep), which uses the MODFLOW one water hydrologic flow model (MODFLOW-OWHM) (Boyce et al., 2019) with the latest version of the Farm Process (FMP4), covers the years

1964–2014 and was used as the primary source of data to quantify the Pajaro Valley WEF Nexus.

The PVHM was developed to provide local water managers the capability to simulate and analyze BMP project components as the water supply is partially converted from a primarily groundwater system to one that also uses captured runoff and reclaimed water, which are delivered through the CDS in order to reduce coastal pumpage and mitigate groundwater system overdraft and SWI (Hanson et al., 2010). The operation of the CDS was simulated as part of the PVHM for a 13 year period (2002–2014) to evaluate the potential effects of conjunctive use in place of pumpage in several zones of the basin near the coast (Hanson et al., 2014, 2010). The reader is referred to Hanson et al. (2014) for additional details about the PVHM. In this study, I use data related to various PVHM components, including the CDS supplemental water supply, to analyze relationships within the Pajaro Valley WEF Nexus.

2.1.1 Water Balance subregions (WBS)

The PVHM is discretized into water-balance subregions (WBSs) (see Figure 2C in Hanson et al. (2014)) that represent accounting units for water use, movement, and consumption. WBSs can be used to estimate the water balance of land use, streamflow, and groundwater by calculating supply and demand components through time. Many WBSs represent groups of local watersheds, groups of actual farms, or other unique supply and demand subregions (Hanson et al., 2014). Here, I grouped WBSs by location in the coastal region and inland region (based on groupings in Figure 2C in Hanson et al. (2014)). I further subdivided WBSs in the coastal region depending on whether or not they are connected to the CDS (i.e., located within the Delivered Water Zone). I then compare and contrast the WEF Nexus relationships and linkages of the entire Pajaro

Valley as well as various subregions: the coastal region of the Pajaro Valley, the inland region of the Pajaro Valley, and the Delivered Water Zone (Figure 4).

2.1.2 Land Use

The Farm Process component of the PVHM can be used to simulate an assortment of irrigation settings. Land use attributes in the Pajaro Valley are defined on a cell-by-cell basis, and the land use (i.e., urban, agricultural, water bodies, or natural vegetation) covering the largest fraction of each cell (about 15 acres) is considered the representative use of that entire cell. There are 20 land-use categories, which include 17 agricultural classes, urban vegetation, native vegetation, and water (Hanson et al., 2014). In this study, I focus on three of the most dominant agricultural classes: strawberries, lettuce (i.e., vegetable row crops), and apples (i.e., deciduous trees).

Land-use maps were developed by Hanson et al. (2014) and Earll et al., (in prep) for 13 land-use periods, which span the period of the updated PVHM model simulation (1964–2014). Land-use maps are correlated to periods when data are available (Hanson et al., 2014), and in more recent years there exist more precise data allowing for more frequent land-use maps. The reader is referred to Table 2 in Hanson et al. (2014) for a description of the land-use periods. I use these land-use maps to calculate irrigated acreage of strawberries, lettuce, and apples as part of quantifying the Pajaro Valley W-F Nexus relationships.

2.1.3 Crop selection

Because my study focuses primarily on the Water-Food Nexus and the Energy-Water Nexus related to energy consumption for food production, I only analyze Nexus relationships related to agricultural water use (as opposed to municipal and domestic water use). Though a variety of crop types are grown in the Pajaro Valley, I analyze WEF Nexus relationships associated with the cultivation of strawberries (using PVHM crop category 2, "strawberries"), lettuce (using PVHM crop category 1, "vegetable row crops"), and apples (using PVHM crop category 6, "deciduous trees"), which are some of the primary crops, based on area, grown in the Pajaro Valley (see Figure 12 in Hanson et al. (2014)). Over the model period, vegetable row crops (which include lettuce), strawberries, and deciduous trees (i.e., apple orchards) encompassed an average annual percentage of the model area of 11.7%, 6.8%, and 4.6%, respectively (Hanson et al., 2014). In 2013, vegetable row crops, strawberries, and apple orchards encompassed 31%, 24.9%, and 7.3%, respectively, of the PV Water area. I use area weighting methods detailed in section 2.2.1.3 below to determine the fraction of PVHM crop category 1 associated with lettuce. I assume that all of PVHM crop category 6 is comprised of apples.

Another reason I chose to focus on these crops is that strawberries and lettuce are among the most water-intensive crops grown in the Pajaro Valley. The Pajaro Valley has experienced a shift in more water intensive crops such as strawberries, bushberries, and vegetable row crops as growers replace low water-use crops (i.e., apples) with higher value, more water-intensive crops (Hanson et al., 2014; PV Water, 2014). Data related to the three crop types of interest (strawberries, lettuce, and apples) come from updated PVHM output and the County of Santa Cruz Agricultural Commissioner Annual Crop and Livestock Reports (County of Santa Cruz, 2018) and are used to quantify the Pajaro Valley W-F Nexus relationships.

2.2 Water-Energy-Food (WEF) Nexus Analyses

To quantify the WEF Nexus within the Pajaro Valley, I first address the W-F Nexus, followed by the E-W Nexus. The W-F Nexus describes water use for food production and the E-W Nexus describes energy use for agricultural groundwater pumping. By characterizing and quantifying these Nexus relationships, I am then able to identify linkages (i.e., synergies, alterations, and trade-offs) that can be optimized to more sustainably use groundwater within the Pajaro Valley agricultural WEF Nexus. Identifying linkages also allows for the comparison of relationships surrounding water use and availability, energy consumption, and food production. Understanding these relationships is useful in making suggestions for modest land-use changes that may reduce trade-offs, alterations, and SWI.

2.2.1 Quantifying the Pajaro Valley Water-Food (W-F) Nexus

To quantify the W-F Nexus of the Pajaro Valley, I calculate, per crop type, annual values of irrigated area, applied water, cost of applied water, crop yield, crop price, crop production, crop revenue, and water-use efficiency (WUE). I then characterize W-F Nexus relationships and linkages by evaluating temporal trends of these parameters from 1964–2014.

2.2.1.1 Land-use

Understanding land-use (i.e. irrigated area occupied by each virtual crop type) is at the core of the Nexus, as it influences many relationships within the W-F Nexus (e.g., applied water and food production). Land-use data were collected from updated PVHM land-use maps and output (Earll et al., in prep). Calculating land-use using PVHM output likely results in some uncertainty in the actual land-use value because the dominant crop type or land-use is assumed to be homogeneous within each model grid cell (about 15 acres) (Hanson et al., 2014). However, given my goal to achieve a broad perspective of land-use changes over time and associated influences on the Nexus, these PVHM-based estimates are sufficient for the purpose of my study. Furthermore, because farm-scale land-use data were not available, I assumed that crops undergo one crop rotation per year, which likely underestimates some crop production in the study area. For instance, since the mid-1990s, some growers in the Pajaro Valley have used groundwater to increase multiple harvests per year of strawberries and selected vegetable row crops (Hanson et al., 2014).

2.2.1.2 Crop water demand

Quantifying crop water demand is a foundational component required to calculate and understand many WEF Nexus relationships (e.g., agricultural WUE, groundwater head levels, and energy required to pump groundwater). Crop water demand data, provided in biweekly time steps, were collected using updated PVHM output (Earll et al., in prep). Crop water demand is equivalent to applied water in units of acre-ft (hereinafter applied water is used to represent crop water demand). Biweekly data were summed into annual values per WBS per crop type.

The PVHM produces two types of output files that include applied water. The first file presents applied water (as "demand") per WBS per crop type, and the second file presents applied water (as "Total Farm Delivery Requirement" (TFDR)) for all crops per WBS. The second file (containing the TFDR) also includes a breakdown of the TFDR into portions of applied water that come from the CDS (as "NR-SWD-FIN") and from groundwater pumping (as "Q-FIN"). I calculated ratios of each of these parameters relative to the total TFDR, and then weighted crop-specific demand values (from the first file) by these ratios to determine the fraction of crop-specific demand associated with water deliveries from the CDS and groundwater pumping.

I subsequently calculated the cost of applied water, which allows for the analysis of the economic impacts of temporal changes in water use per acre. The cost of applied water was calculated based on PV Water's 2014 rates (PV Water, 2014). PV Water provides two types of water service associated with BMP projects: 1) a supplemental water service, funded by the PV Water augmentation charge and provided to groundwater users in the Pajaro Basin, and 2) a delivered water service, funded by the PV Water delivered water charge and provided to property owners within the Delivered Water Zone ("DWZ"), which is the region served by the CDS (PV Water, 2015a). PV Water's water infrastructure projects associated with the CDS are designed to enhance the quantity and quality of groundwater underlying coastal areas by increasing supplemental water supply to reduce groundwater pumping. PV Water imposes service chargers on users and beneficiaries to recover capital, operating, and other costs of providing supplemental and delivered water (PV Water, 2015a). Agency Water User Categories include (1) Metered Water Users inside the DWZ, (2) Metered Water Users outside the DWZ, (3) Delivered Water Users, and (4) Unmetered Water Users (i.e., rural residential water users, which are not covered in this study). Water User Categories 2 and 4 are subject to the augmentation charge. Category 3 is subject to the delivered water charge. Category 1 is subject to a higher augmentation charge that reflects a higher level of service in that area (PV Water, 2015a). Service charges are assigned based on PV Water rate zones (i.e., whether farms are located within the DWZ) (Figure 4) and these Agency Water User categories (Table 1).

For WBS's within the DWZ (i.e., with CDS connections), I calculated the cost of applied water by calculating (1) the cost of groundwater pumped (equation 1), (2) the cost of water delivered by the CDS (equation 2), and (3) a sum of the two products (equation 3).

$$\text{Cost of groundwater pumped } (\text{inside the DWZ}) = \left(\text{Volume of groundwater pumped } (\text{acre-ft}) \times \frac{\$210}{\text{acre-ft}}\right) \tag{1}$$

where the volume of groundwater pumped comes from PVHM output.

$$\text{Cost of water delivered by the CDS} = \left(\text{Volume of water delivered by the CDS (acre-ft)} \times \frac{\$329}{\text{acre-ft}}\right) \tag{2}$$

where the volume of water delivered by the CDS comes from PVHM output.

$$\text{Cost of applied water (inside the DWZ)} = \text{Cost of groundwater pumped (\$)} + \text{Cost of water delivered by the CDS (\$)} \tag{3}$$

where the cost of groundwater pumped (inside the DWZ) comes from equation (1) and the cost of water delivered by the CDS comes from equation (2).

For WBS's outside the DWZ (i.e., with no CDS connections), I calculated the cost of applied water by multiplying the volume of groundwater pumped by the PV Water augmentation charge (equation 4).

$$\text{Cost of groundwater pumped (outside the DWZ)} = \left(\text{Volume of groundwater pumped (acre-ft)} \times \frac{\$329}{\text{acre-ft}}\right) \tag{4}$$

where the volume of groundwater pumped comes from PVHM output data.

There are several sources of error associated with using this method (equations 1–4) to quantify the cost of applied water in the Pajaro Valley. PV Water rates were enacted in 1993 and rates vary year to year (PV Water, 2015b). However, I use the 2014 costs of service for the four user groups (PV Water, 2014) for all model years to account for inflation. In addition, I apply the adjusted augmentation charge and delivered water charge to farms within the DWZ during years prior to when CDS was implemented. Furthermore, although the CDS was implemented in 2002, PV Water did not start charging adjusted rates for users within the DWZ until 2011 (PV Water, 2015b). Second, I apply delivered water charges to all users within the DWZ, even though PV Water only charges property owners a delivered water charge who have applied for and received delivered water from the Agency through the CDS (PV Water, 2015a) (i.e., not all users within the DWZ necessarily use water from the CDS).

2.2.1.3 Food production

Shifts in market demand are known to be a primary influence on land-use patterns. To understand market drivers influencing agricultural development and to quantify crop production and revenue, I use both publicly available data from the County of Santa Cruz Agricultural Commissioner Annual Crop and Livestock Reports (County of Santa Cruz, 2018) and PVHM land use data. Although the Pajaro Valley spans portions of both Santa Cruz and Monterey Counties, Santa Cruz County crop data is assumed to be more representative of the Pajaro Valley because Monterey County crop values are heavily influenced by production in the Salinas Valley, adjacent to the Pajaro Valley (PV Water, 2014).

Data obtained from the County of Santa Cruz include annual values of crop yield (tons/acre) and crop price ($/ton). Because the Annual Crop and Livestock Reports only date back to 1986, for prior model years (1964–1986) I use the 1986 data when available. For the apple crop, production data was unavailable for 1986, so the 1987 data were used for the years 1964–1987. For the lettuce crop, the County of Santa Cruz crop production data were split into categories of "Lettuce, Head" (also referred to as "Lettuce, Iceberg" (1993–1999) and "Lettuce" (1986–1987)) and "Lettuce, Leaf" (also referred to as "Lettuce, Leaf and Romain" (1995–2001) and "Lettuce, Leaf & Cos" (1993–1994)). For the "Lettuce, Leaf" category, data were unavailable for the years 1986–1988 (so the 1989 data were used for years 1964–1989) and for the year 2007 (so the 2006 data were used).

I summed data for "Lettuce, Leaf" and "Lettuce, Head" to generate data for the total lettuce crop category for annual crop yield and annual crop price.

Temporal trends in crop yield (tons/acre) and crop price ($/ton) were analyzed to understand the influence of market drivers on shifts in agricultural development. Annual values of crop yield (tons/acre) and crop price ($/ton) were then used to determine total annual crop production (tons) (equation 5) and total annual crop revenue ($) (equation 6) of the Pajaro Valley:

$$\text{Crop production (tons)} = \text{irrigated area (acres)} \times \text{crop yield(tons/acre)} \qquad (5)$$

where irrigated area comes from PVHM land use data (Hanson et al., 2014) and crop yield comes from the County of Santa Cruz annual data (County of Santa Cruz, 2018).

$$\text{Crop value (\$)} = \text{crop production (tons)} \times \text{crop price(\$ / ton)} \qquad (6)$$

where crop production comes from the product of equation (5) and crop price comes from County of Santa Cruz annual data (County of Santa Cruz, 2018). An analysis of temporal trends in crop production and crop revenue provides a more comprehensive understanding of how shifts in commodities prices influence agricultural development in the Pajaro Valley.

The County of Santa Cruz crop data were also used to calculate a ratio that I used to estimate lettuce crop data from PVHM crop category 1 ("vegetable row crops"). For this method, I first calculated annual ratios of acres of lettuce (head + leaf) to acres of total vegetables in the County of Santa Cruz crop reports. I then weighted PVHM data associated with PVHM crop category 1 by these annual ratios to calculate annual irrigated area and crop water demand data for the lettuce crop. There is likely substantial but unknown uncertainty associated with calculating the lettuce crop water demand using this method because water intensities of the crops comprising PVHM category 1 vary, and thus require different quantities of applied water, which cannot be determined using area weighting.

There is additional uncertainty associated with this method of equating PVHM crop category 1 to the County of Santa Cruz total vegetables category, because the acreage of total vegetables in the County of Santa Cruz crop reports are not always within 30% of acreage associated with PVHM crop 1 category, indicating that these two categories cannot always be equated. For the years 1963–1996, the ratio between the two categories is substantially larger than 30%, and thus there exists considerable uncertainty associated with lettuce analyses for these years. For the years 1996–2014, the ratio between the two categories is less than 30%. Another source of uncertainty associated with using County of Santa Cruz crop data is that these data may also reflect crops grown in areas of Santa Cruz County located outside the Pajaro Valley.

2.2.1.4 Water Use Efficiency (WUE) for agricultural production

Calculating WUE allows for an assessment of the magnitude of inefficiencies within the W-F Nexus, which can be used to make suggestions for more optimal use of water for agriculture. Parameters used to measure WUE include crop per drop (Brauman et al., 2013; Smidt et al., 2016) and water use per acre (Johnson and Cody, 2015). Crop per drop (tons/acre-ft) (equation 7) describes the quantity of a given crop produced per acre-ft of water applied to that crop:

$$\text{Crop per drop}\left(\frac{\text{tons}}{\text{acre-ft}}\right)=\frac{\text{Crop production}(\text{tons})}{\text{Applied water}(\text{acre-ft})} \tag{7}$$

where crop production comes from equation 5 and applied water comes from PVHM output. Water use per acre (equation 8) describes the volume of water applied per irrigated acre of a given crop type:

$$\text{Water use per acre } (\text{acre-ft/acre}) = \frac{\text{Applied water } (\text{acre-ft})}{\text{Irrigated area } (\text{acre})} \tag{8}$$

where applied water and irrigated area come from PVHM output data. The higher the crop per drop and the lower the water use per acre, the more water efficient a region is in terms of the Water-Food Nexus. Understanding temporal patterns in WUE in conjunction with temporal trends in land use and market drivers allows for a better understanding of how to reduce tradeoffs and increase synergies within the W-F Nexus.

2.2.2 Quantifying the Pajaro Valley Energy-Water (E-W) Nexus

To quantify the E-W Nexus of the Pajaro Valley, I calculate groundwater level data (groundwater head, ground surface elevation, and depth to groundwater (DTW)), the quantity and cost of energy required to pump groundwater, greenhouse gas emissions associated with energy consumed to pump groundwater, and the energy intensity of the basin. I then characterize and analyze E-W Nexus relationships and linkages by evaluating temporal trends of these parameters from 1964-2014.

2.2.2.1 Groundwater level data

Temporal patterns in groundwater level data, particularly groundwater head and depth to groundwater (DTW), are at the core of all E-W Nexus relationships and linkages and are largely influenced by shifts in the W-F Nexus (e.g., applied groundwater and WUE). Analyzing temporal changes in groundwater level data contributes to understanding impacts of agricultural water-use in the W-F Nexus, E-W Nexus tradeoffs and alterations, and how to reduce SWI. To determine median groundwater head, ground-surface elevation, and depth to groundwater (DTW) for the entire Pajaro Valley, coastal region, and inland region, I used updated PVHM output data associated with the strawberry crop, because strawberries are consistently present in a wide spatial range of model cells throughout the entire model period. Output data from the PVHM include groundwater head (m above sea level (asl)) and ground-surface elevation (m asl) per cell per time step. From these data, I calculated DTW using equation (9):

$$\begin{aligned}&\text{Depth to groundwater }(\text{m}) = \\ &\text{Ground surface elevation }(\text{m asl}) - \text{Groundwater head }(\text{m asl})\end{aligned} \tag{9}$$

where ground surface elevation (m asl) and groundwater head (m asl) come from PVHM output. I collected groundwater level data from cells with the longest temporal records and used annual data values from January 1, because January is in the middle of California's rainy season.

I aggregated these data by region (coastal, inland, and the entire Pajaro Valley), and calculated an annual median value of each parameter (groundwater head, ground surface elevation, and DTW) for each region. To best represent the range of groundwater head and DTW levels that exist spatially throughout the Pajaro Valley, I also calculated annual (January 1) minimum and maximum values for each parameter; these minimum and maximum values represent the range of uncertainty associated with the median values.

There are various other sources of uncertainty that arise from using this method to calculate groundwater level data. First, in calculating groundwater level data based on annual January 1 values, I do not account for interannual seasonal influence. There exists considerable interannual variability associated with water table elevations, which can even fluctuate on a daily time scale. Second, by aggregating data into broad regions, I do not account for spatial variability throughout the valley. From the perspective of spatial distribution, water levels near wells differ significantly from those located further away due to the influence of the well's cone of depression.

2.2.2.2 Energy required to pump groundwater

Energy consumption in the Pajaro Valley, which I assume to be supplied by fossil energy sources, is primarily a function of DTW and agriculture water-use in the W-F Nexus (i.e., applied groundwater). Quantifying the energy required to pump groundwater allows for a complete understanding of the E-W Nexus relationships and linkages. The related cost of energy required to pump groundwater provides another representation of E-W Nexus relationships and linkages. To calculate the energy (kWh) and associated cost ($) required to lift groundwater to land surface, I used a method developed by Mehl et al. (2015) (equation 10):

$$\text{Energy required to lift groundwater } (\text{kWh}) = \frac{\text{Applied groundwater } (\text{acre-ft}) \times \text{DTW } (\text{ft}) \times \text{Energy per foot of lift} \left(\dfrac{\text{kWh}}{\text{ft} \bullet \text{acre-ft}}\right)}{\text{Overall pumping efficiency } (\%)} \quad (10)$$

where applied groundwater and DTW come from PVHM output and the energy required per foot of lift comes from equation (11). The theoretical energy in the numerator of equation (10) is scaled by the overall pumping efficiency to obtain the true energy. For the overall pumping efficiency, I used a recorded value from the nearby Salinas Valley of ~56% (Orvis et al., 2011). The energy per foot of lift (kWh/ft) is the energy required to lift one acre-ft of water by one vertical foot and was calculated by multiplying the specific weight of water by the following conversion factors (equation 11):

Energy per foot of lift =

$$62.4\frac{\text{lb}}{\text{ft}^3}\times\frac{\text{hp}}{550\frac{\text{ft-lb}}{\text{second}}}\times\frac{0.7457\text{kW}}{\text{hp}}\times\frac{43,560\text{ft}^3}{\text{acre-ft}}\times\frac{\text{hr}}{3,600\text{ seconds}}=1.023697\frac{\text{kWh}}{\text{ft}\bullet\text{acre-ft}} \quad (11)$$

To obtain the cost of the calculated energy consumption, I multiply the required energy to lift groundwater (equation 10) by the 2014 reported energy rate, ~ \$0.20/kWh, based on the cost of power on an electric rate schedule for agricultural power (PG&E, 2014) (equation 12):

$$\text{Cost of energy} = \text{Energy required to lift groundwater}\left(\text{kWh}\right)\times\frac{\$0.20}{\text{kWh}} \quad (12)$$

2.2.2.3 Greenhouse gas emissions (GHG)

Shifts in greenhouse gas emissions (GHG) are a function of temporal trends in the energy consumed to pump groundwater and provide another representation of E-W Nexus relationships and linkages. To calculate GHG emissions as a result of energy consumed to pump groundwater, I use assume that all electricity was supplied by PG&E and use the PG&E GHG emission factors (PG&E, 2015). PG&E provide emission factors based on historical emissions for the years 2003–2013. For the year 2014, PG&E provide a GHG emissions factor based on the CPUC GHG Calculator, which provides an independent forecast of PG&E's emission factors (PG&E, 2015). For early model years (1964–2008) for which no PG&E GHG emissions factor is available, I used the 2008 value.

2.2.2.4 Energy intensity

The energy intensity (kWh/acre-ft) (CA DWR, 2017; Liu, 2017, 2016) of groundwater pumped is used to measure the efficiency of energy use in the Pajaro Valley; calculating energy intensity allows for an assessment of the magnitude of inefficiencies within the E-W Nexus. Furthermore, energy intensity is largely influenced by agricultural water-use within the W-F Nexus (i.e., applied groundwater and water use per acre) and groundwater levels. Temporal trends in energy intensity can thus be used as a measure for optimal levels of efficiency and sustainability within the entire WEF Nexus. Energy intensity (kWh/acre-ft) (equation 13) describes the amount of energy (kWh) required per acre-ft of groundwater pumped:

$$\text{Energy intensity}\left(\frac{\text{kWh}}{\text{acre-ft}}\right)=\frac{\text{Energy required to pump groundwater }(\text{kWh})}{\text{Applied water from groundwater }(\text{acre-ft})} \tag{13}$$

where the energy required to pump groundwater is calculated using equation (10) and the volume of applied groundwater is calculated using PVHM output. The greater the energy intensity, the less energy efficient a region is in the context of the E-W Nexus.

2.3 Analyzing SWI

The PVHM can be used to simulate the historical flux of water entering (as SWI) and exiting (as groundwater discharge) the Pajaro Valley aquifer each year, between coastal and offshore zones. SWI data were obtained from updated PVHM output. SWI volumes for each hydrogeologic layer were summed to obtain annual SWI volumes (acre-ft) for the entire Pajaro Valley aquifer.

Hanson et al. (2014) demonstrate that the influence of the sustained and climatically-driven pumpage on the Pajaro Valley's water budget results in overdraft conditions, including sustained storage depletion and coastal inflows. I demonstrate this relationship by correlating the temporal trends in irrigated acreage and applied groundwater for strawberries and lettuce with temporal trends in SWI. Data for SWI, irrigated area of strawberries and lettuce, and applied groundwater for strawberries have non-normal distributions (α=0.05, p-value$_{SWI}$ = 0.0018, p-value$_{irrigated_area_strawberries}$ = 0.0001, p-value$_{irrigated_area_lettuce}$ = 0.0018, and p-value$_{applied_groundwater_strawberries}$ = 0.0017), and thus I used the non-parametric Spearman's ρ test for the multivariate correlation. Data for applied groundwater for lettuce has a normal distribution (α=0.05, p-value$_{applied_groundwater_lettuce}$ = 0.1034), and thus I used the parametric Pearson's r test for this correlation. A positive result for the Spearman's ρ or Pearson's r test would indicate a positive correlation between the parameters of interest, and a result closer to 1 indicates a stronger correlation. Establishing these kinds of correlations allows for an assessment of the factors that contribute to SWI; these relationships can then be used to determine how SWI may be reduced while having minimal effect on the agricultural economy of the Pajaro Valley.

3. Results and discussion

3.1 WEF Nexus Analyses

Here I present the calculation and analysis of the WEF Nexus of the Pajaro Valley coastal aquifer by first addressing the Water-Food Nexus followed by the Energy-Water Nexus. The Water-Food Nexus describes water use for food production and the Energy-Water Nexus describes energy use for groundwater pumping.

3.1.1 Quantifying the Pajaro Valley Water-Food Nexus

The Water-Food Nexus of the Pajaro Valley encompasses the relationships among irrigated area, applied water (i.e., the applied water from groundwater and delivered from the CDS), the cost of applied water, crop yield, crop price, food production, crop revenue, and water use efficiency (WUE). In this study, I do not analyze the total applied water (i.e., the sum of applied water from groundwater and CDS deliveries), because the amount of water applied from CDS deliveries is comparatively very small relative to groundwater pumped.

3.1.1.1 Land use and applied water from groundwater

Here I describe trends in irrigated acreage and groundwater use for apples, strawberries, and lettuce, as well as the relationships between these two closely linked variables. Irrigated acreage of apples, strawberries, and lettuce are shown for the entire Pajaro Valley (Figure 5A) as well as the inland (Figure 5B) and coastal (Figure 5C) areas from 1964–2014. Applied water from groundwater (i.e., groundwater pumpage) for apples, strawberries, and lettuce is shown for the entire Pajaro Valley (Figure 6A) as well as the inland (Figure 6B) and coastal (Figure 6C) areas from 1964 to 2014.

Irrigated acreage of apples consistently decreased over time within the Pajaro Valley (Figure 5A). Consequently, applied water from groundwater for apple production gradually declined over the study period (Figure 6A). Because minimal apples were grown in the coastal region relative to the inland region (Figures 5B-C), coastal applied groundwater for apples was commensurately low (Figures 6B-C).

Conversely, for strawberries across the entire Pajaro Valley, irrigated acreage (Figure 5A) and applied water from groundwater (Figure 6A) generally increased over time (1964–2011), followed by a notable recent decrease from 2012–2014 (Figure 5A). Finer scale shifts in temporal trends of applied groundwater for strawberries (Figure 6) generally follow trends in irrigated area (Figure 5), and some shifts correspond to climatic periods (i.e., wet vs. dry periods); climatic wet and dry periods are delineated on figures in blue and yellow, respectively.

Shifts in temporal trends in applied groundwater for strawberries (Figure 6) appear to more closely correspond to climatic periods through the early 1990s and after the start of the most recent dry period and drought (2008–2010 and 2012–2014). During the dry periods, applied groundwater generally increases, and during the wet periods, the applied groundwater generally decreases (Figure 6). However, from the early 1990s through the present, trends appear to less closely follow shifts in climatic periods, and are thus likely driven by other factors, such as economic forces associated with commodities prices. The shifts in irrigated acreage (Figure 5) during the early 1990s–present substantially influence temporal trends in groundwater use (Figure 6). For example, strawberry cultivation spiked in 1993 (Figure 5), consistent with a notable increase in applied groundwater for strawberries from 1993–2011 (Figure 6). From 2008 to 2011, applied groundwater considerably increased (Figure 6A), corresponding to the start of the most 2008–2010 dry period. A recent, notable decrease in strawberry acreage (Figure 5) and applied groundwater (Figure 6) from 2012–2014 corresponds to PV Water's increase in augmentation fee rates in 2011 (PV Water, 2015b) and the recent (2012–2016) historic drought in California. Because the cost of water associated with the PV Water augmentation fees is miniscule relative to crop revenue, the recent drought is likely the major driver influencing this decrease in irrigated acreage and associated decrease in applied groundwater for strawberries. However, more recent years of data are required to support this interpretation.

The previously described temporal trends in irrigated area and applied groundwater for strawberries appear to closely correspond to temporal trends associated with agricultural groundwater use in the Pajaro Valley documented by Hanson et al. (2014). The amount of water used for irrigation is very sensitive to climatic conditions. During wet periods, applied groundwater is typically reduced, because irrigation demand is supplemented by precipitation. During sustained dry periods, applied groundwater for irrigated agriculture is known to increase by more than ten percent (Hanson et al., 2014). Hanson et al. (2014)

note two distinct periods in the Pajaro Valley: (1) a period of more traditional seasonal agriculture from 1964–92 during which substantial applied groundwater only occurred during dry periods and less applied water was used during wet periods, and (2) a period of more intensified agriculture from 1993–present corresponding to a shift in cultivation of more water intensive crops (e.g., strawberries, bushberries, and vegetable row crops) and additional rotational plantings per year. The start of the latter agricultural period corresponds with the end of the last multi-year drought from 1984–92 (Hanson et al., 2014).

Irrigated acreage (Figures 5B-C) and applied groundwater (Figures 6B-C) for strawberries in the inland and coastal region follow the same general temporal trends, respectively, as in the entire Pajaro Valley through 1996 (Figures 5A and 6A). From 1996–2011, irrigated area of strawberries in the inland region (Figure 5B) remained relatively steady, while the irrigated area of coastal strawberries (Figure 5C) increased. Yet, applied groundwater increased in both regions during this period (Figures 6B-C), albeit more dramatically in the coastal region (Figure 6C). The increase in inland applied groundwater for strawberries during a period in which irrigated area remained relatively steady may be due to increases in crop rotations, requiring more annual applied water.

From 1964–2008, strawberry acreage (Figures 5B-C) and thus applied groundwater (Figures 6B-C) were greatest in the inland region. However, in recent years (2009–2014), irrigated acreage of strawberries and applied groundwater in the coastal region increased substantially and were greater than in the inland region. This increase in coastal strawberry cultivation (Figure 5C) follows a long-term rise in strawberry acreage and applied groundwater (1977–2011) and occurred after the implementation of the CDS system in 2002. The substantially larger applied groundwater for the water-intensive strawberry crop from 2009-2014 (Figures 6B-C) is counter to the CDS and PV Water project goals of reducing groundwater pumping in the coastal region to slow SWI.

Furthermore, strawberries have a low salt tolerance (PV Water, 2014), and impacts of SWI are most pervasive in the coastal areas.

Across the Pajaro Valley, irrigated acreage (Figure 5A) and applied groundwater (Figure 6A) for lettuce generally increased from 1964–1992, followed by a considerable decrease in 1993, which may be attributed to the prolonged dry period from 1984 through 1993. From 1964 to 1992, temporal trends in applied groundwater for lettuce (Figure 6A) appear to fluctuate with climatic periods. From about 1993 through 2010, irrigated acreage (Figure 5) and applied groundwater (Figure 6) follow opposing trends; while irrigated area of lettuce decreased, applied groundwater for lettuce gradually increased (excluding a spike in 1997). From 2011–2014, both irrigated acreage and applied groundwater for lettuce increased. These post-1992 temporal trends, notably the contrasting increase in applied groundwater and decrease in irrigated area for lettuce (1993–2010), correspond to the start of the more intensified agricultural period when growers began increasing their water use associated with additional rotational plantings per year (Hanson et al., 2014).

Irrigated acreage (Figures 5B-C) and applied groundwater (Figures 6B-C) for lettuce in the inland and coastal region follow the same general temporal trends, respectively, as irrigated area (Figure 5A) and applied groundwater (Figure 6A) for lettuce in the entire Pajaro Valley. For the entire model period, irrigated area (except 1993–96) and applied groundwater for lettuce were greater in the inland region than the coastal region.

During the period of less intense, seasonal agriculture from 1964 to the early 1990s (Hanson et al., 2014), more apples were grown in the Pajaro Valley than strawberries (1964–1992) and lettuce (1964–1977) (Figure 5A). Yet, applied groundwater (Figure 6A) for lettuce and strawberries was greater than it was for apples. From the mid-1990s to present, strawberries became a much more prominent crop in the Pajaro Valley, as lettuce and apples became the least prominent and declined in irrigated area (Figure 5A). Simultaneously, applied groundwater for strawberries and lettuce substantially increased while applied groundwater for apples gradually declined (Figure 6A). This shift in crop type prominence and increased groundwater use for strawberries and lettuce corresponds to the more intensive period of agriculture in the Pajaro Valley from 1993–present. During this period, growers used increasing amounts of water to support increased acreages of vegetable row crops (i.e., lettuce), strawberries, and bushberries, which are all high water-use crops (Hanson et al., 2014). These trends in crop production and groundwater use have a direct influence on the Water-Food and Energy-Water Nexus. For example, increased cultivation of the higher water-intensive strawberry crop mitigates any reduction in water stress on the system that may result due to the decreasing trend in lower water-intensity crops, such as apples. Shifts in prominence of one crop relative to another are often and likely influenced by economic drivers, such as an increase in market value of strawberries over time.

In comparing irrigated acreage to groundwater use for the three crop types, lettuce and strawberries require substantially more applied groundwater than apples (Figure 6A). Even during periods when irrigated acreage of apples was greater than either or both strawberries and lettuce (Figure 5A), more groundwater was used for the latter crop types (especially for strawberries) than for apples (e.g., 1964–1996). Furthermore, in later model years (1997–2014) when irrigated acreage of apples was lowest of the three crops but not substantially lower than that of lettuce, applied groundwater for apples was much lower than applied groundwater for lettuce and strawberries, indicating apples require much less applied water.

3.1.1.2 Applied water delivered from the CDS

Here I describe temporal trends in applied water delivered from the CDS. While no applied water from the CDS was used for apple production, lettuce and strawberry production in coastal farms within the DWZ used increasing volumes of applied water from the CDS from 2002–2014 (Figure 7A). Between 2005 and 2014, substantially more applied water from the CDS was used for strawberries than lettuce, corresponding to an increase in irrigated acreage of strawberries relative to lettuce within the DWZ of the coastal area (Figure 7B). Although the volume of water delivered from the CDS continually increased from its inception in 2002 through 2014, over the same period groundwater pumpage still supplied the most substantial portion of the water demand for agriculture in the DWZ and the entire coastal region (Figures 7C and 6C). Thus, the availability of supplemental water from the CDS likely has no influence on the increase in irrigated acreage of strawberries within the DWZ. Furthermore, this indicates that the use of supplemental water from the CDS was not offsetting groundwater use in the coastal region, counter to BMP goals to reduce coastal pumpage.

3.1.1.3 Cost of applied water (groundwater and CDS deliveries)

In the entire Pajaro Valley, trends in the cost of total applied water (i.e., the sum cost of groundwater pumpage and water delivered from the CDS) (Figure 8A) for all three crop types follow trends in applied groundwater (Figure 6A). Because almost all apples were grown in the inland region (Figure 5B-C), inland apple growers collectively paid considerably more for applied water than coastal growers (Figures 8B-C). From 2009–2014 (except 2011) strawberry growers in the coastal region paid more than inland growers (Figures 8B-C), which is consistent with trends in irrigated area (Figure 5B-C) and applied groundwater (Figure 6B-C). Lettuce growers in the inland region paid more than coastal growers (Figures 8B-C) for applied water until 2011 (except 1993, 1995–96), at which point coastal growers paid more. However, irrigated area (except 1993–96) (Figures 5B-C) and applied groundwater (Figures 6B-C) for lettuce was greater in the inland region than the coastal region throughout the entire model period. The increased costs of applied water in the coastal area from 2011–2014 were due to increased acreage of lettuce grown in the DWZ over the same period (Figure 8D).

3.1.1.4 Food production

I describe food production of the Pajaro Valley Water-Food Nexus using crop yield, crop price, crop production, and crop revenue. County of Santa Cruz data (County of Santa Cruz, 2018) for crop yield and crop price were only available from 1986–2014, and hence any pre-1986 County of Santa Cruz data were held constant. Because crop production and crop revenue are based on crop yield and crop price data, respectively, there is considerable uncertainty in values from 1964–1986.

3.1.1.4.1 Crop yield

Crop yield in the Pajaro Valley (Figure 9) generally increased over time for all three crops, with the exception of some short periods of decline. A sharp increase in crop yield, particularly for strawberries and lettuce, occurred from the early-1990s through the present, which corresponds to the period of more intensive agriculture in the Pajaro Valley. However, in recent years (2011–2014), yields declined for all three crops. This recent decline in crop yield is counter to the recent research and technologic improvements that help to increase yields. Thus, this decline in crop yield may be a response to the recent (2012–2016) historic drought in California. Furthermore, it is possible that increased salinity of coastal groundwater from SWI may have damaged crops, resulting in lower crop yields. Additional data is needed to evaluate whether these mechanisms contributed to lower crop yields.

Smaller scale temporal fluctuations in crop yield exist for each crop type, such as a brief period of increased yield for lettuce relative to strawberries from 1993–2000. These differences in yield may be attributed to the ability of a crop to withstand climatic fluctuations, changes in groundwater chemistry resulting from SWI, or changes in farm management (e.g., management of soil and irrigation). However, temporal trends in crop yield do not appear to correspond with climatic periods as do trends in irrigated area (Figure 5) and applied groundwater (Figure 6).

3.1.1.4.2 Crop price

Crop prices (i.e., a commodity's market value) in the Pajaro Valley were consistently the lowest for apples and highest for strawberries (Figure 10). Strawberry value exhibited the greatest increase over the study period, which is likely a major driver of the corresponding increase in strawberry cultivation (Figure 5A) and the intensified period of agriculture from 1993–present in the Pajaro Valley. From 2001–2014, strawberry value increased substantially, whereas the other crop prices leveled off. Lettuce value increased briefly from about 1994–2000, but from 2001 to 2014 its value declined. Lettuce prices started to slightly increase again from 2013–2014. The slight 2013 increase in lettuce value corresponds to an increase in irrigated area from 2011–2014 (Figure 5A); this increase in value may be driving the increase in irrigated area, though more recent data is needed to determine the significance of this trend. Over time, the price of apples gradually increased, whereas apple cultivation (Figure 5A) gradually decreased; although apple value increased, the increase is likely too slight to justify the growth of apples over a higher-value crop from the perspective of farmer profit. Temporal trends in crop price do not appear to correspond with shifts in climatic periods.

3.1.1.4.3 Crop production

Apart from in the inland region, apple production was generally the lowest of the three crops, even during periods (e.g., 1993–96) when irrigated area of apples was greater than irrigated area of strawberries and/or lettuce, because strawberry and lettuce yields are much greater than apple yield. Corresponding to trends in irrigated area (Figures 5B-C), apple production in the inland region was much greater than in the coastal region. Concurrent with the start of the more intensified agricultural period in the Pajaro Valley, strawberry production in all regions (Figure 11) increased considerably in the early 1990s. In the inland region (Figure 11B), strawberry production remained relatively high through 2010 but gradually decreased; conversely, in the coastal region, strawberry production gradually increased through 2010 (Figures 11C). From 2011–2014, strawberry production in both regions decreased considerably (Figure 11), corresponding to a 2010 decrease in strawberry yield (Figure 9) and a 2012 decrease in irrigated area (Figure 5). Strawberry production in the coastal region was greater than the inland region from 2009–2014 (Figures 11B-C), corresponding to trends in irrigated area (Figure 5). In 1992, lettuce production (Figure 11) considerably decreased; then by 1995, lettuce production began to slowly increase through 2014, corresponding to an increased in lettuce yield (Figure 9) and counteracting the effects from a decrease in irrigated area (Figure 5). Lettuce production in the inland region was greater the coastal region for the entire model period, apart from the years 1993–1996 (Figures 11B-C). Overall, temporal trends in crop production (Figure 11) closely follow trends in irrigated area (Figure 5), dampened by the influence of commodity yield (Figure 9), but do not appear to be influenced by climatic periods.

3.1.1.4.4 Crop revenue

In the entire Pajaro Valley, apple revenue (Figure 12A) remained relatively steady over time. Apple revenue in the inland region was considerably greater than the coastal region (Figures 12B-C) because most apples were grown in the inland region (Figures 5B-C). In the entire Pajaro Valley, strawberry revenue (Figure 12A) greatly increased from 1993 to 2014, corresponding to a considerable increase in crop price (Figure 10), and the more intensified period of agriculture in the valley. Strawberry revenue in the inland and coastal regions (Figures 12B-C) generally follow the same temporal trends until 2008, when coastal revenue increased more sharply than inland revenue, coincident with trends in irrigated area (Figures 5B-C) and crop production (Figures 11B-C). Interestingly, inland strawberry revenue (Figure 12B) increased sharply during the latter part of the model period (2000–2014), concurrent with a decrease in inland strawberry production (Figure 11B). This trend highlights the impact of increasing commodity prices (Figure 10); even as irrigated area (Figure 5B) and crop production (Figure 11B) decrease, crop revenue can still increase. From 2009–2014, coastal strawberry revenue became greater than inland revenue, which also corresponds with previously mentioned trends in irrigated area (Figures 5B-C) and crop production (Figures 11B-C). In the entire Pajaro Valley, lettuce revenue (Figure 12A) started to gradually decline in the early 1990s until it slightly increased again in recent years (2011–2014), coincident with trends in crop price (Figure 10) and crop production (Figure 11A). Lettuce revenue in the inland region was greater than the coastal region (Figures 12B-C) (except 1993–1996).

When comparing revenue among the three crop types in the entire basin (Figure 12A) for the period 2001 to 2014, strawberry revenue increased the most and was much greater than revenue from lettuce and apples. Apple revenue was very low relative to revenue from strawberries and lettuce. Strawberry revenue was greater than lettuce revenue over the model period (except 1978–1992). These differences in crop revenue (Figure 12), a function of crop yield (Figure 9) and crop price (Figure 10), constitute the major driver influencing land use patterns in Pajaro Valley (Figure 5A), which in turn heavily impact the sustainability of groundwater resources.

3.1.1.5 Water use efficiency (WUE) for agricultural production

Crop per drop describes the quantity of a given crop type produced (tons) relative to the amount of water applied to that crop (acre-feet) and can be used to describe the WUE of a given crop type (Brauman et al., 2013; Smidt et al., 2016). The crop per drop of apples generally increased over the model period (Figure 13A). The crop per drop of strawberries generally decreased from the early 1990s through 2011, at which point crop per drop slightly increased through 2014 (Figure 13A). This decrease in crop per drop corresponds with the period of intensified agriculture from 1993–present in the Pajaro Valley. The crop per drop of lettuce generally decreased over the entire model period (excluding a considerable increase from 1995–2005), with a sharp decrease from 2006 to 2014 (Figure 13A). The crop per drop of strawberries and lettuce followed the same trends in the coastal and inland region as in the entire Pajaro Valley, but crop per drop was slightly greater in the coastal region (Figure 13B-C). The interannual variation in crop per drop for all three crop types is likely influenced by interannual variation in applied groundwater (Figure 6) associated with climate variability.

Another measure of WUE is water use per acre (acre-ft/acre) (Figure 14), which describes the amount of water applied (acre-feet) to one acre of a given crop type. During the first half of the model period (1964–1992), the water use per acre of strawberries was considerably higher than that of lettuce and apples (Figure 14A). The water use per acre of apples remained low over the entire model period, but in 1993, the water use per acre of lettuce increased substantially, becoming greater than that of strawberries for a short period beginning in 2009. The large increase in water use per acre for lettuce and strawberries from about 1993–2014 corresponds with a more intensified agricultural period in the Pajaro Valley. This increase in water use per acre for lettuce corresponds to the period when irrigated area of lettuce decreased (Figure 5) yet applied groundwater for lettuce increased (Figure 6). The water use per acre of strawberries and lettuce slightly decreased in 2012, corresponding with previously mentioned trends in irrigated area (Figure 5), applied groundwater (Figure 6), and crop per drop (Figure 13).

For many years, the water use per acre for strawberries and lettuce was greater in the inland region than the coastal region (Figures 14B-C). The water use per acre for apples was greater in the coastal region. However, the difference in water use per acre between the two regions was minimal and the temporal trends are very similar in the two regions.

The higher the crop per drop and the lower the water use per acre, the more water efficient a given crop type is. The trends in crop per drop and water use per acre (Figures 13 and 14) show that over the last 20-30 years, the cultivation of strawberries and lettuce became less water efficient. This decrease in WUE may be attributable to several factors, including the recent dry periods and droughts in California (2002 – 2005, 2008 – 2009, and 2012 – 2014). The decrease in WUE may also be a function of the changing farming practices during the latter more intensified period (1993-2014) of agriculture associated with increased water use for multiple crop rotations per year. Another driver may be that farmers often over-water to assure crop needs are met; for farm managers, water costs are a low expense, especially relative to revenue loss from a poor crop (PV Water, 2014).

3.1.2 Quantifying the Energy-Water Nexus

The E-W Nexus of the Pajaro Valley includes the analysis of the relationships between groundwater head, depth to groundwater, the quantity and cost of energy required to pump groundwater, the greenhouse gas emissions from energy consumed to pump groundwater, and energy intensity. The components of the E-W Nexus are largely impacted by decreases in WUE within the W-F Nexus; as water-use and inefficiencies increase, aquifer levels decline, impacting all E-W Nexus relationships.

3.1.2.1 Aquifer level data

Median groundwater head levels in all regions (Figure 15A) follow the same general downward trend over the study period. Throughout the entire model period, median groundwater head was lowest in the coastal region and predominantly below sea level, concordant with reports of SWI into the Pajaro Valley aquifer since the 1950s (PV Water, 2014). Though coastal overdraft was largely impacted by coastal applied groundwater (Figure 6C), intensive applied groundwater for inland crops (Figure 6B) likely also significantly impacted coastal overdraft and SWI by capturing groundwater that would have otherwise contributed to coastal recharge.

This difference in coastal and inland groundwater head levels was most substantial from 1964–1991. In the early 1990s, the difference became smaller between coastal and inland median groundwater head as inland groundwater levels fell below sea level; coastal groundwater levels still remained lower through the entire model period. By about 1992, groundwater head levels dropped lower than they had ever been during the model period, remaining largely below sea level in both regions through 2014. The timing of this decline corresponds with the start of the more intensified agricultural period in the Pajaro Valley (1993), a considerable increase in applied groundwater for strawberries (Figure 6), and decreased WUE for strawberries and lettuce, all of which are likely drivers of the increased groundwater overdraft.

Until the early 2000s, increases and decreases in groundwater head levels closely followed climatic periods, increasing during wet periods and decreasing during dry periods (Figure 15A). During the latter part of the model period, trends in groundwater head followed climatic periods less closely, corresponding to a period of decreased WUE and intensified agriculture. However, during the most recent dry periods from 2008–10 and 2012–14, groundwater levels dropped to their lowest point at relatively fast rates (>3 m decline over the seven-year period). This rapid decline also corresponds to a considerable decrease in WUE over the same time period (Figures 13-14). From about 2012–2014, during the historic drought in California, the rate of groundwater head decline started to level off, corresponding to a slight increase in WUE for strawberries and lettuce.

Figures 15B-D show the possible range in groundwater head in all three study regions. The inland region of the Pajaro Valley has a greater range in groundwater head levels than the coastal region, with the lowest minimum (except 1983) and highest maximum (except 1969 and 1974) groundwater head levels throughout the model period. This range may be a function of a stronger orographic effect in the inland region.

Similar to median groundwater head, trends in median DTW (Figure 16A) closely follow climatic periods in the Pajaro Valley, generally increasing during dry periods and decreasing during wet periods. Median DTW generally increased over the entire model period, with a large increase in recent years (2007–2014), corresponding to the recent dry periods and California drought as well as decreased WUE (Figures 13-14). Median DTW was greatest in the coastal region, a response to lower median groundwater head levels in the coastal region. Differences in DTW across regions may also be attributed to differences in topography. Figures 16B-D show the possible range in DTW in all three study regions. The minimum DTW was periodically greater in the coastal region (1964-1977, 1983-1987, 1990-1991, 1993, 1995-1998), and maximum DTW was consistently greatest in the inland region (except from 1993-1993), likely due to the orographic effect.

3.1.2.2 Energy consumption – quantity, cost, and greenhouse gas emissions (GHG)

For apples, the energy required to pump groundwater (Figure 17A) gradually decreased over time, reflective of a decrease in irrigated area (Figure 5) and applied groundwater

(Figure 6). Energy required to pump groundwater for apples was greater in the inland region (Figures 17B-C), corresponding to a greater irrigated acreage of inland apples. For strawberries and lettuce, conversely, the energy required to pump groundwater generally increased overtime, with a sharp increase from 2002–2014 (Figure 17A). This notable increase in energy consumption corresponds to a considerable decrease in median groundwater head (Figure 15A) and WUE (Figures 13-14) as well as the recent dry period and California drought (2008–10 and 2012–14). Energy required to pump groundwater for strawberries decreased from 2012–2014, corresponding to an increase in WUE (Figures 13-14) and the leveling off of median groundwater head levels (Figure15A). Generally, the energy required to pump groundwater closely followed trends in climatic periods (i.e., increased energy was required during dry periods) through the early 1990s, the start of the more intensified period of agriculture. Dry periods are thus a major driver of the WEF Nexus, resulting in increased water and energy use.

For the entire model period, the energy required to pump groundwater for strawberries and lettuce was greatest in the coastal region (except 1978–1992 and 1997–1998 for strawberries) (Figures 17B-C). Although less groundwater was pumped in the coastal region than the inland region over the majority of the model period (1964–2008), a greater quantity of energy was required to pump groundwater, corresponding to lower coastal groundwater head levels. Intensive inland pumping (Figure 6B) likely decreases coastal recharge, impacting coastal groundwater head levels (Figure 15A) and consequently coastal energy consumption (Figure 17C). Thus, the W-F and E-W Nexus of the two regions are connected, even though the regions have large differences in agricultural practices and groundwater management projects.

The cost of energy required to pump groundwater (Figure 18) and the GHG related to energy (sourced from fossil fuels) consumed to pump groundwater (Figure 19) follow the same trends as the energy required to pump groundwater (Figure 17). Thus, any factors that impact the energy required to pump groundwater will also affect the cost of energy and GHG in the Pajaro Valley. In 2001, 10,560 Gig-Watt-hours (GWh) of electricity were used in California's agricultural water sector, which resulted in a related GHG emission of 3.4 million metric tons of carbon dioxide equivalent ($MMTCO_2$-e) (Liu, 2017). In the Pajaro Valley in 2001, electricity use and related GHG emissions associated with agricultural water use for strawberries, lettuce, and apples, totaled approximately 6,000,000 kWh (equivalent to 6 GWh) and 1600 metric tons of CO2-e, respectively. In 2011, the Pajaro Valley contained approximately 28,270 acres of irrigated farmland (PV Water, 2014), approximately 0.47 percent of California's 6 million acres of irrigated farmland (Liu, 2017). In 2001, the estimated electricity used for agricultural water in the Pajaro Valley was approximately 0.06% of electricity used for agricultural water in California, and the estimated related GHG emissions were approximately 0.05% of GHG emissions related to agricultural water use in California. The relatively lower electricity use and GHG emissions of the Pajaro Valley is likely attributed to the relatively shallow depths to groundwater, as compared to the aquifers in the Central Valley and many other agricultural regions of California.

3.2 Energy intensity

Similar to trends in median DTW (Figure 16), trends in energy intensity (Figure 20) closely followed climatic periods in the Pajaro Valley, generally increasing during dry periods and decreasing during wet periods. Energy intensity steadily increased over the period of record with a relatively large increase in recent years (2007–2014). Energy intensity was greatest in the coastal region, which can be attributed to a consistently greater coastal DTW. Differences in energy intensity across regions may also be attributed to differences in topography.

Energy intensity can be used as a metric to describe E-W Nexus relationships, including the connection between trends in groundwater head, the quantity and cost of energy required to pump groundwater, and GHG emissions from energy consumed to pump groundwater. As groundwater head decreases, energy intensity increases, which leads to negative impacts, such as increased energy consumed to pump groundwater, greater energy costs, and increased GHG emissions.

3.3 Analyzing SWI

When collective outflows (including groundwater pumpage) in an aquifer system exceed collective inflows for a prolonged period, groundwater overdraft occurs and coastal aquifers are thus susceptible to SWI (Hanson et al., 2014), as in the case of the Pajaro Valley aquifer. SWI into the Pajaro Valley aquifer (Figure 21) increased over the model period, with the most notable increase beginning in the early 1990s through the end of the model period, when agriculture intensified in the Pajaro Valley.

Correlations between (1) strawberry irrigated area and SWI and (2) applied groundwater for strawberries and SWI were both significant (α=0.05, p-value = <0.0001) with a Spearman's ρ of 0.6293 and 0.6443, respectively. Correlations between (1) lettuce irrigated area and SWI and (2) applied groundwater for lettuce and SWI were also significant (α=0.05, p-value = <0.0001) with a Spearman's ρ of -0.58 and Pearson's r of 0.096, respectively. The relationship between the temporal variability of SWI and strawberry cultivation show a strong positive correlation with both irrigated area of strawberries and applied groundwater for strawberries. The relationships between temporal variability of SWI and lettuce cultivation show a weak negative correlation with irrigated area of lettuce and a weak positive correlation with applied groundwater for lettuce; these contrasting relationships can be attributed to an increase in applied groundwater for lettuce (Figure 6) corresponding to a decrease in lettuce irrigated area (Figure 5), likely related to increased crop rotations per year.

These correlations between more intensive agricultural cultivation (e.g., strawberry and lettuce cultivation) and SWI highlight the general influence of more water-intensive land use and farming practices on the Pajaro Valley's groundwater system. However, the influence of irrigated agriculture on the Pajaro Valley groundwater aquifer is much more complex than these two crops alone, which are just two examples of numerous other water intensive crops grown in the valley. There are various other factors of the basin's water budget that potentially influence intensive water use and SWI, including the cultivation of other crops, municipal well pumping (i.e., associated with the city of Watsonville), variations in precipitation due to climate variability, surface water diversions, population growth and more. An increased understanding of all the contributing factors to groundwater overdraft will aide the GSA in achieving groundwater sustainability in the Pajaro Valley.

3.4 Pajaro Valley WEF Nexus linkages

Within the previously described quantitative WEF Nexus relationships, there exist various linkages (e.g., trade-offs, alterations, and synergies, as described in section 1). Here I describe the linkages of the Pajaro Valley WEF Nexus.

As a result of climate variability, water demand increased during dry periods in the Pajaro Valley. Dry periods also result in decreased recharge due to decreased precipitation. A series of trade-offs arise during dry periods, because the need to pump more groundwater results in the lowering of head levels, which in turn results in increased SWI and requires increased energy, leading to greater associated costs and GHG emissions. Increased groundwater pumpage also appears to be associated with more intensive agriculture involving increased cultivation of high water-intensity crops and increased crop rotations in the valley. The resultant SWI from groundwater overdraft due to intensive and/or inefficient use of groundwater can also be described as an alteration, in that SWI leads to altered and degraded groundwater quality, primarily in the coastal region, and can damage crop yields. Similarly, the energy consumed to pump groundwater to land surface can also be described as an alteration, in that electricity is consumed and altered into GHG emissions; these emissions contribute to climate change and likely reductions in precipitation (Pierce et al., 2012), which will further increase stresses within the WEF Nexus.

The increase in irrigated area and crop rotations of high water-use crops (e.g., an increase in the cultivation of strawberries from 1993–2014) results in increased water-use, and often decreased water use efficiency (as in the case of strawberries and lettuce). This is a trade-off, in that the cultivation of water-intensive, albeit high-value, crops results in increased revenues but decreased WUE, as measured by crop per drop and water use per acre.

Within nearly 100% of agricultural water use in the Pajaro Valley supplied by groundwater, there is a need for supplemental water sources to offset the intensive use of groundwater and bring the basin back into hydrologic balance. To support this objective, PV Water developed the CDS and other supplemental water projects (PV Water, 2014). The development and implementation of these types of supplemental water projects is a synergy. For example, in the case of the Watsonville Recycled Water Facility, water that would otherwise be disposed of is reclaimed and delivered to coastal farms to replace the use of groundwater. However, there also exists a trade-off associated with growing crops, especially high water-use crops like strawberries, within the DWZ; the augmentation fees implemented by the PV Water are higher for growers within the DWZ, resulting in increased costs associated with agricultural water use.

3.5 Guiding policy and management decisions in the Pajaro Valley

Many of the relationships described in this WEF Nexus analysis can help guide policy and management decisions to reduce groundwater overdraft by increasing agricultural WUE in the Pajaro Valley. Together with PV Water's BMP project and programs (PV Water, 2014), these suggestions can contribute to the development of an effective GSP to meet SGMA's 2040 goal of achieving groundwater sustainability in the basin.

First, it is important to note that the physical impacts of overdraft and SWI (i.e., low groundwater head levels and saltwater contamination of groundwater) affect the coastal region more directly than the inland region. While water levels are lowest, energy consumption is highest, and impacts of SWI are greatest in the coastal region, for most of the model period, inland groundwater pumping was greater than coastal pumping. The impacts of pumping more groundwater in the inland region likely contributes to decreased recharge in the coastal region. This influences drawdown of coastal groundwater levels, which is compounded upon the influence of coastal groundwater pumping for agriculture. Thus, applied groundwater for irrigated agriculture in both the coastal and inland regions contributes to the overdraft and SWI. Yet, coastal farming operations are most directly and severely impacted (e.g., lower groundwater levels and direct impacts of SWI) and pay more for management solutions (e.g., higher PV Water rates associated with agricultural water use) and electricity associated with groundwater pumping. Thus, it is imperative that management solutions focus on minimizing groundwater pumping in both the coastal and inland regions, and not just the coastal region.

To achieve groundwater sustainability goals, groundwater consumption must be balanced with supply (i.e., recharge). Currently, groundwater in the Pajaro Valley is used in excess of recharge, leading to overdraft conditions. Management strategies should include both increased supply (e.g., the CDS and related facilities) as well as multiple water conservation methods to stop the reliance on over-pumping groundwater as an insurance strategy (Smidt et al., 2016). Even modest improvements to agricultural WUE can save tremendous volumes of groundwater (Famiglietti, 2014). Of the projects and programs proposed in PV Water's 2014 BMP (PV Water, 2014), irrigation efficiency alone is anticipated to provide 40% of the reduced groundwater pumping needed to bring the basin back into hydrologic balance (PV Water, 2014).

Qualitatively described trade-offs, alterations and synergies can be used as a framework to identify modest changes that can be made to land use and farm practices to increase agricultural WUE. For example, the growth of a higher water-use, high-value crop (e.g., strawberries) over a lower water-use crop (e.g., apples) can be considered a trade-off; though farmers may gain a greater revenue from the higher-value, high water-use crop, this results in increased water consumption, further propelling issues of overdraft. Because farming practices generally follow economic incentives, water managers should develop conservation strategies that will provide economic incentives to profitably reduce water use, as opposed to implementing water use restrictions that will impede the ability of farmers to maintain their livelihoods (Smidt et al., 2016). For example, this trade-off can be turned into a synergy, in which water-use is profitably reduced by incentivizing farmers to grow lower water-use crops that still have a high enough commodity value for farmers to maintain revenues (Smidt et al., 2016). Using metrics of WUE in conjunctive with a commodity's market value and yield, a cost-benefit analysis can be conducted to determine which crops provide the greatest return per acre-foot of water applied per irrigated acre (Smidt et al., 2016). This allows water managers to design programs that will not just promote the mitigation of groundwater depletion but also promote farmer profit by making decisions from an economically-driven lens (Smidt et al., 2016). Additionally, if a strong enough synergy does not exist, managers may encourage the growth of crops with sufficiently high WUE and market value through subsidies (Smidt et al., 2016). This trade-off-synergy pair could lead to considerable water savings in the Pajaro Valley and thus reduced overdraft and SWI. This in turn would diminish the severity and impacts of the previously mentioned trade-offs and alterations, with minimal effect on the agricultural economy of the Pajaro Valley.

Climate variability must also be seriously considered as a part of the Pajaro Valley's management solutions. There exists a clear relationship between climate variability (i.e., wet and dry periods) and agricultural water use. Thus, water managers must plan for a suite of projects that provide sufficient sources of supplemental water during drought periods to offset the need for increased groundwater pumping due to decreased precipitation. During dry periods, this will prevent the rebound of overdraft and SWI issues while allowing farmers to maintain their revenues. These types of new and existing supplemental water projects have been proposed by PV Water in the 2014 BMP Update (PV Water, 2014). Coupled with agricultural water conservation, hydrologic modeling shows these projects and programs can increase the Pajaro Valley groundwater basin's water supply by 12,100 acre-ft/yr; this increase is estimated to solve 90% of the SWI and 100% of the basin overdraft problems.

4. Conclusion

Socioeconomic changes and climate change are increasing the demand for water, energy, and food in California and globally, leading to an increasing number of trade-offs and conflicts among the three resources. These increased demands for water, energy, and food often result in unintended yet severe environmental consequences. Given the intrinsic relationships among water energy and food, the use of a WEF Nexus approach can provide a beneficial framework to address these consequences by focusing on system efficiency as opposed to the productivity of individual sectors (Golam Rasul and Sharma, Bikash, 2015). In this study, I address issues of long-term groundwater overdraft and SWI in the coastal Pajaro Valley aquifer along California's Central Coast using a hydrologic science-based WEF Nexus approach in the context of SGMA regulations.

I use results from an updated version of the PVHM (Earll et al., in prep) and publicly available data to quantify relationships and linkages (i.e., synergies, alterations, and trade-offs) within the W-F and E-W Nexus relationships. I frame the Pajaro Valley WEF Nexus using data associated with the cultivation of strawberries, lettuce, and apples. I find that, as previously delineated by Hanson et al. (2014), two distinct agricultural periods exist in the Pajaro Valley during the model period (1964–2014): (1) a period of more traditional seasonal agriculture from 1964–92 during which substantial withdrawals of groundwater only occurred during dry periods, and (2) a period of more intensified agriculture from 1993–present corresponding to a shift in cultivation of more water intensive crops (e.g., strawberries, bushberries, and vegetable row crops) and additional rotational plantings.

Over the model period, irrigated area of strawberries (a high water-use crop) increased as irrigated area of apples (a low water-use crop) decreased, resulting in increased water-use associated with increasing acreage of strawberries. Increased water-use was associated with applied groundwater for lettuce; even though irrigated area of lettuce decreased, applied groundwater for lettuce increased during the more intensified agricultural period, likely due to increased rotational plantings. These trends in crop production and water-use have a direct influence on the Water-Food and Energy-Water Nexus. For example, increased cultivation of the higher water-intensity strawberry crop mitigates any reduction in water stress on the system that may result due to the decreasing trend in lower water-intensity crops such as apples. Shifts in prominence of one crop relative to another are often influenced by economic drivers, such as in the case of the Pajaro

Valley, in which an increase in strawberry cultivation coincided with a temporal increase in market value of strawberries.

When comparing irrigated acreage to water use of the three crop types, lettuce and strawberries appear to require considerably more groundwater than apples. Trends in metrics for WUE (i.e., crop per drop and water use per acre) show that over the last 20-30 years, the cultivation of strawberries and lettuce became less water efficient. This may be attributed to multiple factors, including recent dry periods and droughts, increased crop rotations associated with a more intensified period of agriculture, and the tendency of farm managers to over water to ensure crop needs are met to prevent revenue losses from a poor crop (PV Water, 2014).

Of the three crops analyzed in this study, strawberries consistently provided the greatest revenue collectively for farmers in the Pajaro Valley, while apples provided the lowest collective revenue. Lettuce revenue was greater than apple revenue, but considerably lower than revenue from strawberries. These differences in crop revenue, a function of crop yield and crop price, are the major drivers behind shifts in land use patterns, which heavily impact groundwater use and sustainability.

Associated with increased agricultural groundwater use and decreased water use efficiencies, groundwater head levels across the entire Pajaro Valley decline over the model period. Median annual coastal groundwater levels were predominantly below sea level for the entirety of the study period, but by 1993, median annual groundwater levels across the entire valley (i.e., the inland and coastal regions) dropped below sea level. By 2007, median annual groundwater levels in all regions within the Pajaro Valley dropped to their lowest elevations at relatively fast rates. The decrease in median annual groundwater head levels from the early 1990s–present corresponded to the more intensified period of agriculture in the Pajaro Valley, a substantial increase in applied groundwater for strawberries, and decreased WUE for strawberries and lettuce, all of which are likely drivers of overdraft conditions in the valley. Furthermore, both inland and coastal agricultural production contributes to the low coastal groundwater levels that induce SWI; over time, substantial inland agricultural development has been capturing recharge that would otherwise flow to the coastal region. Combined with coastal agricultural pumping, these factors induce coastal overdraft and SWI.

Extensive agricultural water use in the Pajaro Valley likely contributes to overdraft conditions and results in a variety of trade-offs and alterations, such as increased energy required to pump groundwater and SWI. Characterizing WEF Nexus linkages (i.e., trade-offs, alterations, and synergies) can help guide policy and management to reduce groundwater consumption by increasing agricultural WUE in the Pajaro Valley. Together with PV Water's projects and programs that increase supplemental water to offset groundwater use, these Nexus-based suggestions can contribute to the development of an effective GSP to meet SGMA's 2040 goal of achieving groundwater sustainability in the basin.

My project is novel and significant because it addresses coastal groundwater sustainability using Nexus-based science to help guide policy and management decisions when developing GSPs. Findings are transferrable to other coastal aquifer systems in California, including practical guidelines on how WEF Nexus concepts can be used to help develop effective GSPs. On a global-scale, this project highlights the importance of approaching issues of sustainability and human and environmental security from a WEF Nexus perspective when implementing policy and management decisions.

4.1 Future work

The conclusions presented in this study would be benefit from support by related future studies. More concrete suggestions for modest land-use changes to improve agricultural WUE in the valley would require repeating these W-F Nexus analysis methods using data associated with all crop groups in the valley (as opposed to just apples, strawberries, and lettuce). To gain a more comprehensive understanding of the impacts of climate variability and PV Water's supplemental water projects on WEF Nexus relationships, these analyses should be repeated using data from recent model runs that examine updated BMP components (PV Water, 2014) under different climate regimes.

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6. Tables

Table 1. The Pajaro Valley Water Management Agency (PV Water) 2014 rates (PV Water, 2014) charged for water users in the Pajaro Valley. The PV Water augmentation charge, provided to groundwater users in the Pajaro Basin, funds the supplemented water service. The delivered water charge, provided to property owners in the Delivered Water Zone (DWZ) with CDS connections, funds the delivered water service (PV Water, 2015a).

PV Water Augmentation Charge [$/acre-ft]			**Delivered Water Charge [$/acre-ft]**
Metered Users – Outside DWZ	**Metered Users – Inside DWZ**	**Unmetered (Rural Residential)**	$329.00
$174.00	$210.00	$168.00	

7. Figures

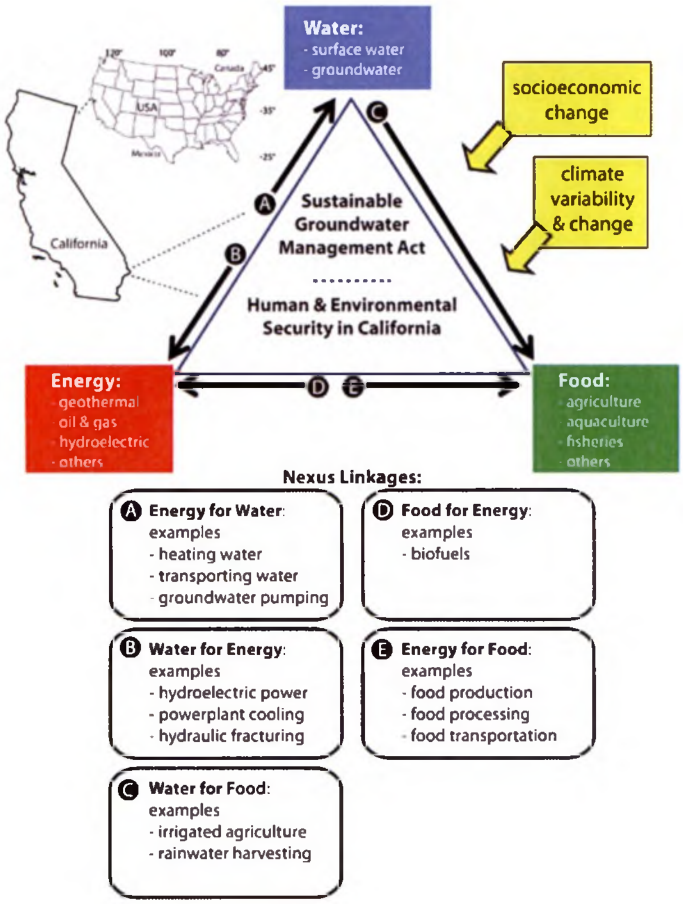

Figure 1. Conceptual diagram showing Water-Energy-Food (WEF) Nexus relationships and drivers (Gurdak, 2017).

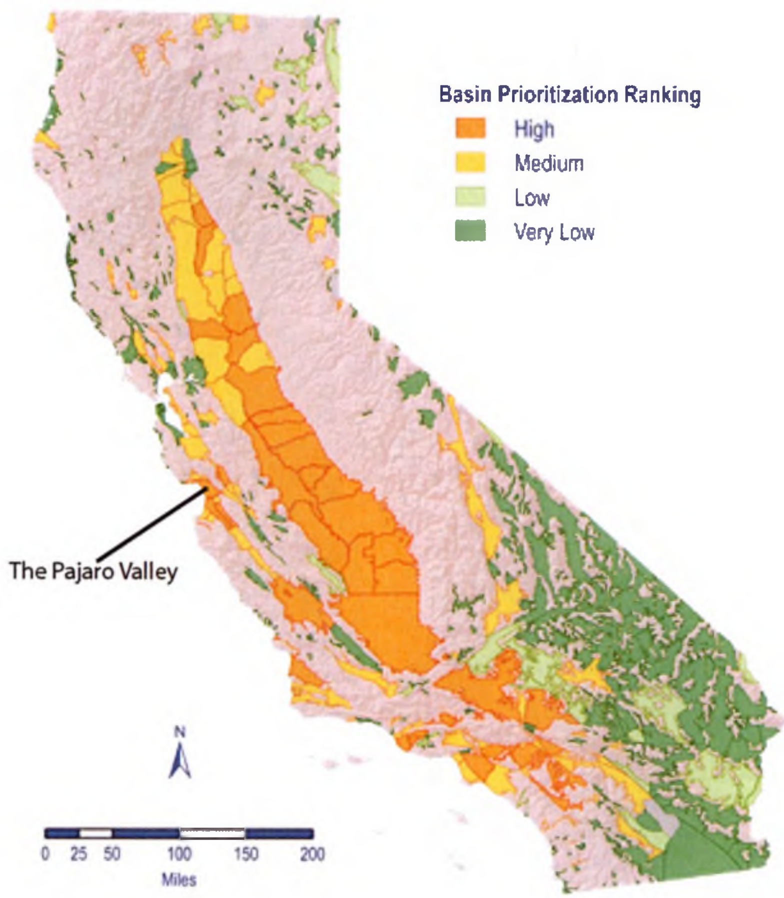

Figure 2. Map of the state of California showing basins addressed under the Sustainable Groundwater Management Act (SGMA) and their prioritization ranking (CA DWR, 2015). The Pajaro Valley, a high priority basin, is located next to Monterey Bay on California's Central Coast.

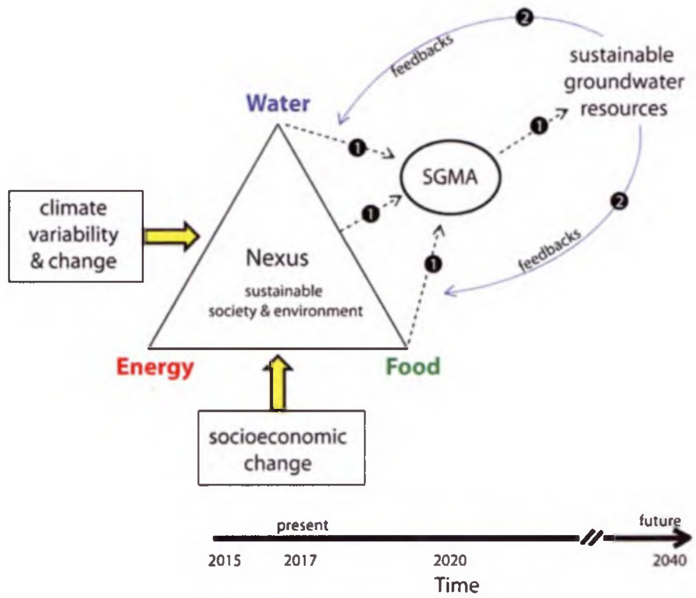

Figure 3. Conceptual diagram of the Water-Energy-Food (WEF) Nexus showing relationships and feedbacks with California's Sustainable Groundwater Management Act (SGMA) and sustainable groundwater resources. The two most significant drivers or perturbations within the WEF Nexus are climate variability and change and socioeconomic change. The impacts of the WEF Nexus concepts on SGMA planning are represented by the dashed arrows (#1), and the feedbacks of sustainable groundwater resources on the Nexus are represented by the blue arrows (#2). Key dates of SGMA are shown along the x-axis, including 2015 (January 1) when SGMA took effect, 2017 when Groundwater Sustainability Agencies (GSAs) must be formed, 2020 when Groundwater Sustainability Plans (GSPs) must be finalized for high priority basins by the GSAs and begin implementation, and 2040 when high priority basins must achieve sustainability (Gurdak 2017).

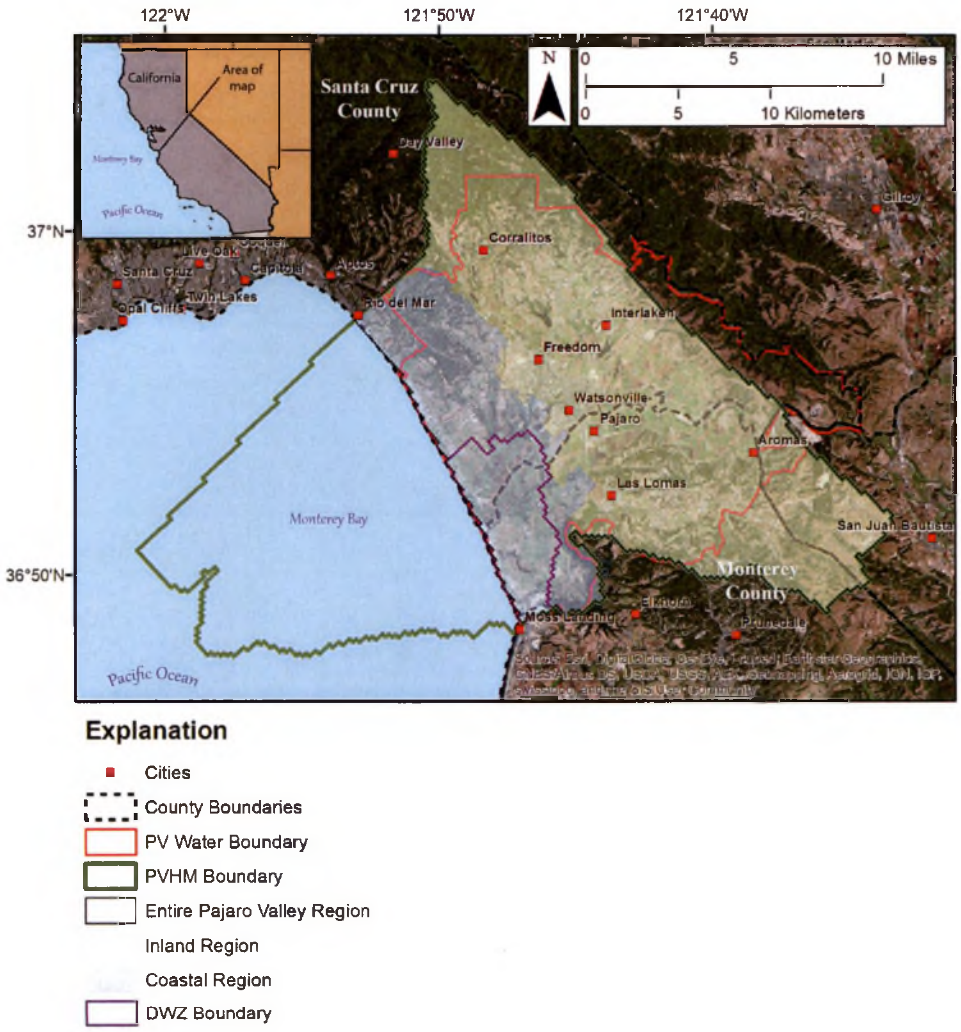

Figure 4. Study area map showing the location of the Pajaro Valley on California's Central Coast, Santa Cruz and Monterey Counties, the PV Water boundary in red, the PVHM boundary in green, and the study regions of interest: the entire Pajaro Valley (outlined in black), the inland region (shaded in green), the coastal region (shaded in blue), and the Delivered Water Zone (DWZ) (outlined in purple).

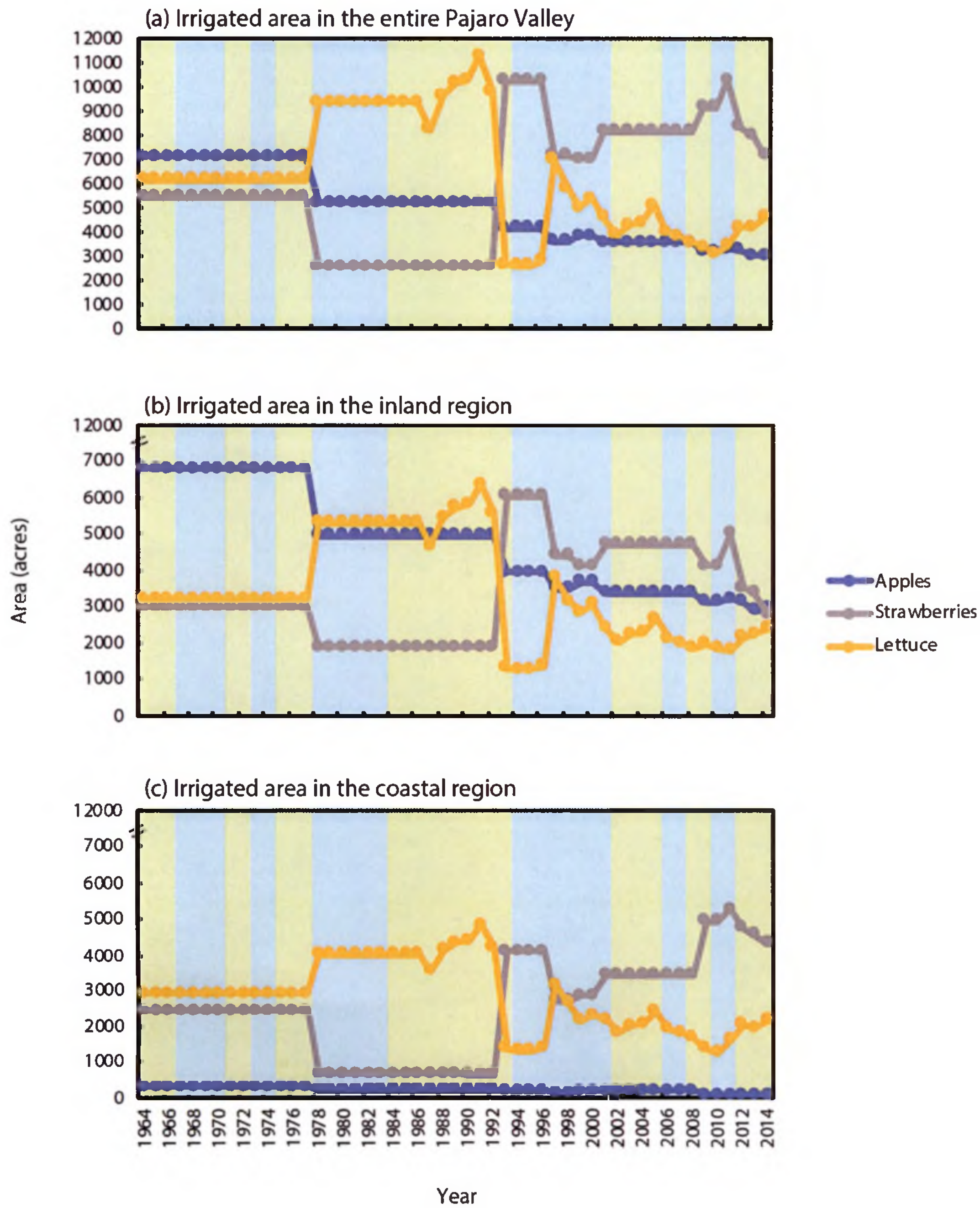

Figure 5. Irrigated area of apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region of Pajaro Valley, and (c) the coastal region of Pajaro Valley. Climatic wet and dry periods are delineated in blue and yellow, respectively.

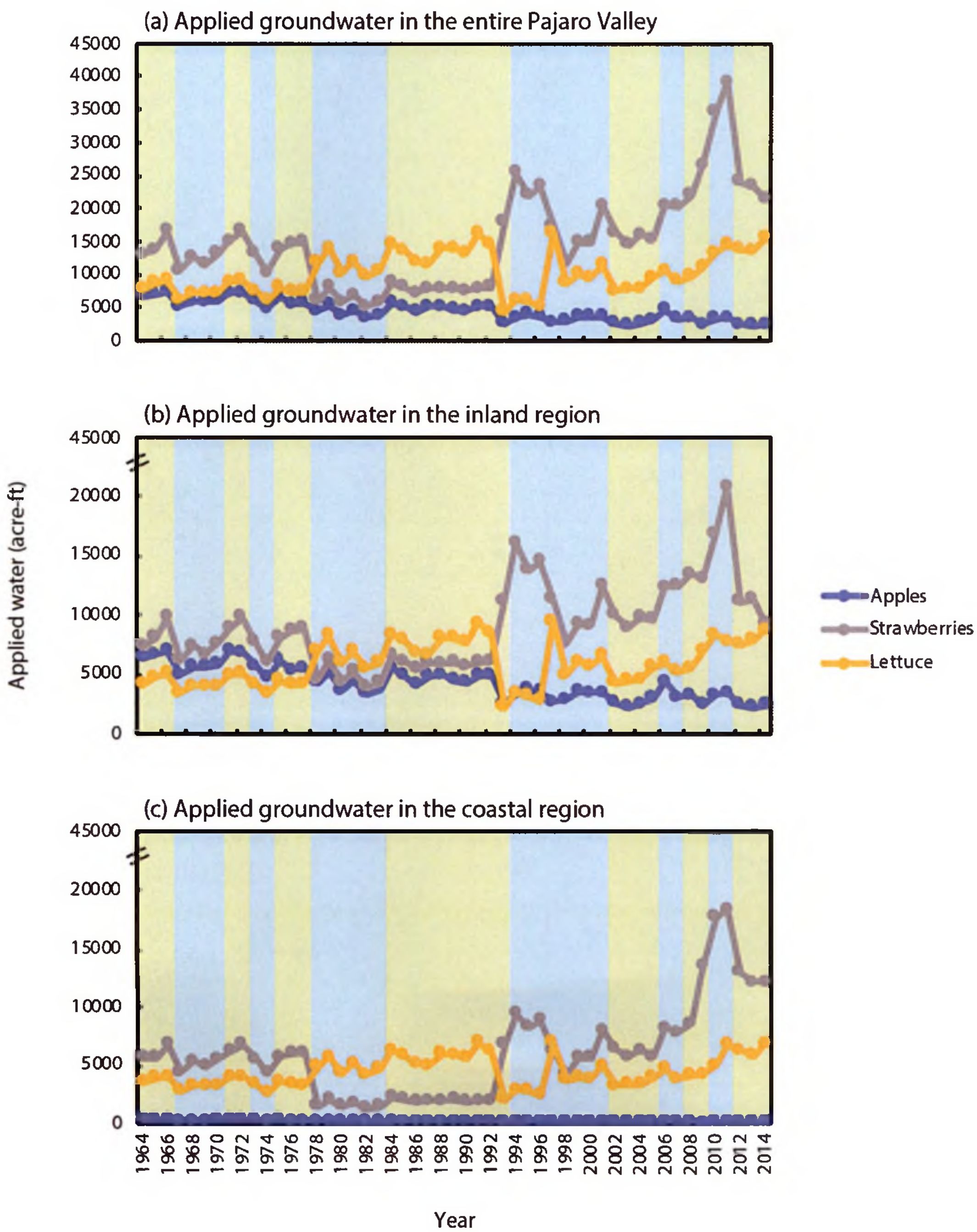

Figure 6. Applied water from groundwater for apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region of Pajaro Valley, and (c) the coastal region of Pajaro Valley. Climatic wet and dry periods are delineated in blue and yellow, respectively.

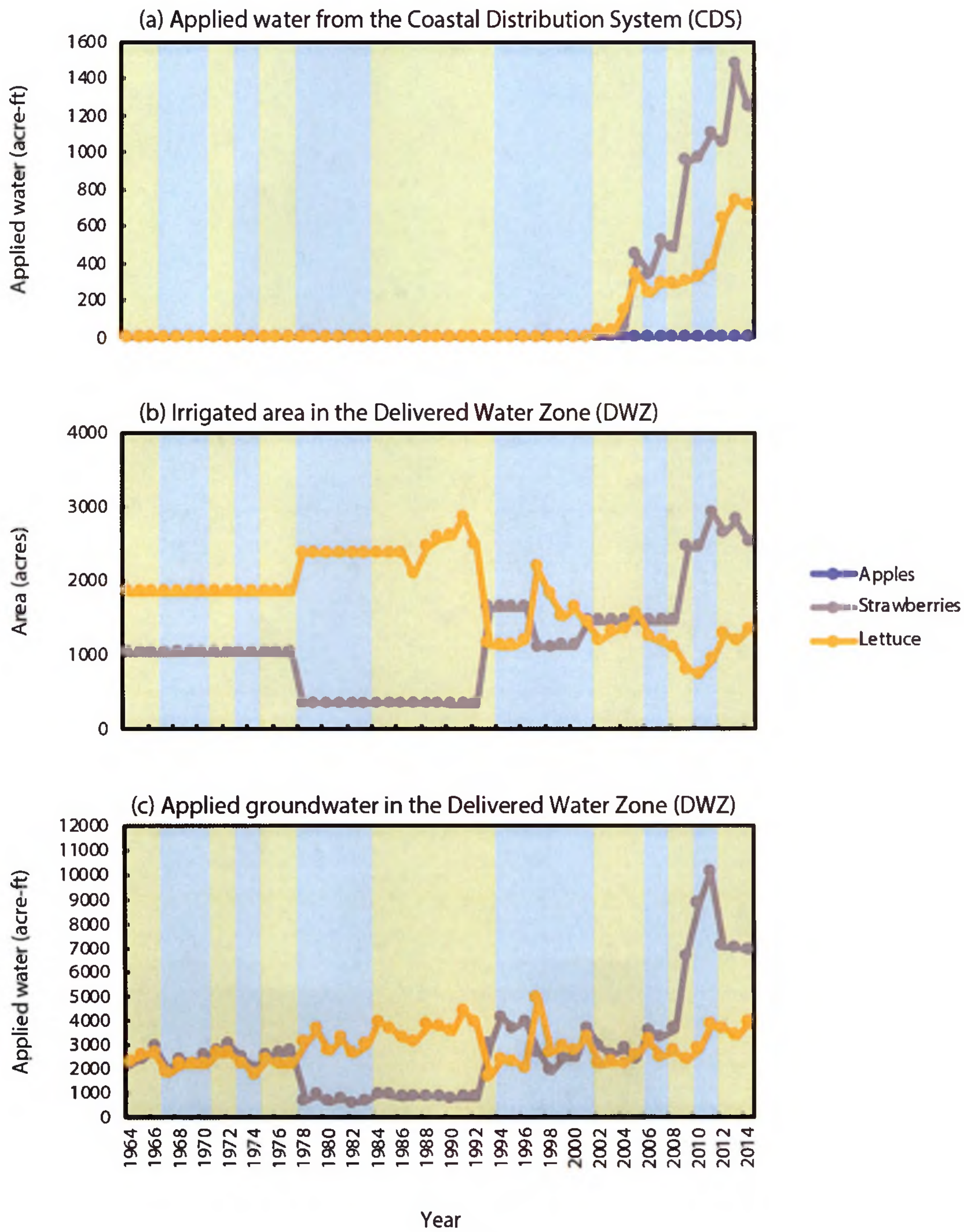

Figure 7. (a) Applied water from the Coastal Distribution System (CDS) for apples, strawberries, and lettuce located in the Delivered Water Zone (DWZ), which is the portion of the coastal region served by the CDS. (b) Irrigated area of strawberries and lettuce within the DWZ. (c) Applied water from groundwater for strawberries and lettuce within the DWZ.

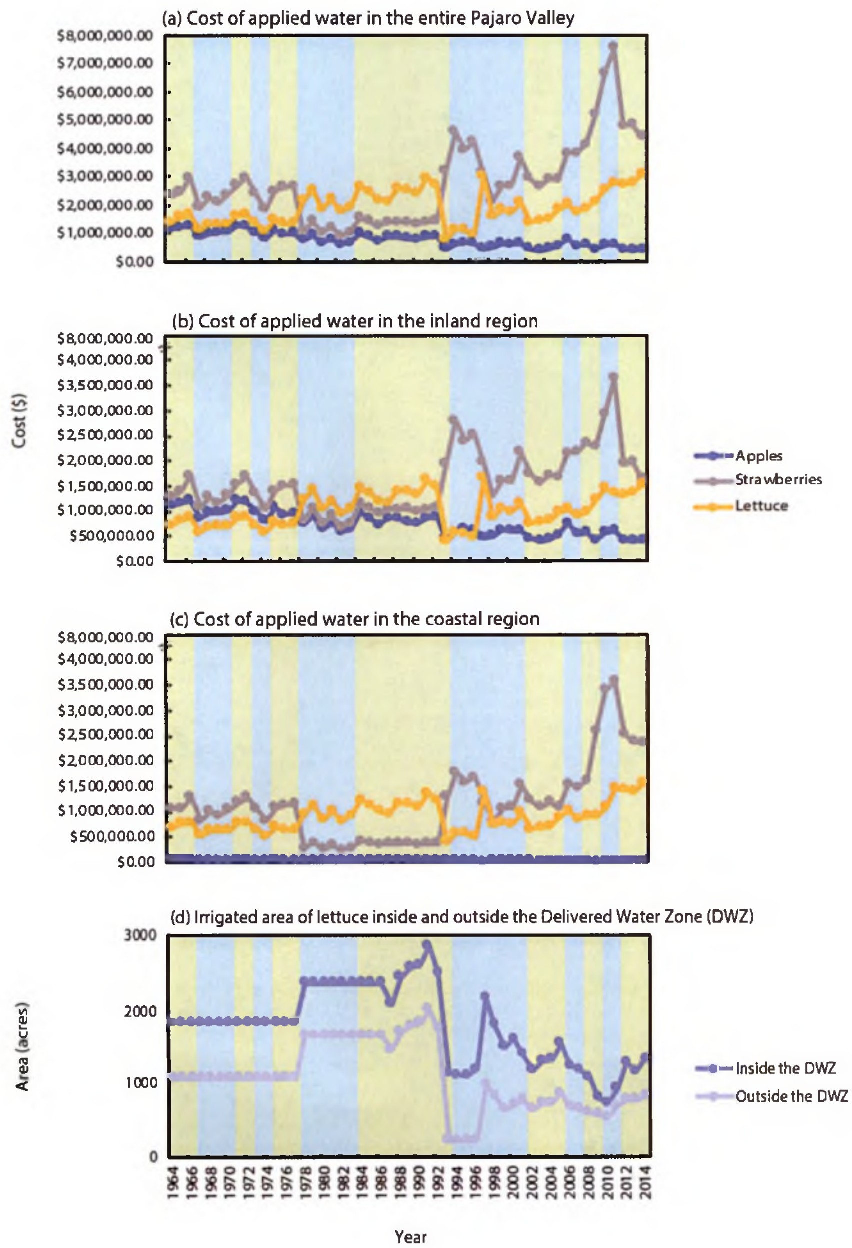

Figure 8. Cost of applied water for apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region of Pajaro Valley, and (c) the coastal region of Pajaro Valley based on 2014 PV Water rates. Note that PV Water was established in 1993, and thus PV Water augmentation fees were not charged prior. PV Water began charging growers different rates based on rate zone (i.e., whether farms are located inside vs. outside the Delivered Water Zone (DWZ) in 2011, though the pre-2011 values reported here reflect 2014 rates. (d) Irrigated area of lettuce inside and outside the DWZ of the coastal region.

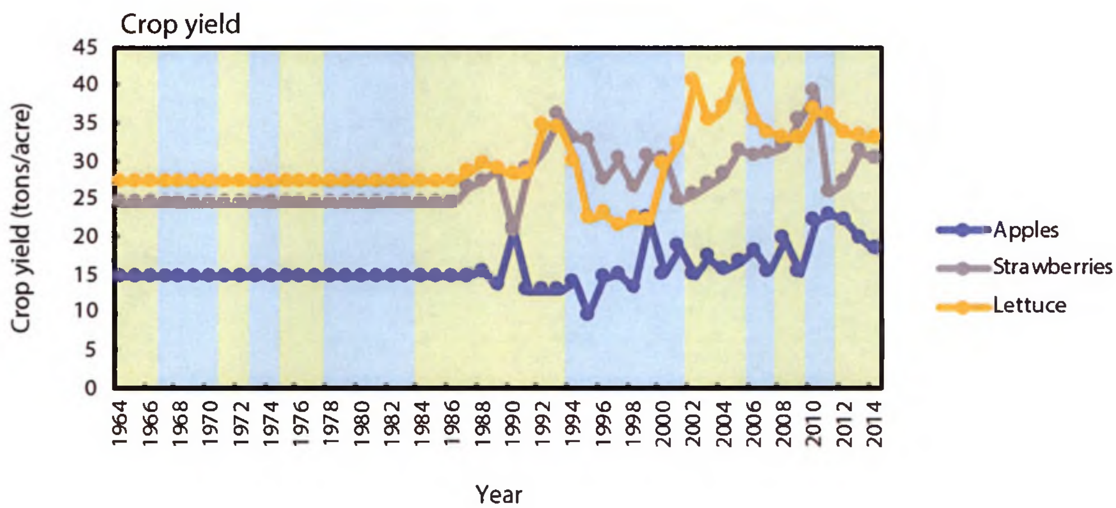

Figure 9. Crop yield in tons per acre. Values are from County of Santa Cruz Agricultural Commissioner Annual Crop and Livestock Reports (County of Santa Cruz, 2018), for which data is only available from 1986-2016, which is why pre-1986 values are held constant. Climatic wet and dry periods are delineated in blue and yellow, respectively.

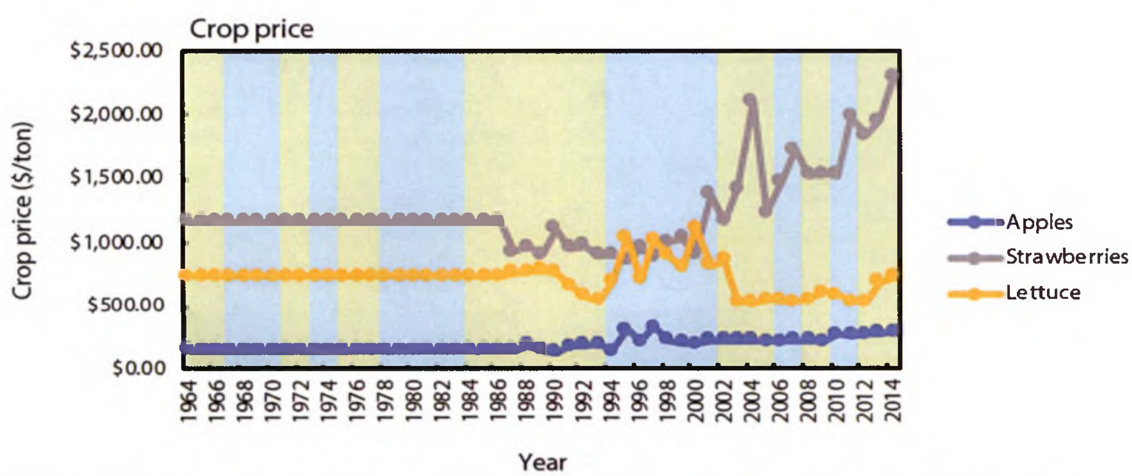

Figure 10. Crop price in U.S. dollars per ton. Values are from County of Santa Cruz Agricultural Commissioner Annual Crop and Livestock Reports (County of Santa Cruz, 2018), for which data is only available from 1986-2016, which is why pre-1986 values are held constant. Climatic wet and dry periods are delineated in blue and yellow, respectively.

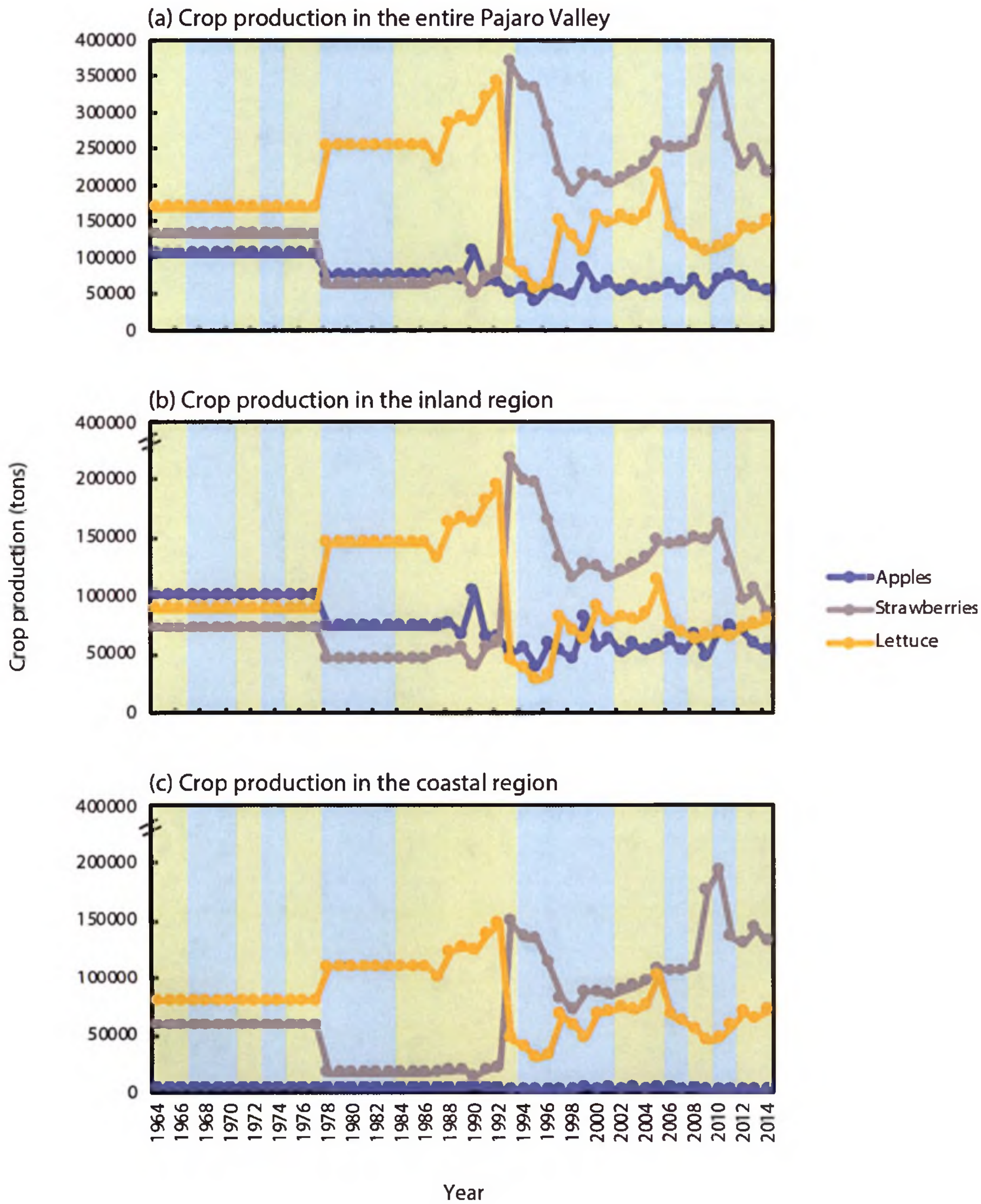

Figure 11. Crop production in tons for apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Note that pre-1986 values are a function of 1986 County of Santa Cruz data (County of Santa Cruz, 2018). Climatic wet and dry periods are delineated in blue and yellow, respectively.

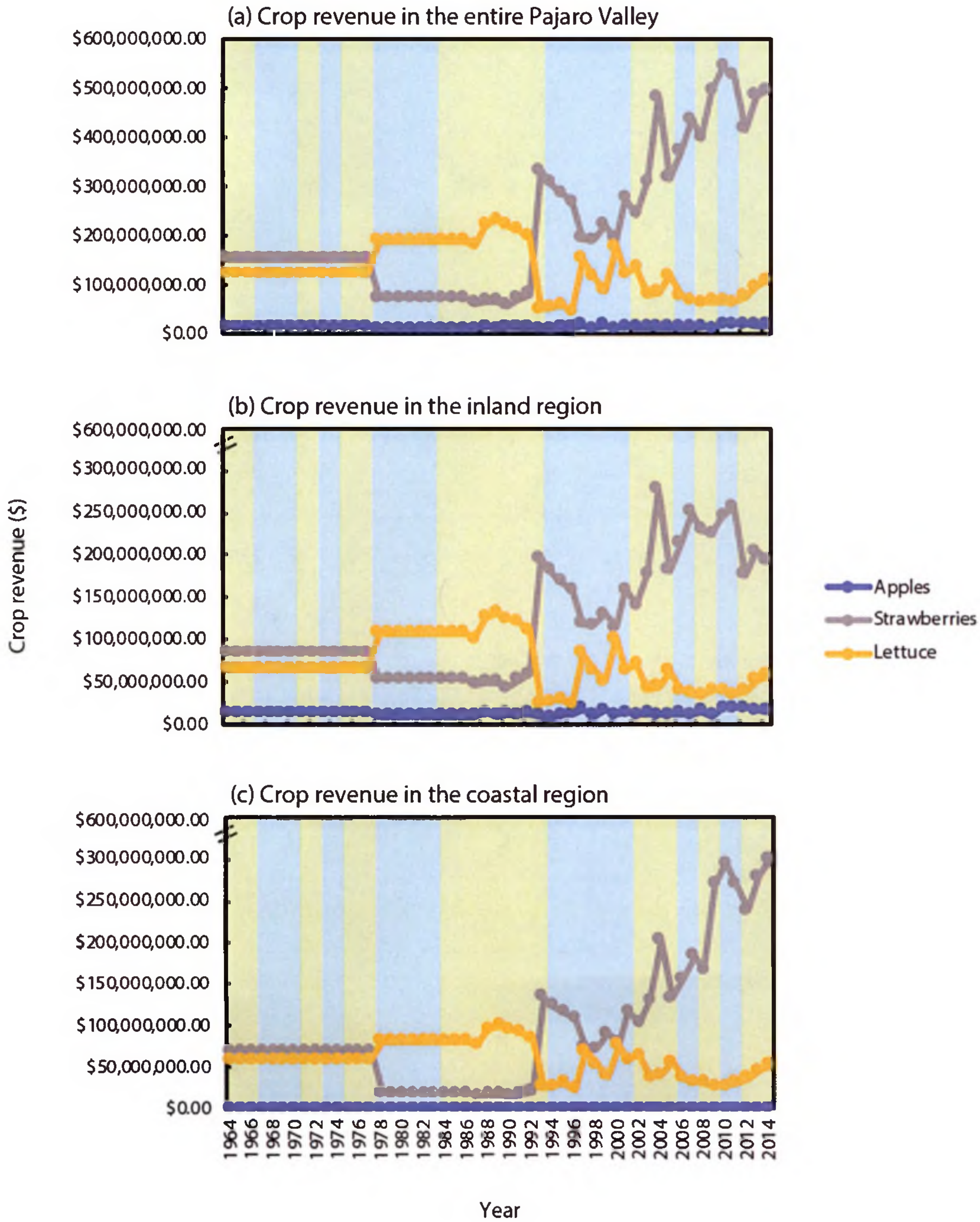

Figure 12. Crop revenue in U.S. dollars for apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Note that pre-1986 values are a function of 1986 County of Santa Cruz data (County of Santa Cruz, 2018).

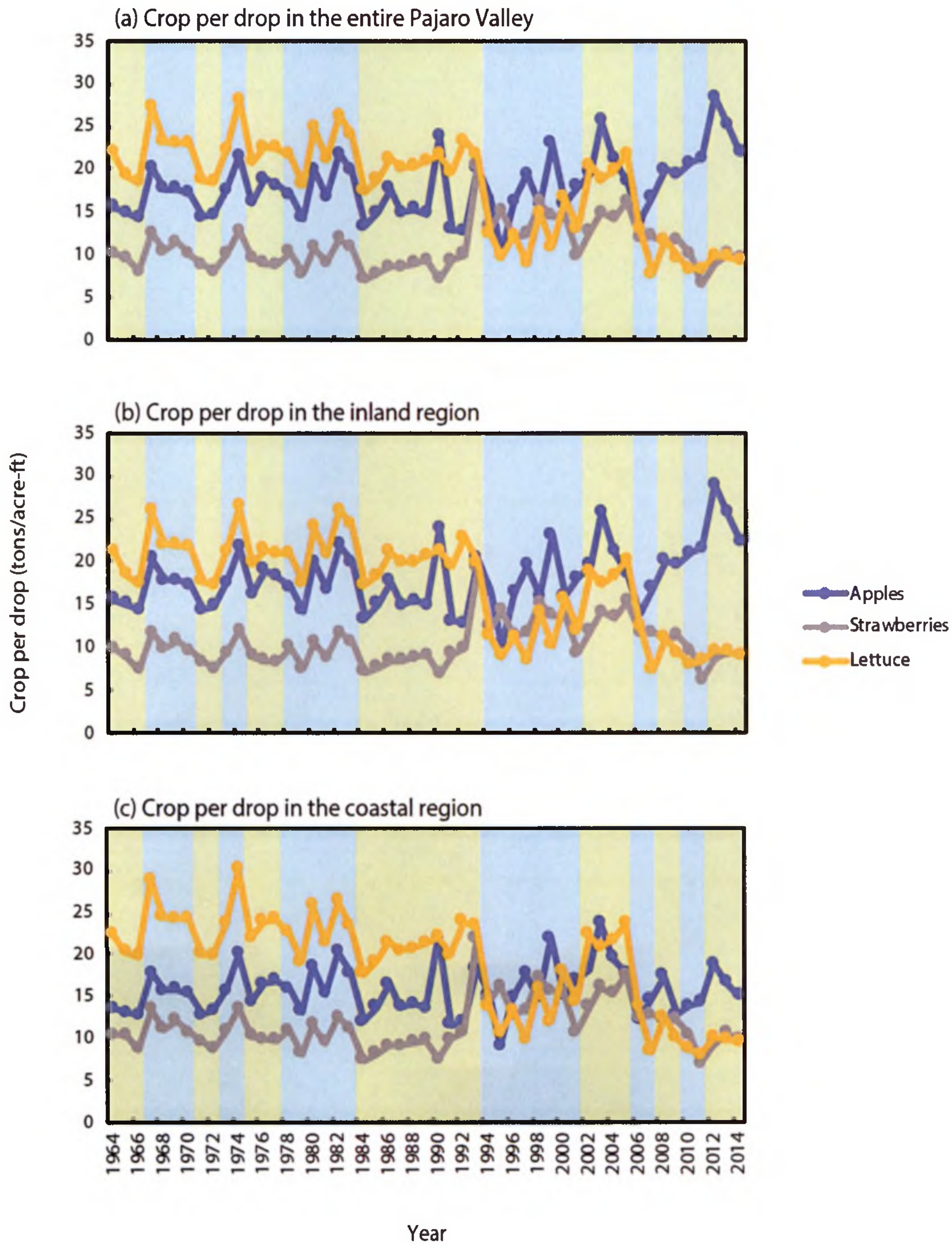

Figure 13. Crop per drop in tons per acre-ft for apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

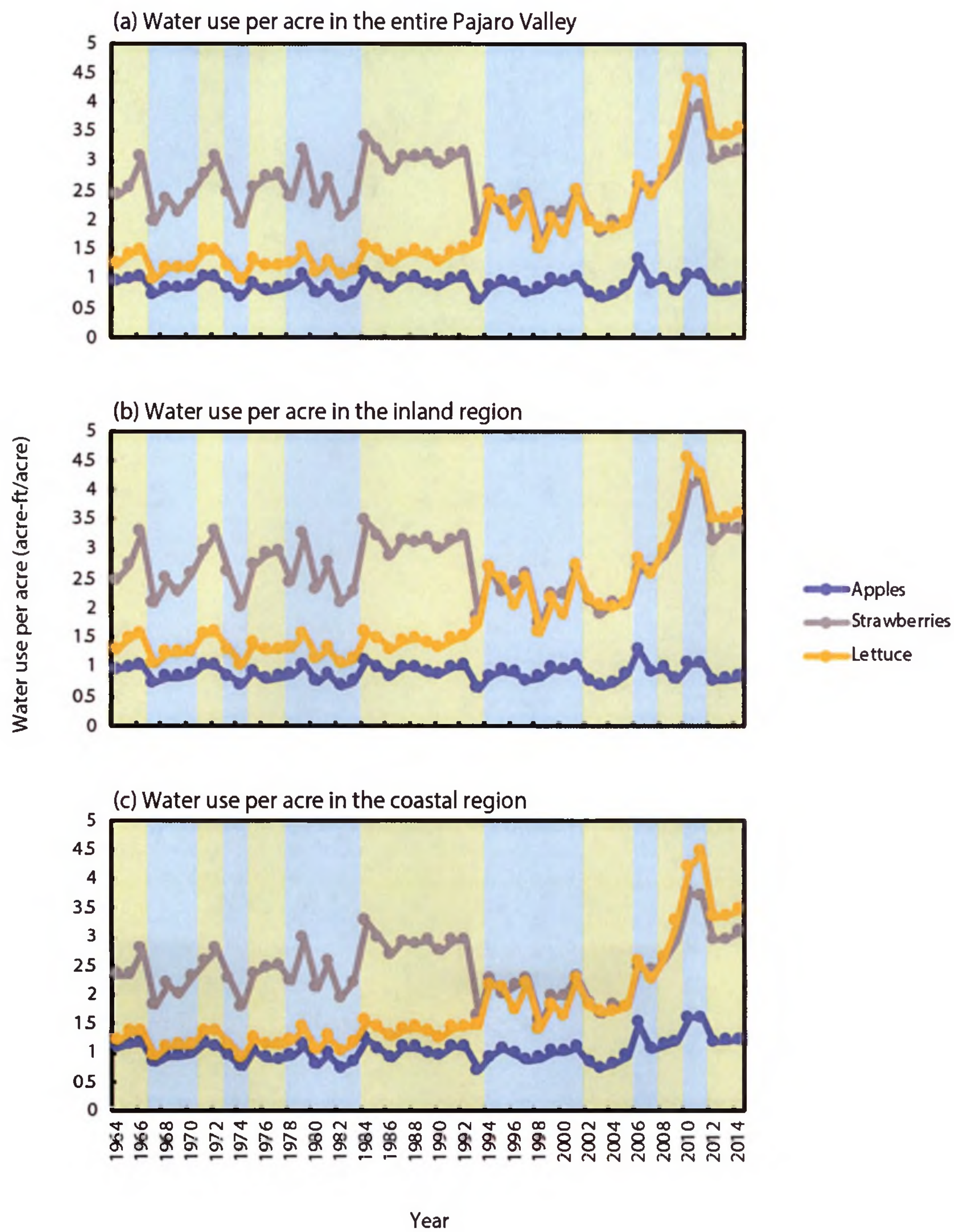

Figure 14. Water use per acre in acre-ft per acre for apples, strawberries, and lettuce in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

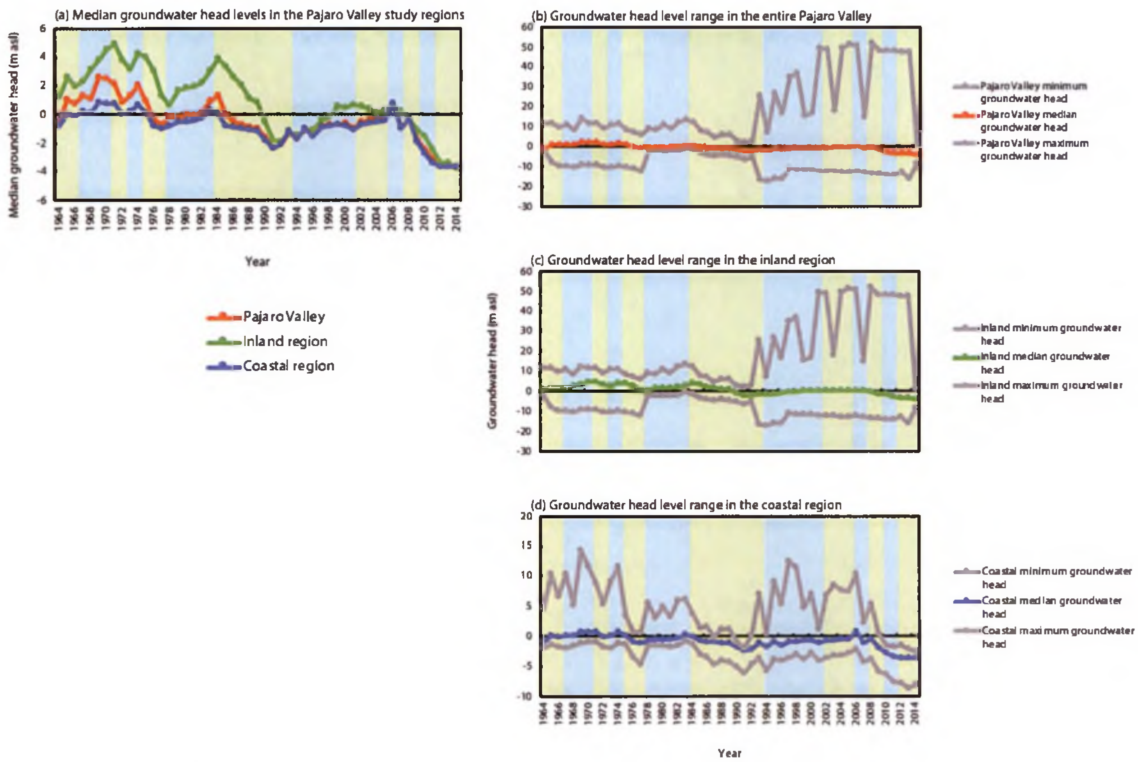

Figure 15. Median annual (January 1) groundwater head levels for all three regions in the Pajaro Valley including (a) median groundwater head in the entire Pajaro Valley, the inland region, and the coastal region; and the range of groundwater head levels (i.e., minimum, median, and maximum values) in (b) the entire Pajaro Valley, (c) the inland region, and (d) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

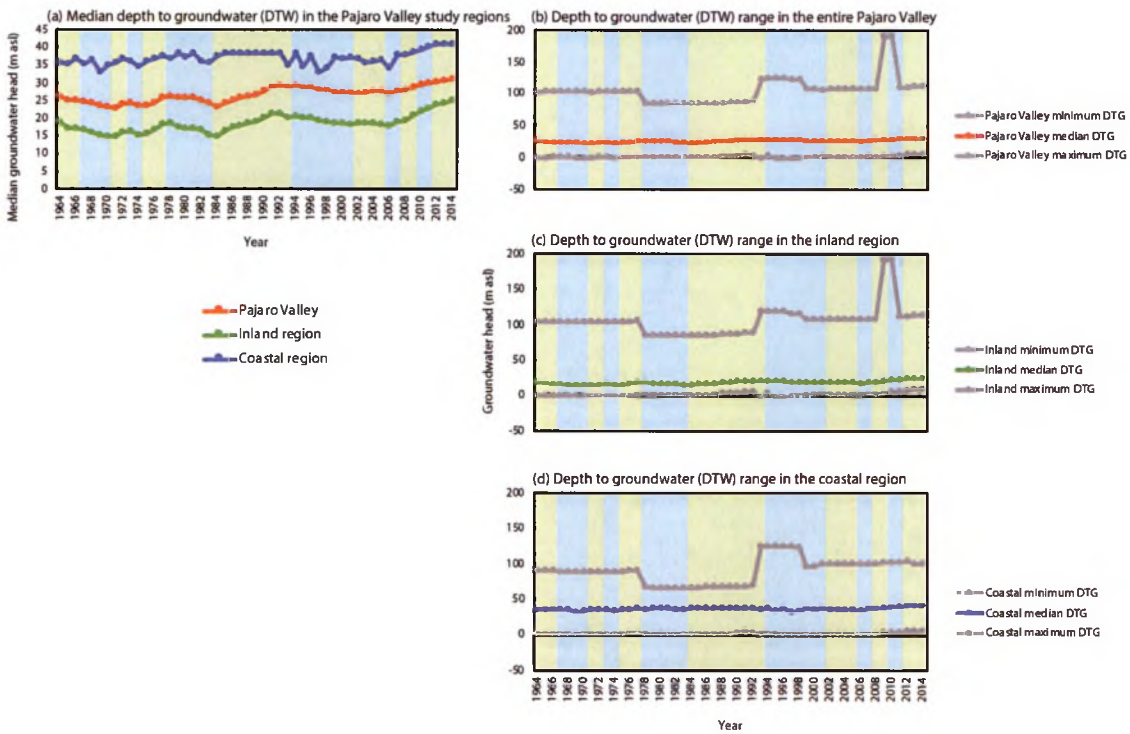

Figure 16. Median annual (January 1) depth to groundwater (DTW) values for all three regions in the Pajaro Valley including (a) median DTW in the entire Pajaro Valley, the inland region, and the coastal region; and the range of DTW values (i.e., minimum, median, and maximum values) in (b) the entire Pajaro Valley, (c) the inland region, and (d) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

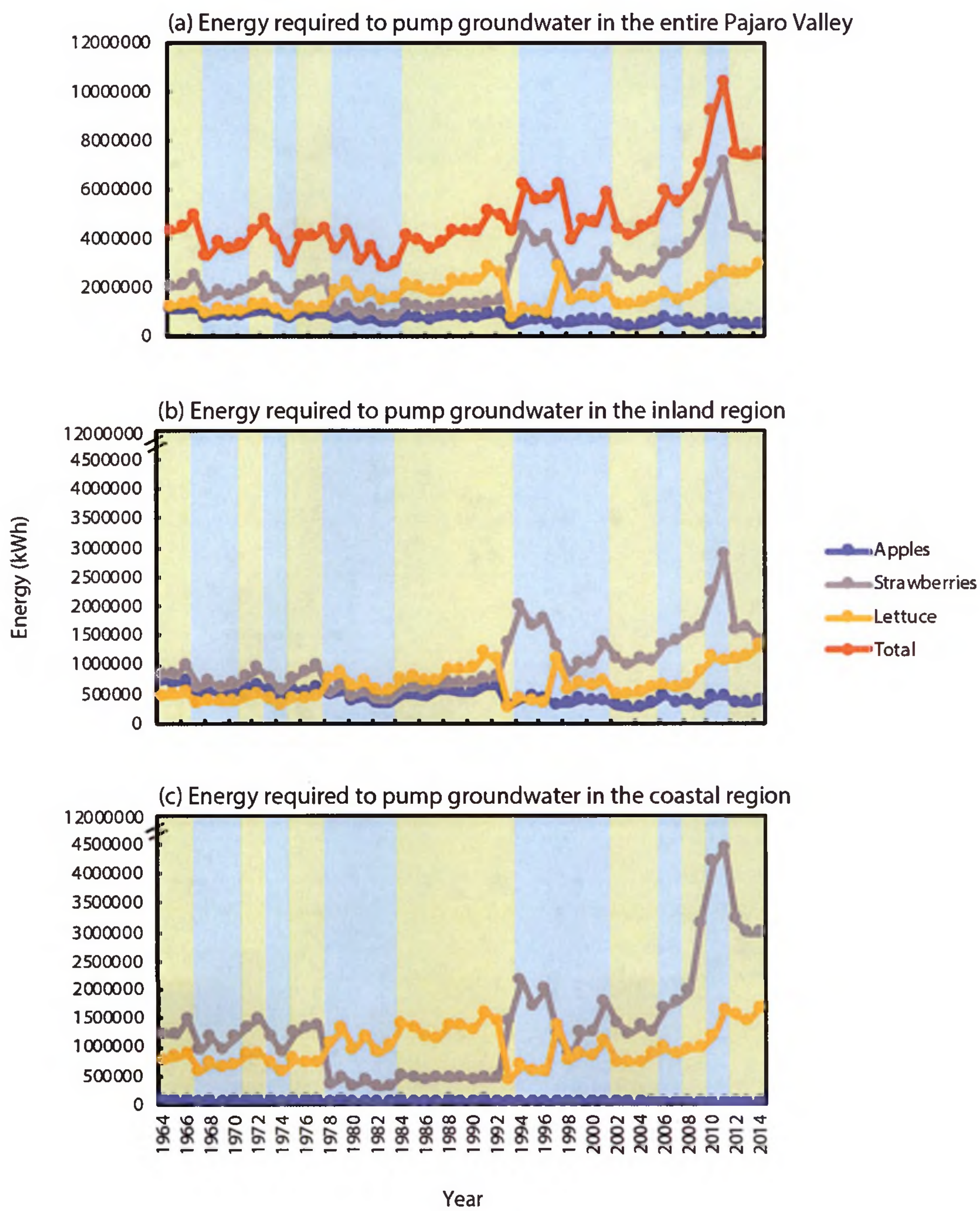

Figure 17. The calculated energy required to pump groundwater in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

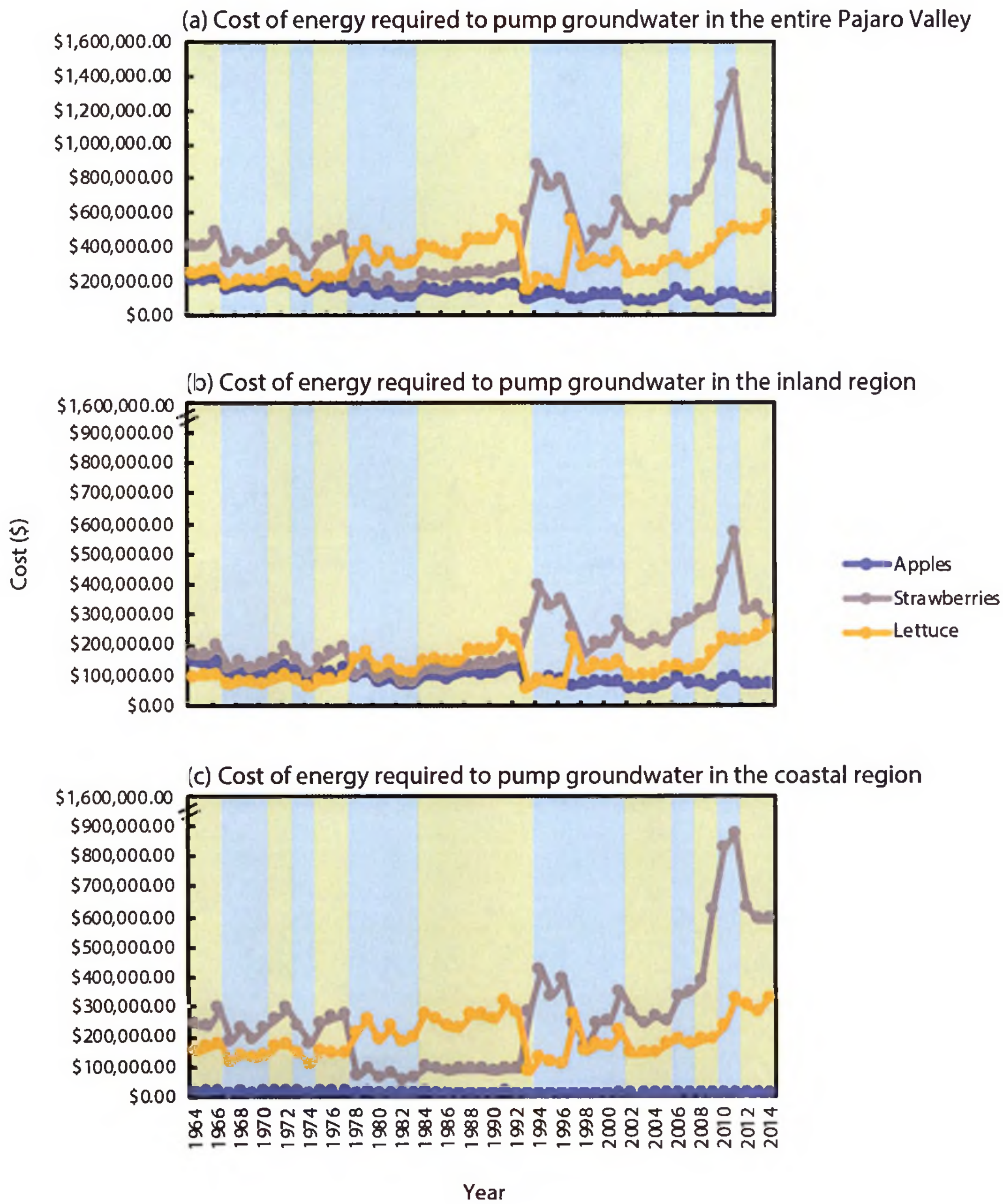

Figure 18. The calculated cost of energy in U.S. dollars required to pump groundwater in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

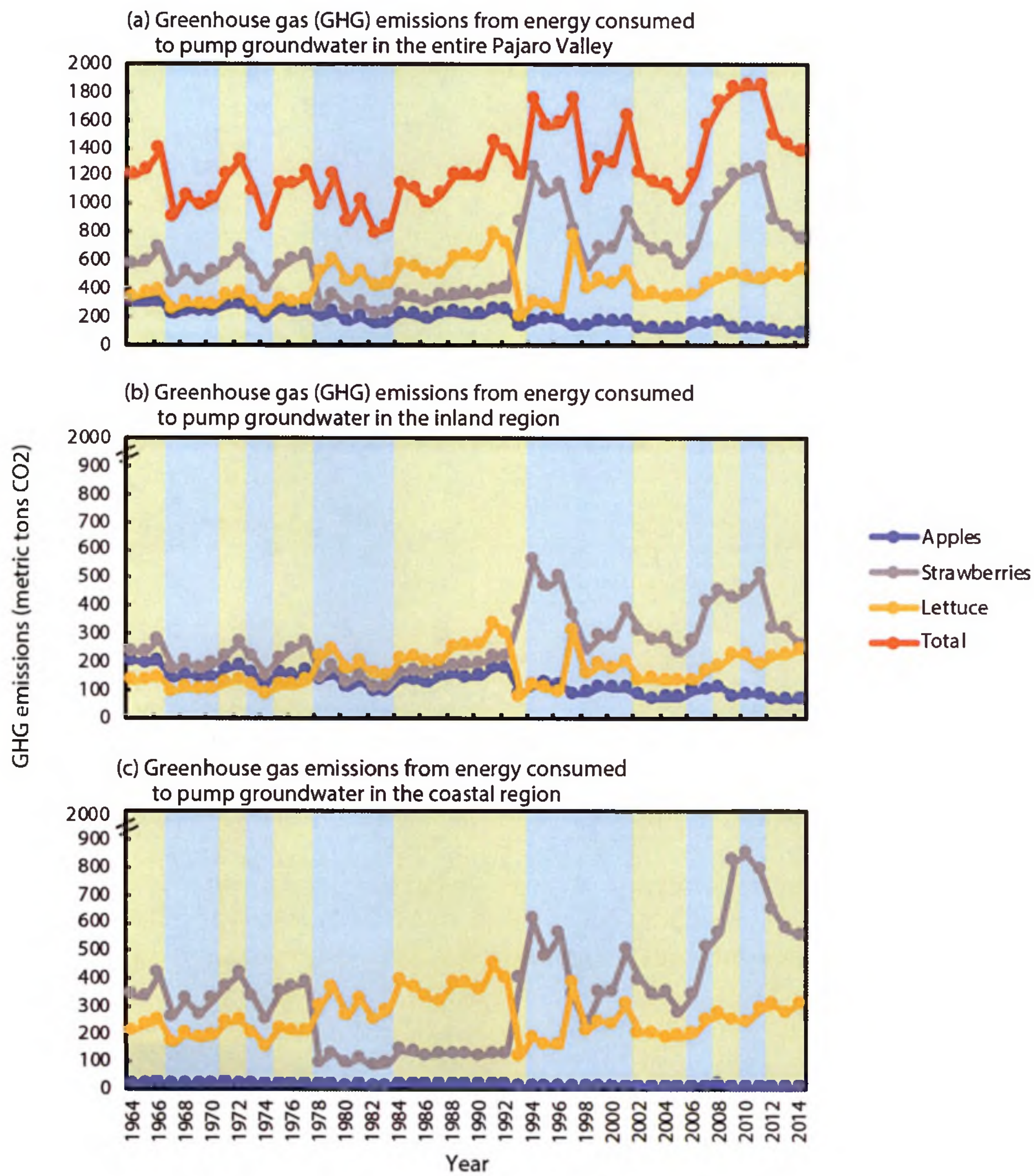

Figure 19. The greenhouse gas emissions in metric tons of CO_2 associated with the calculated energy required to pump groundwater in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

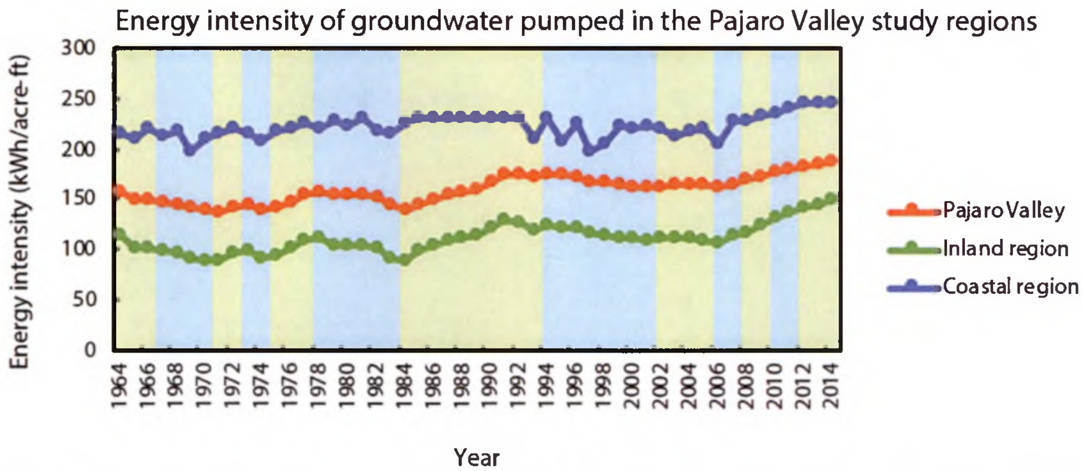

Figure 20. The energy intensity of groundwater pumped in kWh per acre-ft in (a) the entire Pajaro Valley, (b) the inland region, and (c) the coastal region. Climatic wet and dry periods are delineated in blue and yellow, respectively.

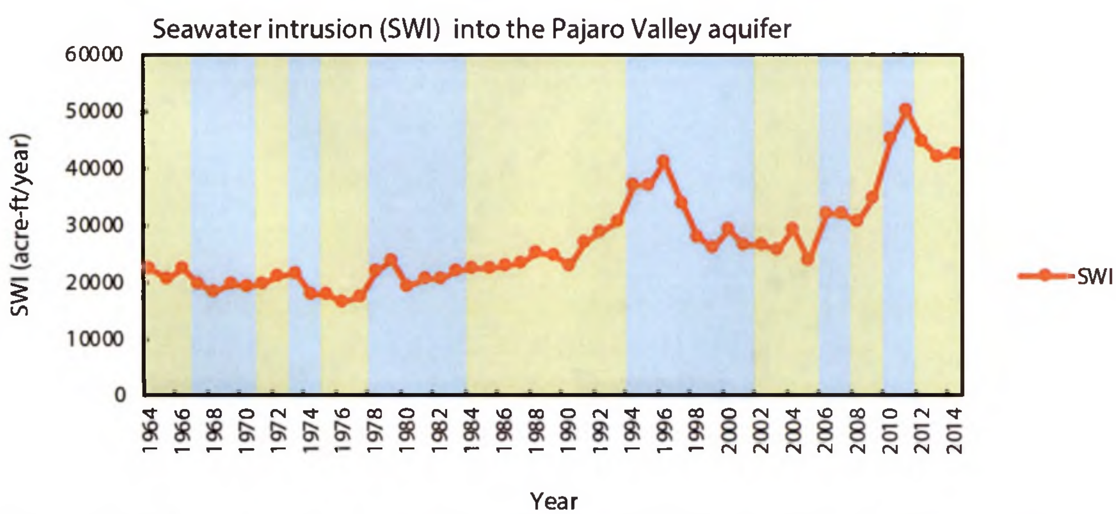

Figure 21. Total seawater intrusion (SWI) in acre-ft per year into the Pajaro Valley aquifer over the model period (1964-2014). Climatic wet and dry periods are delineated in blue and yellow, respectively.