Environmental Pollution 158 (2010) 223–234

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Sensitivity of agricultural runoff loads to rising levels of CO_2 and climate change in the San Joaquin Valley watershed of California

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Agricultural runoff is significantly affected by changes in precipitation, temperature, and atmospheric CO_2 concentration.

A R T I C L E I N F O

Article history:
Received 8 October 2008
Received in revised form
1 April 2009
Accepted 17 July 2009

Keywords:
Watershed modeling
Climate change
Agricultural pollution
Pesticides
California
SWAT

A B S T R A C T

The Soil and Water Assessment Tool (SWAT) was used to assess the impact of climate change on sediment, nitrate, phosphorus and pesticide (diazinon and chlorpyrifos) runoff in the San Joaquin watershed in California. This study used modeling techniques that include variations of CO_2, temperature, and precipitation to quantify these responses. Precipitation had a greater impact on agricultural runoff compared to changes in either CO_2 concentration or temperature. Increase of precipitation by ±10% and ±20% generally changed agricultural runoff proportionally. Solely increasing CO_2 concentration resulted in an increase in nitrate, phosphorus, and chlorpyrifos yield by 4.2, 7.8, and 6.4%, respectively, and a decrease in sediment and diazinon yield by 6.3 and 5.3%, respectively, in comparison to the present-day reference scenario. Only increasing temperature reduced yields of all agricultural runoff components. The results suggest that agricultural runoff in the San Joaquin watershed is sensitive to precipitation, temperature, and CO_2 concentration changes.

1. Introduction

The general consensus of atmospheric scientists is that the earth's temperature is increasing (IPCC, 2007), and as global temperatures increase the hydrologic cycle is becoming more dynamic. Predicted global mean temperature in 2100 will be between 1.1 and 6.4 °C higher than in 1990 with additional changes in rainfall intensity and quantity (IPCC, 2007). Analyses made by leading climate research centers indicate that the global mean surface temperature in 2006 was 0.42–0.54 °C above the 1961–1990 annual average (WMO, 2006). For the next two decades, the Intergovernmental Panel on Climate Change (IPCC, 2007) states that a warming of about 0.2 °C per decade is projected for a range of IPCC emission scenarios. Even if the concentrations of all greenhouse gases and aerosols were to be kept constant at year 2000 levels, a further warming of about 0.1 °C per decade would be expected. Global Climate Models (GCMs) indicate that it is very likely (greater than 90% probability) that heat extremes, heat waves, and heavy precipitation events will become more frequent (IPCC, 2007), and an overall increase in global precipitation will occur. For the state of California, GCM predictions of precipitation vary widely, with both increases and decreases being projected (e.g., Smith and Mendelsohn, 2007). This leads to a lack of confidence in the stability of regional and seasonal patterns of precipitation, implying the possibility of changes to the hydrologic cycle. Even slight changes in precipitation and hydrological conditions can potentially affect crop production and agricultural runoff in highly agricultural watersheds.

Increasing agricultural contamination of surface waters has generated substantial concern since the 1940s (Larson et al., 1995). This concern is especially pertinent in the highly agricultural San Joaquin River watershed in California. This watershed, along with the Sacramento River Watershed, drains into the Sacramento–San Joaquin Delta (Delta), which in recent years has seen an appreciable decline in aquatic species, attributed in part to an increase in water toxicity levels (Werner et al., 1999). Principal contaminant sources to the Delta include agricultural and urban runoff, discharges from abandoned mines, and point source discharges. Detections of agricultural runoff have been reported in the Delta and upstream source waters (e.g., Dileanis et al., 2002; Guo et al., 2004; Weston et al., 2004; Amweg et al., 2006; CVRWQCB, 2006). Pesticide detection frequency in surface waters has become a major concern, as California contains approximately 2–3% of the nation's agricultural land, yet accounts for 25% of the nation's pesticide use (Kegley et al., 2000). In agricultural regions such as the San Joaquin River watershed the primary mode of agricultural non-point source pollution transport is sediment and water runoff (Leonard, 1990). Changes in climate, which impact agricultural pollutant transport through water and sediment runoff,

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doi:10.1016/j.envpol.2009.07.016

will thus directly affect future levels of water quality in the Sacramento–San Joaquin watersheds and the Delta.

Much research has been done on agricultural runoff (e.g., Griffin and Bromley, 1982). However, insufficient work has been done to examine the effects of imminent climatic changes on agricultural runoff (e.g., Panagoulia, 1991; Arnell, 1992; Murdoch et al., 2000). Mander et al. (2000) showed that the contaminant concentrations in agricultural runoff (total-N, total-P, SO_4, and organic material) have decreased in recent years (1987–1997). Chaplot (2007) examined the effects of increasing CO_2 concentrations, rainfall intensity, and surface air temperature on nitrate runoff, finding that atmospheric CO_2 concentration was the main controlling factor for nitrate yield. Studying the impacts of climate change in the southeastern United States, Cruise and LimayeNassim Al-Abed (1999) showed that several watersheds exhibited high nitrogen levels in runoff. Tong et al. (2007) discovered that the probability of eutrophication is likely to increase in future climatic conditions. Hanratty and Stefan (1998) examined the effect of climate change on quality and quantity of runoff from a Minnesota agricultural watershed and found a decrease in mean annual streamflow, nutrient, and sediment yield. To date, there has only been one qualitative study on the impacts of climate change on pesticide fate and transport in the context of environmental protection (Bloomfield et al., 2006). No quantitative estimates of this effect are currently available.

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) watershed model was chosen for this study. SWAT includes algorithms for predicting how CO_2 concentration, precipitation, temperature, and humidity affect plant growth, evapotranspiration (ET), snow, and runoff generation. SWAT, therefore, is an effective tool for investigating climate change effects. Several case studies of climate change impacts on water resources have applied SWAT (e.g., Hanratty and Stefan, 1998; Rosenberg et al., 1999; Cruise and LimayeNassim Al-Abed, 1999; Stonefelt et al., 2000; Fontaine et al., 2001; Eckhardt and Ulbrich, 2003; Chaplot, 2007; Schuol et al., 2008). SWAT has also been used to model portions of the San Joaquin watershed (Flay and Narasimhan, 2000; Luo et al., 2008). This study, however, marks the first time SWAT has been used to model agricultural runoff in the San Joaquin watershed under a changing climate.

Despite many climate change studies, up-to-date quantitative information on the effects of the changes of precipitation and temperature on soil and water resources is still scarce. The objective of this study is to quantify the effects that climate change will have on the fate of agricultural pollutants and transport of such substances within a highly agricultural region in California's Central Valley. For the study, a SWAT model of the San Joaquin watershed in California (Luo et al., 2008) was used to assess the impacts of climate change on the fate and transport of agricultural pollutants. Different scenarios of precipitation (0%, 10%, and 20% increase or decrease in precipitation amount and average daily rainfall intensity), surface air temperature (a 1.1 °C or 6.4 °C increase from current climate), and an increase of CO_2 concentration from the present-day concentration of 330 ppm to an extreme IPCC prediction of 970 ppm were tested using SWAT. Long-term estimates of sediment, fertilizer (nitrate and total phosphorus), and pesticide (diazinon and chlorpyrifos) yields were compared to a benchmark scenario with a CO_2 concentration of 330 ppm and a present-day reference climate.

2. Materials and methods

2.1. Site description

The San Joaquin River watershed was selected for this study (Fig. 1). The watershed area is 14,976 km^2 and includes the counties of San Joaquin, Calaveras, Stanislaus, Tuolumne, Merced, Mariposa, Madera, and Fresno. Latitude and longitude

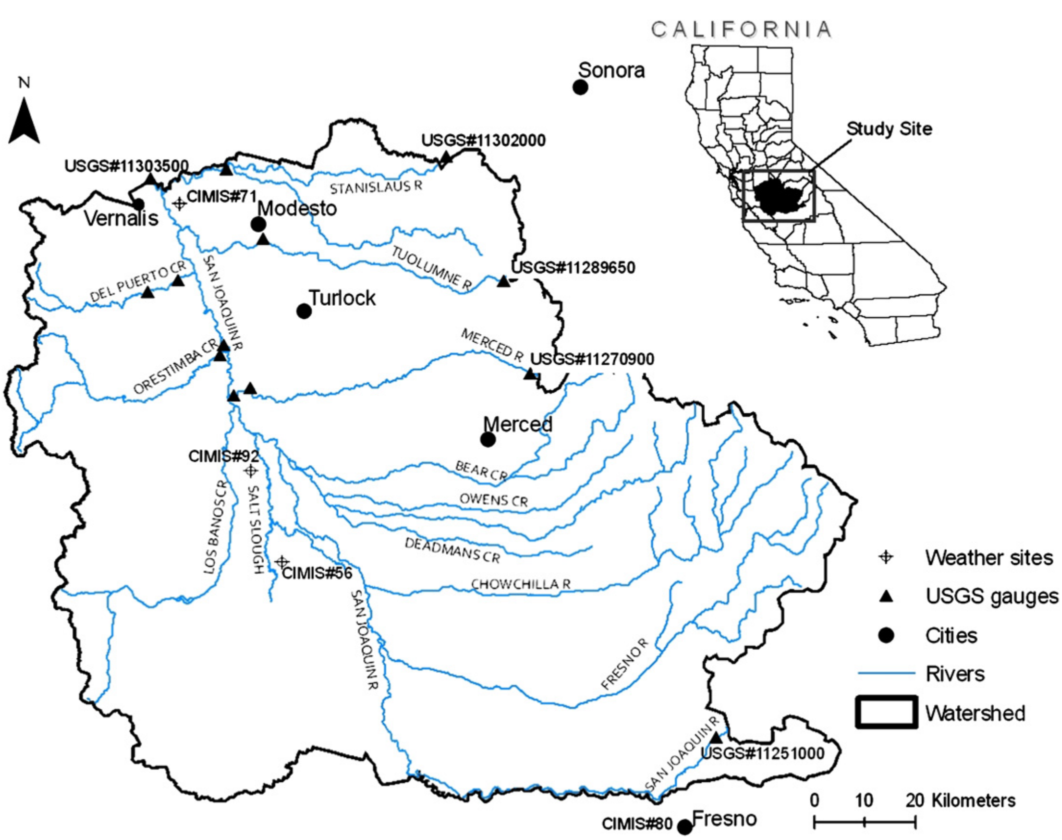

Fig. 1. Study area of the northern San Joaquin Valley watershed.

range from 36°30′N to 38°50′N and from 119°45′W to 121°30′W, respectively. The United States Geological Survey (USGS) river monitoring site at Vernalis (USGS #11303500) was chosen as the outlet for the entire watershed. The discharge inlets of the upper San Joaquin, upper Merced, upper Tuolumne, and upper Stanislaus Rivers were defined at the USGS monitoring sites #11251000, #11270900, #11289650, and #1130200, respectively. The watershed has a typical Mediterranean climate with hot, dry summers and cool, wet winters. Average rainfall is approximately 200–300 mm with most of the rain falling during the period between November and April and negligible precipitation during the summer. Average daily temperature is approximately 15 °C (NOAA, 2008). The watershed is highly agricultural and includes the majority of agricultural areas in the counties of Stanislaus, Merced, and Madera, and part of San Joaquin and Fresno Counties. A large portion (95%) of the crops in the study area are fruit and nuts (38%), field crops (36%), truck, nursery, and bean crops (17%), and grain crops (4%) (DWR, 2007).

2.2. Description of the hydrological model

The watershed hydrology and water quality model SWAT was chosen from several available models (Arnold et al., 1998). SWAT is a continuous-time, quasi-physically based, distributed water quality model designed to simulate water, sediment, and agricultural chemical transport on a river-basin scale. SWAT was designed to be applied for ungauged river basins, and therefore can be used to analyze many watersheds using readily available data. SWAT integrates processes of several other models, allowing for the simulation of climate, hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport, and management practices. The SWAT2005/ArcSWAT version, which is coupled with ESRI's ArcGIS version 9.2, was selected for this study. Full details of SWAT can be found in Neitsch et al. (2005).

In SWAT, the watershed of interest is divided into subbasins, which are then divided into Hydrologic Response Units (HRUs). The HRUs are intended to preserve the heterogeneity of the important physical properties of the watershed and are delineated by overlaying topography, soil data and land use maps in a geographical information system (GIS). This subdivision gives the model the strength to better represent the properties of land uses and/or soils of each subbasin that may have a significant effect on hydrology. HRU water balance is represented by four storage components: snow, soil profile, shallow aquifer, and deep aquifer. Flow, sediment, and agricultural runoff are summed across all HRUs in a subwatershed, and the resulting flows and pollutant loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet.

Predictions of surface runoff from daily rainfall are estimated based on a similar procedure as the CREAMS runoff model (Knisel, 1980). The runoff volume is estimated using the modified SCS curve number method (SCS, 1984), which is a value that incorporates soil, land use, and management information. It is adjusted at each time step based on the amount of soil water present. Sediment discharge at the watershed outlet is calculated using soil erosion and sediment routing equations such as the Modified Universal Soil Loss Equation (MUSLE). Nutrient outputs, including nitrogen and phosphorus, are estimated by tracking their movements and transformations. The nutrient loads are principally estimated by means of nutrient assimilation by plants and daily nutrient runoff losses. These losses are quantified based on the nutrient concentration in the top soil layer, the MUSLE sediment yield equation, and an enrichment ratio that depends on soil and land use type (Arnold et al., 1998). The transport of pesticides in the environment is governed by runoff, soil weathering, and erosion processes. The pesticide component in SWAT simulates pesticide transport in dissolved and particulate phases with surface and subsurface hydrologic processes. The fate and transport of pesticides are determined by its solubility, degradation half-life, and partitioning coefficients (Neitsch et al., 2002).

The plant growth component of SWAT utilizes routines for plant development based on plant-specific input parameters summarized in the SWAT plant growth database. SWAT generates plant growth output characteristics such as biomass and leaf area index (LAI). The heat unit theory is used to regulate the plant growth cycle (Boswell, 1926; Magoon and Culpepper, 1932). In this theory, predictions of plant development can be estimated based on the amount of heat absorbed by the plant. Potential plant growth is calculated each day of a simulation and is based on growth under ideal growing conditions. These ideal conditions consist of adequate water and nutrient supply and a favorable climate. For this study, irrigation in an HRU was automatically simulated by SWAT based on the water deficit in the soil. Depending on the subwatershed, irrigation water was extracted from the nearby reach or a source outside the watershed. Also, fertilization in an HRU was automatically applied based on a plant growth threshold.

Unlike other hydrologic models, SWAT includes equations and factors that allow the user to model future climate conditions. For example, the calculation of ET takes into account variations of radiation-use efficiency and plant growth and transpiration due to changes in atmospheric CO_2 concentrations, which is essential for any study of CO_2-induced climate change. SWAT allows adjustment terms such as CO_2 concentration to vary so that the user is able to simulate greenhouse gas emission scenarios. The impact of the increase of plant productivity and the decrease of plant water requirements due to increasing CO_2 levels are considered following the work of Neitsch et al. (2005). For ET estimation, the Penman-Monteith method must be used for climate change scenarios that account for changing atmospheric CO_2 levels. This method has been modified in SWAT to account for CO_2 impacts on ET levels.

2.3. Data collection and analysis

SWAT input parameter values such as topography, landuse/landcover, soil, and climate data were compiled using databases from various state and government agencies. Elevation, landuse, and stream network data were obtained from the Environmental Protection Agency's (EPA) Better Assessment Science Integrating Point and Non-point Sources (BASINS) database (USEPA, 2007). Data included 1:250,000 scale quadrangles of landuse/landcover data, 1:24,000 scale Digital Elevation Models (DEMs), and 1:100,000 scale stream network data from the National Hydrography Dataset (NHD) (USGS, 2001). Cropland and irrigation areas were defined based on the landuse survey database completed by the California Department of Water Resources (DWR) during 1996–2004, and cropland information was assumed to have remained unchanged since the date of survey completion. Soil properties in the watershed were extracted from the 1:24,000 Soil Survey Geographic (SSURGO) database, which is based on soil surveys (USDA, 2007). Daily weather data, including precipitation and minimum and maximum temperatures, were retrieved from the California Irrigation Management Information System (CIMIS) (Fig. 1).

Pesticide application data was collected from the Pesticide Use Reporting (PUR) system (CDPR, 2007). Since 1990, California has required all commercial pest control operators to report all pesticide applications. These reports include information about the pesticide applied, amount, area treated, timing of applications, and the crop involved with a spatial resolution of one square mile. Pesticide use amounts are recorded on a daily interval for each township/range/section in California and are tabulated by the Department of Pesticide Regulation (DPR). For this study, use amounts of chlorpyrifos and diazinon were retrieved from the database as weekly averages for each township/range/section, and distributed into the agricultural HRUs in each subbasin.

Based on available water quality monitoring data, the fate and transport of two organophosphate pesticides, diazinon and chlorpyrifos, were analyzed. Both pesticides are highly used nationwide and listed on the US Clean Water Act Section 303(d) list of products that may cause water body impairment. According to the U.S. Environmental Protection Agency, diazinon and chlorpyrifos are highly toxic to birds, fish, and aquatic insects. Depending on the formulation, diazinon and chlorpyrifos also have a low to high toxicity to humans. Diazinon and chlorpyrifos are highly soluble and have a low persistence in soil with a half-life of 2–6 weeks depending on climate. Chlorpyrifos has a higher soil adsorption coefficient (6070 μg/g) than diazinon (1000 μg/g) which causes it to adhere to soil particles much more strongly than diazinon.

Many aquatic toxicity surveys have been conducted in the San Joaquin River Watershed. Surface water samples collected from 1988 to 1990 were found to be toxic to the water flea, *Ceriodaphnia dubia* (Foe and Connor, 1991). The cause of this toxicity was not determined but was attributed to pesticides in general. During the winter of 1991–1992, the resultant toxicity was attributed to the presence of chlorpyrifos and diazinon (Foe and Sheipline, 1993; Foe, 1995). Many other toxicity studies have found similar results (e.g., Ross et al., 1996; Domagalaski, 1995). Therefore, toxicity guidelines were established by the Central Valley Regional Water Quality Control Board. The most commonly used guidelines in California for short-term exposure (1-h average) in terms of concentrations are 0.08 μg/L for diazinon and 0.02 μg/L for chlorpyrifos (Siepmann and Finlayson, 2000). The guidelines for long-term exposure (4-day average) are 0.05 μg/L for diazinon and 0.014 μg/L for chlorpyrifos.

The chemical and physical properties of chlorpyrifos and diazinon were primarily obtained from the built-in pesticide database in SWAT. The volatilization transfer coefficient was computed according to the Whitman two-film theory (Ruiz and Gerald, 2001; Neitsch et al., 2005). The pesticide partition coefficient was estimated from the octanol-water partition coefficient (Chapra, 1997). Other transport coefficients were set at the default values suggested by the SWAT model (Neitsch et al., 2005).

2.4. Model calibration and validation

The San Joaquin SWAT model was previously calibrated and validated for streamflow, sediment, nutrient and pesticide loads measured at USGS gauges located on the San Joaquin River and its major tributaries within the study area. Full details of model calibration and validation can be found in Luo et al. (2008). The calibrated model for the previous study provided satisfactory simulation results in estimating temporal trend and spatial variation of streamflow and agricultural pollutant loads. Therefore, the model was deemed suitable for evaluating agricultural management practices and the associated environmental effects on water quality.

The observed monitoring data was split up for calibration (1992–1997) and validation (1998–2005) purposes. The USGS monitoring gauge at the watershed outlet, USGS #11303500 (Vernalis), which includes sediment, nitrate, phosphorus, and pesticide monitoring data, was selected as the primary location for model calibration and validation. This site receives stream flow from all upstream portions of the study area and is assumed to characterize water quality in general. Other gauges with shorter periods of record were also used during the model evaluation procedures.

Table 1
Climate change sensitivity scenarios used for SWAT simulations. "–" represents no change in the CO_2, temperature or precipitation component.

Scenario	CO_2 (970 ppm)	Temperature (°C)	Precipitation (%)
1	✓	–	–
2	✓	6.4	–
3	✓	–	+20
4	–	0	+10
5	–	0	+20
6	–	0	−10
7	–	0	−20
8	–	1.1	0
9	–	1.1	+10
10	–	1.1	+20
11	–	1.1	−10
12	–	1.1	−20
13	–	6.4	0
14	–	6.4	+10
15	–	6.4	+20
16	–	6.4	−10
17	–	6.4	−20

The effects of climate change on agricultural runoff were evaluated based on SWAT model simulations under various climate change scenarios (Table 1). In our previous study, the SWAT model was calibrated for stream flow, sediment, nutrients, and pesticides under the field conditions of the San Joaquin River watershed (Luo et al., 2008). Actual inputs of weather, inlet discharge, and fertilizer and pesticide application during 1992 through 2005 were applied in the model, resulting in satisfactory simulation results. At the Vernalis USGS site, the Nash-Sutcliffe coefficient of efficiency (NS; Nash and Sutcliffe, 1970), which evaluates the goodness-of-fit of simulated and measured data computed from monthly fluxes was 0.95 for stream flow, 0.74 for sediments, 0.85 for nitrate, 0.92 for phosphorus, 0.84 for diazinon, and 0.77 for chlorpyrifos for the validation period (Luo et al., 2008). Nash-Sutcliffe values can range from negative infinity to 1, where 1 is a perfect match of model data to observed data. Full details on the calibration method for streamflow, nutrient, and pesticide loads can be found in Luo et al. (2008).

Due to the use of long-term average data in the simulation, the results were not suitable for conducting month-by-month comparisons to the measured data. For further model evaluation, the annual average in-stream flow and loads predicted by the reference simulation were compared to the measured data during 1992–2005 at the watershed outlet. Throughout the study duration sediment loads were measured daily, 234 and 246 samples of nitrate and phosphate were taken, respectively, and 321 samples of chlorpyrifos and diazinon were taken (CEPA, 2007; USGS, 2007). As expected, the reference simulation generated comparable results for stream flow, sediment, and pesticide loads. The annual average of in-stream loads predicted by the reference simulation during 2000–2100 was 304×10^6 kg for NO_3 and 37.04×10^6 kg for PO_4, indicating a <5% difference compared to the measured data (307.1×10^6 and 35.4×10^6 kg for NO_3 and PO_4, respectively). The model also predicted monthly agricultural pollutant concentrations fairly well (Table 2).

2.5. Scenarios of CO_2 concentration, precipitation, and temperature changes

Assuming accurate estimates of runoff, sediment, nitrate, phosphate, and pesticides, SWAT was used to evaluate the impact of changes in climate and atmospheric CO_2 concentration. The different scenarios selected for this study are based on the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2001a,b) and The Physical Science Basis (IPCC, 2007). The reports describe divergent projections for future CO_2 concentration and climate and their underlying uncertainty. Depending on the greenhouse gases emission scenario, atmospheric CO_2 concentration is expected to increase from the present concentration of 330 ppm to between 540 and 970 ppm by the end of the 21st century (IPCC, 2001a,b). The upper CO_2 limit of 970 ppm was chosen for this study. This projection corresponds to the A1FI emission scenario describing a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. SWAT does not allow a continuous increase of CO_2 concentration throughout the simulation and therefore 100-year simulations with and without climate perturbations were run with a 970 ppm CO_2 concentration. This methodology may result in under- or over-estimation of agricultural constituent loads, but will give insight on how increased atmospheric CO_2 concentrations will affect agricultural runoff.

GCMs predict that an increase of atmospheric CO_2 concentration is likely to increase the average global surface temperature by the end of the 21st century between 1.1 °C (B1 emission scenario) and 6.4 °C (A1FI emission scenario) (IPCC, 2007). The B1 emission scenario corresponds to a future of low economic growth and fossil fuel independency. GCMs vary in their prediction for projected rainfall for California over the 21st century (CMIP3 multi-model dataset, 2008) and therefore arbitrary scenarios (0%, +/−10%, +/−20%) were selected to bracket the range of possible outcomes. Table 1 shows all climate change sensitivity scenarios used in SWAT.

Daily rainfall amount, minimum (T_{min}) and maximum (T_{max}) daily temperatures for the reference and climate sensitivity scenarios were estimated over a 100-year simulated period using the LARS-WG stochastic weather generator (available from http://www.rothamsted.bbsrc.ac.uk/mas-models/larswg/download.php). LARS-WG is based on the series weather generator described by Racsko et al. (1991). It utilizes semi-empirical distributions for the lengths of wet and dry day series and daily precipitation. Daily minimum and maximum temperatures are considered as stochastic processes with daily means and daily standard deviations depending on whether a day is wet or dry. LARS-WG is widely used for climate change studies (e.g., Semenov and Barrow, 1997). Input data for LARS-WG consisted of CIMIS data collected at four weather stations within the study area.

The remaining climate data, solar radiation and relative humidity required for SWAT simulation was generated by the WXGEN weather generator (Sharpley and Williams, 1990) which is a component of SWAT. WXGEN uses rainfall and temperature data of each scenario based on the assumption that the occurrence of rain on a given day has a major impact on the relative humidity and solar radiation on that day.

A number of assumptions were made to address the transient nature of model variables over time. To apply the calibrated SWAT model for climate change sensitivity scenarios, long-term monthly averages of inlet discharges and pesticide applications were calculated from the corresponding actual values during 1990–2005. Since this study was designed to investigate the sensitivity of climate elements on the yields of sediment, nutrients, and pesticides in an agriculture-dominated watershed, the temporal variation of upstream hydrology, such as dam releases, and local pest pressure due to climate change were neglected. To meet the nutrient demand for crop growth under climate change scenarios, the automatic fertilization function in the SWAT model was activated in this study. The function parameters, e.g., nutrient stress threshold, application efficiency, surface application fraction, were calibrated for the reference simulation, and applied to the other scenario. Landuse was assumed to remain unchanged during the 100-year simulation. Climate scenarios, not including the increased CO_2 scenario, were scaled to the 100-year simulation. For example, starting in 2000 each year's T_{min} and T_{max} were increased at equal intervals until the final maximum (1.1 or 6.4 °C) was reached at the end of year 2100. For precipitation, the reference precipitation was increased over the 100-year period, for example, by 0.18% per annum for the 20% scenario.

2.6. Statistical analyses

T-tests for dependent samples were performed to compare all agricultural pollutant annual yields estimated from the climate sensitivity scenarios to the reference scenario. The target level of significance was $\alpha = 0.05$.

3. Results

3.1. Climate characteristics of the reference scenario

The average simulated yearly rainfall for all climate stations during the simulated 100-year reference period was 295.4 mm, approximately 17 mm greater than the observed regional CIMIS average. The 100-year minimum and maximum simulated yearly

Table 2
Mean, median and standard deviation statistics for observed and predicted average monthly agricultural pollutant concentrations.

		Sediment (g/m^3)	Nitrate (g/m^3)	Phosphate (mg/m^3)	Diazinon (μg/m^3)	Chlorpyrifos (μg/m^3)
Observed	Mean	71.5	1.45	109	20.1	9.12
	Median	59.0	1.52	91.6	6.9	5.35
	Std. dev.	48.3	0.61	64.2	58.5	10.2
Predicted	Mean	55.2	1.42	129	17.2	9.46
	Median	45.7	1.15	115	3.20	5.75
	Std. dev.	31.6	0.985	67.6	40.4	12.1

precipitation amounts were 127.5 and 541.8 mm, respectively. The largest amount of precipitation simulated for a single day was 100.2 mm. The average minimum and maximum daily temperature was 7.78 and 23.8 °C, respectively.

3.2. Impact of climate and atmospheric CO_2 concentration changes on agricultural pollutant yields

The climate change sensitivity scenarios are given in Table 1. Changes in water yield, sediment, nitrate, total phosphorus, diazinon, and chlorpyrifos yields due to increasing CO_2 concentration and climate variability are presented in Figs. 2–7. Results for all scenarios can be found in Tables 3 and 4. All results are shown as percent changes compared to the present-day reference scenario.

As expected, water yield changed significantly with a change in precipitation. Elevated temperature affected the magnitude of this change. For example, with a 20% increase in precipitation, a 1.1 °C temperature increase resulted in a 20% increase in water yield while a 6.4 °C increase resulted in an 11.3% increase in water yield. Change in water yield with a 10% precipitation increase and a 6.4 °C temperature increase did not significantly deviate from the reference simulation ($\alpha = 0.05$).

Changes in atmospheric CO_2 concentration also had a significant effect on water yield. Water yield increased for all elevated CO_2 scenarios. Water yield increased by 23.8% relative to the reference scenario when only CO_2 was increased. When temperature was increased to 6.4 °C coupled with an elevated CO_2 concentration, water yield increased by 24.4%. An increase in CO_2 and precipitation increased water yield by 51.8%.

Agricultural pollutant yields were significantly affected by precipitation changes (Table 3). Generally, increasing precipitation while holding temperature and CO_2 constant caused an increase in all agricultural runoff components, and vice versa. With a 20% precipitation increase and constant temperature, nitrate yield exhibited the largest increase compared to the reference scenario by approximately 40.2%, while in the same scenario chlorpyrifos yield decreased by 31.9% compared to the reference scenario. When precipitation was increased by 20% with temperature held constant, nitrate runoff showed the largest increase compared to the reference scenario by approximately 40.2% while chlorpyrifos yield had the largest decrease at 31.9%.

Increasing temperature by 1.1 and 6.4 °C caused a decrease in all agricultural runoff components (Table 3). As expected, an increase in temperature by 6.4 °C had a much larger effect on runoff than a 1.1 °C temperature increase. Nitrate yield had the largest percentage decrease (18.3%) when compared to the reference scenario. For diazinon and chlorpyrifos, an increase of 1.1 °C caused a decrease of less than 1% when compared to the reference scenario. With a 1.1 °C increase, chlorpyrifos showed no significant difference in the mean from the present-day reference scenario ($\alpha = 0.05$). For a 6.4 °C temperature increase, yields of all agricultural runoff components decreased by at least 4% with nitrate and

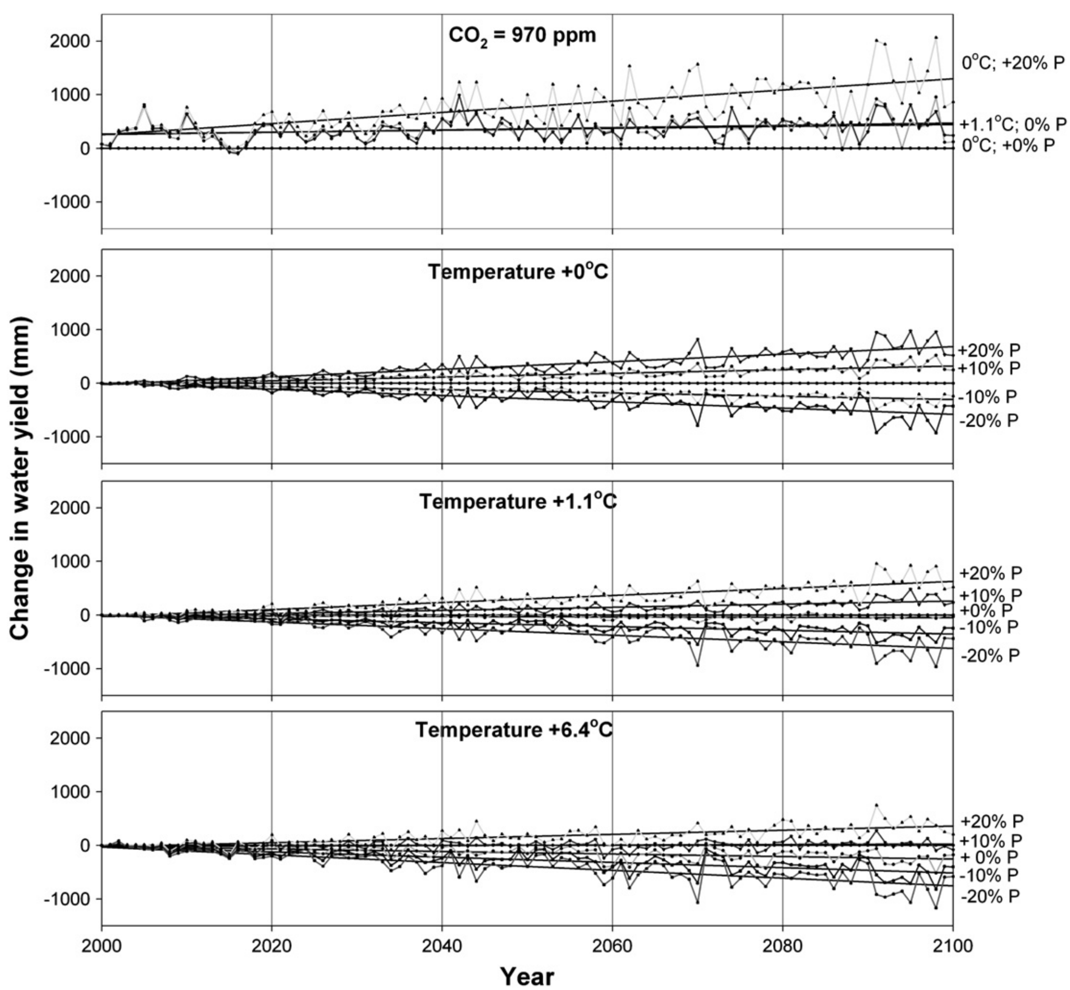

Fig. 2. Change in water yield compared to the reference scenario for the 100-year SWAT simulation.

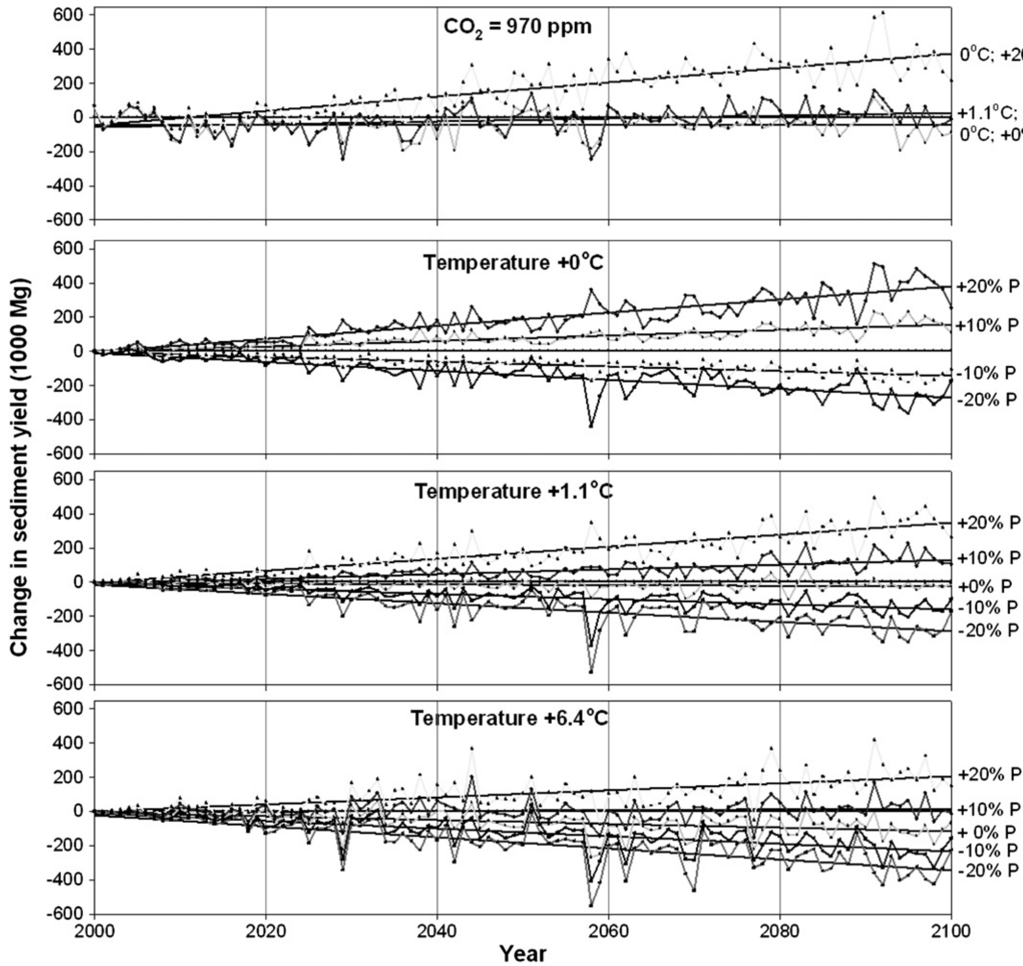

Fig. 3. Change in sediment yield compared to the reference scenario for the 100-year SWAT simulation.

total phosphorus having the largest decreases by 18.3 and 15.3%, respectively, compared to the reference scenario.

When increasing temperature and increasing/decreasing precipitation, the agricultural pollutant yield was generally related to the precipitation change (Table 3). Under both temperature scenarios (1.1 and 6.4 °C), an increase (decrease) in precipitation generally resulted in an increase (decrease) in agricultural runoff. This relation shows that precipitation is the main driving factor of agricultural runoff. Nitrate yield had the largest overall increase (30.8%) with a 1.1 °C temperature and 20% precipitation increase. It also had the largest overall decrease (36.4%) with 6.4 °C temperature and 20% precipitation decrease. It is important to note, however, that with a temperature increase of 6.4 °C and a precipitation increase by 10%, nitrate and total phosphorus decreased by 8.7 and 6.2%, respectively. Also, increasing temperature and precipitation by 6.4 °C and 20%, respectively, did not cause significant change in sediment yield when compared to the present-day reference scenario ($\alpha = 0.05$).

An increase of CO_2 from the present-day concentration of 330 ppm to the extreme IPCC CO_2 scenario of 970 ppm resulted in varying outcomes (Table 4). Increasing CO_2 caused a decrease in sediment and diazinon yields, while nitrate, total phosphorus, and chlorpyrifos yields increased. This trend continued when CO_2 was increased to 970 ppm and temperature was increased by 6.4 °C. It is important to note that increasing CO_2 concentration to 970 ppm and temperature by 6.4 °C did not result in significant change from the present-day reference scenario ($p < 0.05$). When there was an increase of CO_2 to 970 ppm and precipitation by 20%, all agricultural runoff components increased by at least 16% with total phosphorus having the largest increase of 40.3%.

4. Discussion

4.1. Simulation results

All agricultural runoff components were significantly affected by precipitation changes and to a lesser degree by changes in temperature and CO_2 concentration. The relationship between precipitation changes and increased agricultural pollutant runoff is easily understood, as rainfall impacts and runoff are the driving mechanisms for pollutant transport within watersheds.

Nitrate and total phosphorus losses depend on the hydrologic balance, the quantities present in the soil either from natural sources or fertilizer inputs, and the degree to which they are removed by plants at the site (Ferrier et al., 1995). Changes in temperature affected nitrogen and total phosphorus much more strongly than the other agricultural runoff components. The decreased nitrate and total phosphorus yield with higher temperature was related to decreased amounts of both surface runoff and sediment, and by a lesser degree by increased mineralization (Table 3). Decreasing surface water runoff appeared to be the most significant factor in decreasing fertilizer runoff in a study by Mander et al. (2000). The simulation results indicated that sediment yield had greater effects on phosphorus yields compared to

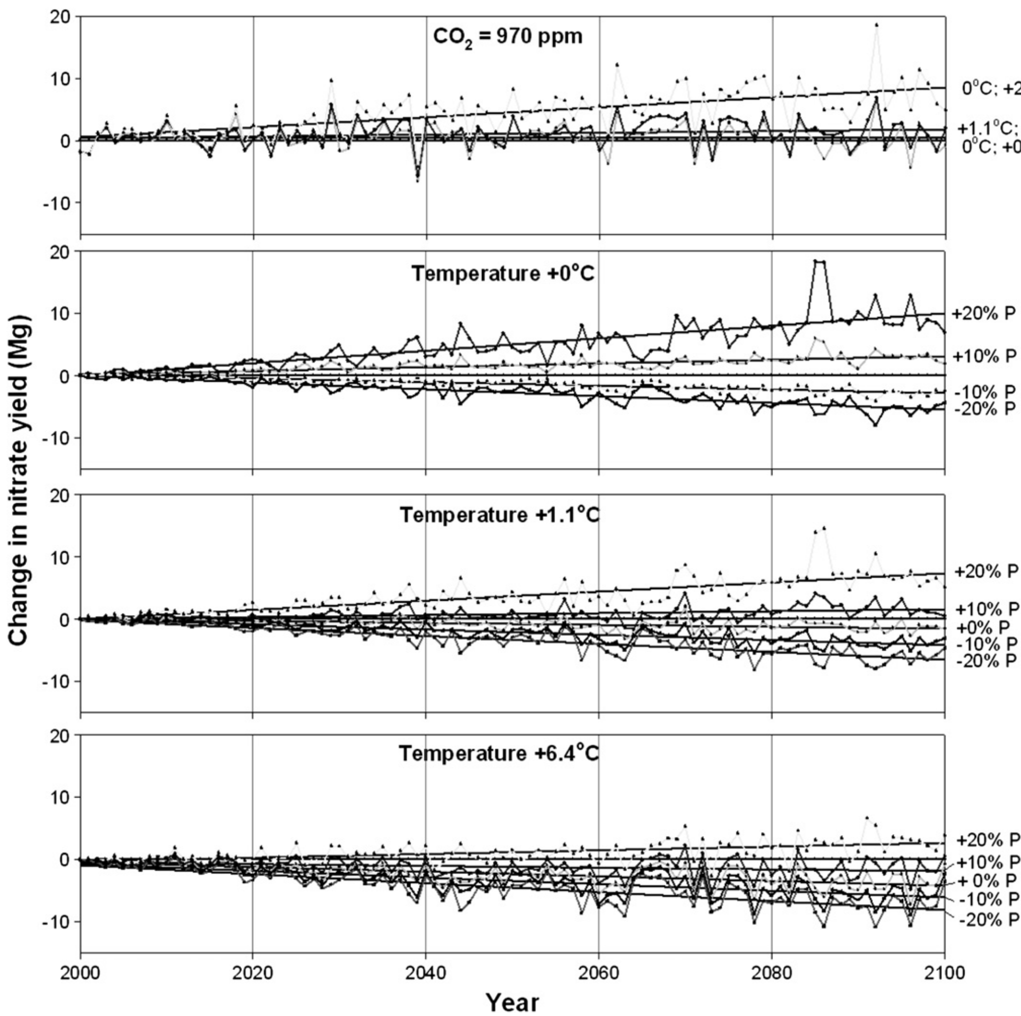

Fig. 4. Change in nitrate yield compared to the reference scenario for the 100-year SWAT simulation.

yields of pesticides. The majority of phosphorus yields were associated with sediment, e.g., 89.2% of total phosphorus yield was predicted in the particle-bound phase (under reference simulation), while only 13.7% and 18.5% of pesticide yields were transported with sediment, for diazinon and chlorpyrifos, respectively. Consequently, total phosphorus yields decreased at larger rates, relative to pesticides, with higher temperature compared to the reference simulation. The nitrate results are from the NSURQ (nitrate surface runoff) data within the SWAT output. Nitrate yield results are associated with dissolved-phase nitrate removal only, and thus 100% of nitrate yield is water-associated.

Annual fertilizer use was not significantly decreased under higher temperatures. Seasonally, fertilizer automatically applied to the watershed was increased during early spring due to more rapid development of plant with higher temperatures. This was consistent with our previous results of monthly variation in leaf area index (LAI) with elevated temperature (Ficklin et al., 2009). Less fertilizer was applied during the summer months due to greater temperature stress on crops.

With increased atmospheric CO_2 concentrations from 330 to 970 ppm, watershed-wide annual sediment yield decreased by 6.3% during the simulation period. Sediment yield was simulated by the SWAT model based on MUSLE. Therefore, increased CO_2 concentration affected the sediment yield through two mechanisms: [1] increasing surface runoff and peak runoff rate, and [2] increasing soil surface residue and thus decreasing the MUSLE cover and management factor (MUSLE_C). Experimental evidence indicates that plant stomata generally open less widely under increased CO_2 concentration, which reduces transpiration and thus increases surface runoff and peak runoff rate (e.g., Morison and Gifford, 1983). Previous research focused solely on evaluating the effects of a doubled atmospheric CO_2 concentration in SWAT report a wide range of increases in average annual streamflow (Stonefelt et al., 2000; Fontaine et al., 2001; Chen, 2001; Chaplot, 2007). With high CO_2 concentration, the simulation results indicated that the MUSLE_C was the dominant parameter for estimating sediment yield, and the overall effect of increased CO_2 concentration was a decrease in sediment yield.

It is noteworthy, however, that in-stream sediment load predicted at the watershed outlet was increased by 52.3% with increased CO_2 concentration. Based on our previous study (Ficklin et al., 2009), stream flow rate increased by 32.3% at the watershed outlet with increased CO_2 concentration compared to the reference simulation. Therefore, sediment transport capacity in the channels (indicated by "the maximum concentration of sediment that can be transported by the water" in the SWAT simulation) was increased with the peak flow rate. This finding was consistent with the modeling results by Chaplot (2007) who predicted a sediment yield

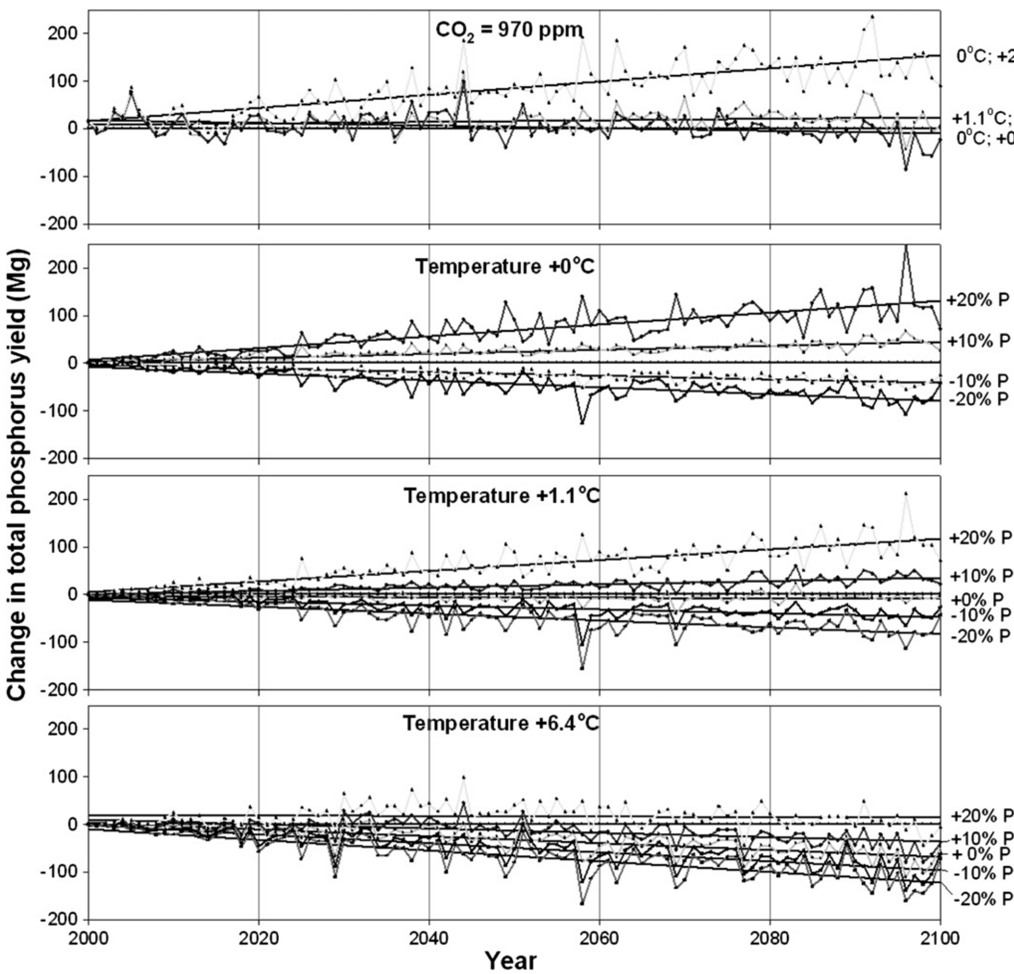

Fig. 5. Change in total phosphorus yield compared to the reference scenario for the 100-year SWAT simulation.

increase with an increased CO_2 concentration in an agricultural watershed in Iowa.

Nitrate and total phosphorus yields increased with an increase in atmospheric CO_2 concentration. This is to be expected as greater nitrogen and phosphorus inputs to the system through plant assimilation and soil fixation are considered in SWAT. Also, the increase in water yield as discussed in our previous study (Ficklin et al., 2009) would allow for more nitrate and total phosphorus transport. These results are consistent with Chaplot (2007) and Bouraoui et al. (2002), who found that an increase in CO_2 concentration increased nitrate loads.

Changing levels of CO_2 had varying effects on the total (dissolved and particle-bound) pesticide yield in the watershed. By increasing the CO_2 concentration, the annual average yield of diazinon decreased by 5.3% relative to the result of our reference simulation, whereas average annual chlorpyrifos yield increased by 6.4% (Table 3). The different behaviors of the two pesticides could be attributed to landscape and stream transport processes under conditions of increased CO_2 concentration. Changes in pesticide yield due to the physical processes of surface runoff and sediment yield resulted in an increase of both dissolved and particle-bound pesticide yields. For example, yields of dissolved diazinon and chlorpyrifos were increased by 9.9 and 13.1%, respectively, by an increased surface runoff rate. Particle-bound yields of both pesticides were decreased with less sediment yield predicted (Table 3). Due to its large soil adsorption coefficient, (SK_{oc}: 6070 for chlorpyrifos and 1000 for diazinon according to the SWAT built-in pesticide property database), chlorpyrifos has moderate-to-low mobility in the soils. In the calibrated SWAT model in this study, the lower soil mobility of chlorpyrifos was demonstrated by a large value of the pesticide percolation coefficient (PERCOP) of 0.5, compared to 0.2 for diazinon (Luo et al., 2008). This suggests that a larger proportion of chlorpyrifos transport occurs when pesticide is bound to sediment rather than when it is in its dissolved phase. Therefore, where sediment yield is decreased, chlorpyrifos yield will also decrease in comparison to diazinon, explaining the contrasting results for the two pesticides.

For the in-stream transport processes with increased CO_2 concentration, pesticide loss from water to bed sediment was increased due to the increased suspended sediment loadings. In addition, the pesticide re-suspension rate was decreased with more water available in streams, since the re-suspension in the SWAT simulation was inversely proportional to water depth. Finally, total pesticide loss in the channel routing was increased with increased CO_2 concentration. For diazinon, the slightly increased dissolved yield could not compensate for the losses in particle-bound yield and in channel routing, resulting in lower in-stream load at the watershed compared to the reference simulation. For chlorpyrifos with a relatively large increment of dissolved yield, however, the in-stream load at the watershed outlet was increased with an increase in CO_2 concentration.

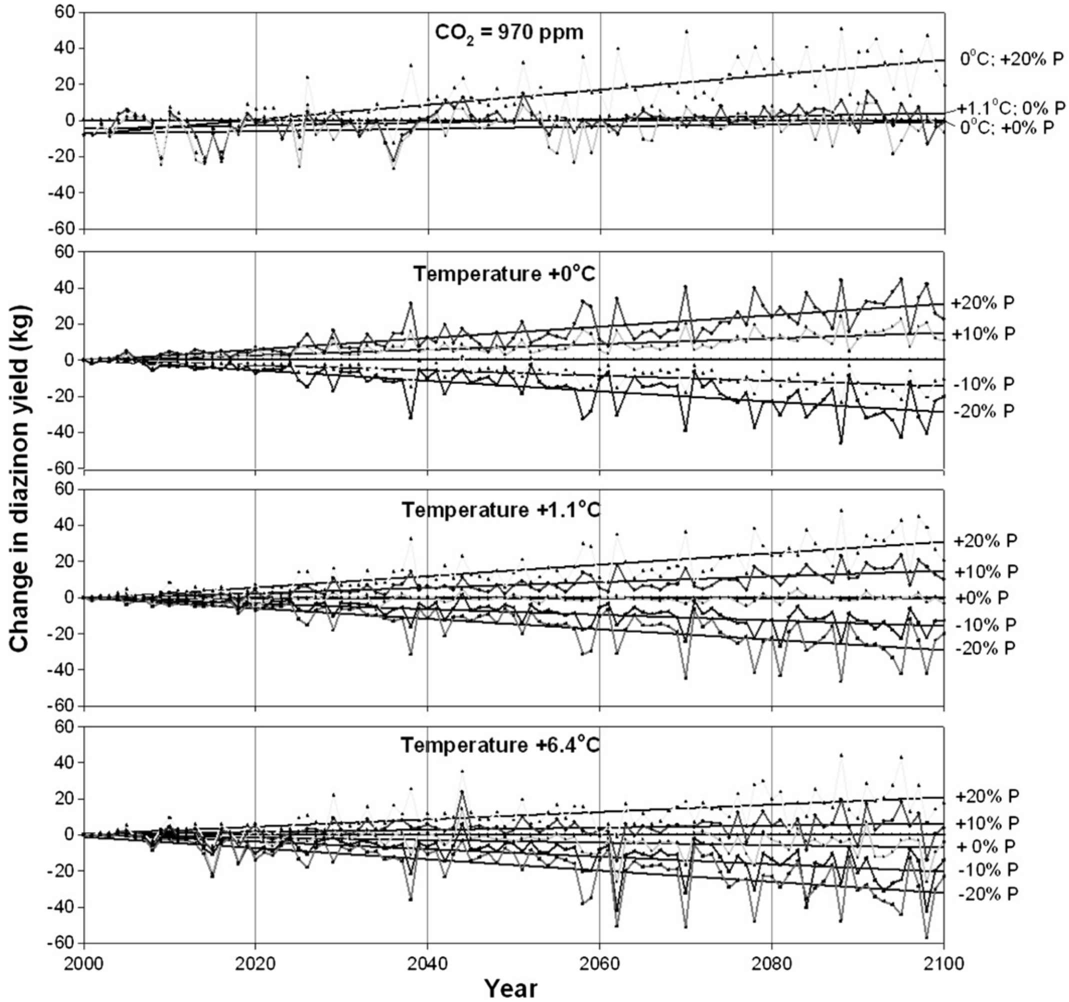

Fig. 6. Change in diazinon yield compared to the reference scenario for the 100-year SWAT simulation.

4.2. Implications

Water resource managers wishing to anticipate and integrate the effect of climate change into their management plans must have an understanding of the local factors that control water quality and volume, and the sensitivity of these factors to climate change. Our results suggest that changes in climate (precipitation and temperature) and CO_2 concentration may have a significant effect on the water quality of surface waters in the San Joaquin watershed. This is directly dependent on the agricultural chemical inputs from the surrounding landscape, and the biogeochemical processes that transform these inputs. For this study, fertilizer inputs (nitrate and total phosphorus) were based on plant requirements for optimum growth, while pesticide inputs were based on present-day average usage. It is important to understand that these inputs may change in the future, which may alleviate or increase water quality concerns in a changing climate.

Water resources that appear to be the most vulnerable to changes in water quality as a result of climate change are those already near their climatic thresholds for chemical change. These are water resources where competition between urban, agricultural, and natural uses is high or increasing, and where climate change will act in concert with other existing human-driven stresses (Murdoch et al., 2000). Currently, the San Joaquin River has 12 violations of water quality objectives (Lee and Jones-Lee, 2006). These violations include organophosphate pesticides (diazinon and chlorpyrifos), selenium, salinity, and oxygen demand. In addition, research is currently being done on potential future water quality objective violations, which include nutrients and sediments. Changes in water quality during storms and periods of elevated temperature may cause conditions that may exceed present-day Total Maximum Daily Loads (TMDLs), an estimate of the maximum amount of a pollutant that a given water body can receive and still meet water quality standards (USEPA, 2008). This problem may be further exacerbated by consumptive water use, such as for irrigation and domestic water supplies, as such use will reduce in-stream flows and thus increase the concentration of contaminants introduced by non-point agriculture sources.

5. Conclusions

This study illustrates changes in agricultural runoff related to potential climate change based on SWAT model simulations in an agriculturally dominated area of the San Joaquin River watershed. The results indicate that the hydrological system in the study area is very sensitive to climatic variations on an annual basis and/or over a long time period. As expected, precipitation had a greater impact on agricultural runoff compared to changes in either CO_2 or

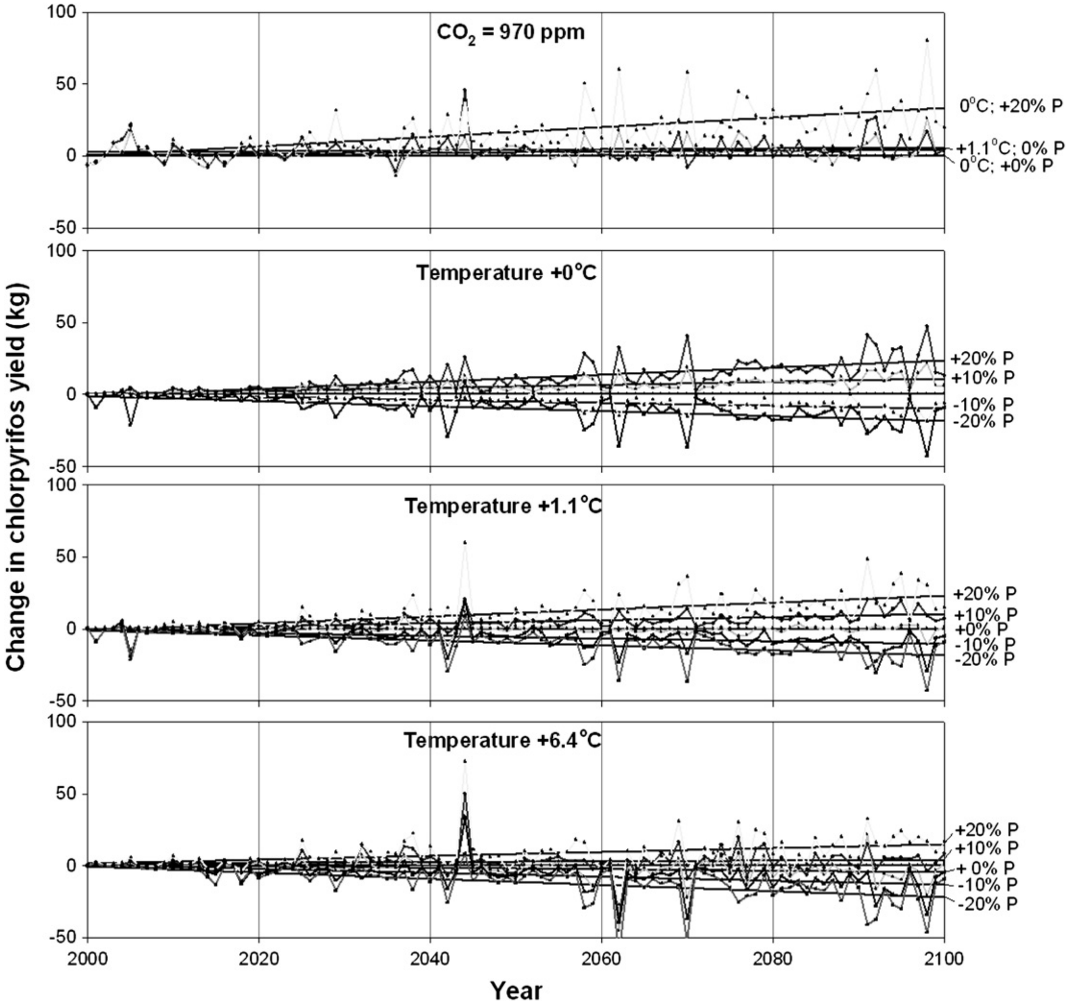

Fig. 7. Change in chlorpyrifos yield compared to the reference scenario for the 100-year SWAT simulation.

temperature. Changes in precipitation by ±10% and ±20% generally changed agricultural runoff proportionally. Increasing CO_2 and leaving temperature and precipitation constant resulted in an increase in nitrate, total phosphorus, and chlorpyrifos yield and a decrease in sediment and diazinon yields. A temperature increase with no precipitation or CO_2 change caused a decrease for all agricultural runoff components.

The results of this study suggest that an increase in CO_2 and changes in temperature and precipitation have significant effects on agricultural runoff in the San Joaquin River watershed. These effects might be complicated by the agricultural activities and irrigation water diversion in the study area. The results generated from this study are valuable as a tool for guiding water resource managers

Table 3
Predicted changes relative to present day conditions for average annual yields of sediment, nitrate, total phosphorus, diazinon, and chlorpyrifos for the lower San Joaquin River watershed at Vernalis, California, for temperature and precipitation climate change sensitivity simulations.

	Reference	Temperature change (°C)	Precipitation changes (%)				
			0	10	20	−10	−20
Water yield (%)	1493.62 mm	0	x	10.1	22.3	−9.9	−19.2
Sediment (%)	6.09×10^8 kg	0	x	11.5	28	−10.7	−20.8
Nitrate (%)	12,550 kg	0	x	13.2	40.2	−11.9	−21.9
Phosphorus (%)	209,174 kg	0	x	11.6	33.1	−10.7	−20.9
Diazinon (%)	75.96 kg	0	x	9.9	20.4	−9.3	−18.6
Chlorpyrifos (%)	41.57 kg	0	x	13.1	27.5	−11.6	−31.9
Water yield (%)	1493.62 mm	1.1	−2.0	7.86	20.0	−11.9	−21.1
Sediment (%)	6.09×10^8 kg	1.1	−2.1	9.3	25.6	−12.5	−22.3
Nitrate (%)	12,550 kg	1.1	−6.1	6.4	30.8	−16.9	−27.2
Phosphorus (%)	209,174 kg	1.1	−2.5	8.7	29.5	−12.9	−22.7
Diazinon (%)	75.96 kg	1.1	−0.8	9.3	19.9	−10.4	−19.4
Chlorpyrifos (%)	41.57 kg	1.1	−0.4*	12.1	26.4	−13.2	−23.3
Water yield (%)	1493.62 mm	6.4	−9.2	0.14*	11.3	−17.9	−26.4
Sediment (%)	6.09×10^8 kg	6.4	−9.3	0.9*	15.3	−18.4	−27.4
Nitrate (%)	12,550 kg	6.4	−18.3	−8.7	9.3	−27	−36.7
Phosphorus (%)	209,174 kg	6.4	−15.3	−6.2	8.3	−23.3	−31.4
Diazinon (%)	75.96 kg	6.4	−4.6	4.6	14.2	−13.3	−21.9
Chlorpyrifos (%)	41.57 kg	6.4	−4.9	6.7	19.4	−15.3	−26.5

*Differences between the reference and climate change scenarios are not significant at $\alpha = 0.05$.

Table 4
Predicted changes relative to present day conditions for average annual yields of sediment, nitrate, total phosphorus, diazinon, and chlorpyrifos for the lower San Joaquin River watershed at Vernalis, California, for CO_2 climate change sensitivity simulations.

	Reference	CO_2 only	CO_2 + 6.4 °C	CO_2 + 20% P
Water yield (%)	1493.62 mm	23.8	24.4	51.8
Sediment (%)	6.09×10^8 kg	−6.3	−2.2	24.5
Nitrate (%)	12,550 kg	4.2	8.7	37.2
Phosphorus (%)	209,174 kg	7.8	1.5*	40.3
Diazinon (%)	75.96 kg	−5.3	−0.4*	16.8
Chlorpyrifos (%)	41.57 kg	6.4	9.8	39.6

*Differences between the reference and climate change scenarios are not significant at $\alpha = 0.05$.

and those required to comply with legislation for water quality guidelines to make appropriate decisions on land management and/or measures for environmental protection.

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