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Fens as whole-ecosystem gauges of groundwater recharge under climate change

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SUMMARY

Currently, little is known about the impact of climate change on groundwater recharge in the Sierra Nevada and southern Cascade Range of California or other mountainous regions of the world. The purpose of this study was to determine whether small alpine peatlands called fens can be used as whole-ecosystem gauges of groundwater recharge through time. Fens are sustained by groundwater discharge and are highly sensitive to changes in groundwater flow due to hydrologic disturbance including climate change. Seven fens in the Sierra Nevada and southern Cascade Range were studied over a 50–80 year period using historic aerial photography. In each aerial photograph, fen areas were identified as open lawn and partially treed areas that exhibited (1) dark brownish-green coloring or various shades of gray and black in black and white imagery and (2) mottling of colors and clustering of vegetation, which signified a distinct moss canopy with overlying clumped sedge vegetation. In addition to the aerial photography study, a climate analysis for the study sites was carried out using both measured data (U.S. Department of Agriculture Natural Resources Conservation Service SNOwpack TELemetry system) and modeled data (a downscaled version of the Parameter-elevation Regressions on Independent Slopes Model) for the period from 1951 to 2010. Over the study period, the five fens in the Sierra Nevada were found to be decreasing between 10% and 16% in delineated area. The climate analysis revealed significant increases through time in annual mean minimum temperature (T_{min}) between 1951–1980 and 1981–2010. In addition, April 1 snow water equivalent and snowpack longevity also decreased between 1951–1980 and 1981–2010. For the fens in the Cascade Range, there were no discernible changes in delineated area. At these sites, increases in T_{min} occurred only within the past 20–25 years and decreases in snowpack longevity were more subtle. A conceptual model is presented, which illustrates that basic differences in hydrogeology of the Sierra Nevada vs. the Cascade Range may control the threshold at which changes in delineated fen areas are discernible. Overall, the results from this study show that fens in the Sierra Nevada have strong potential as whole-ecosystem gauges for determining long-term changes in groundwater recharge under climate change. Due to either more moderate climate change and/or hydrogeological differences, fens in the southern Cascade Range currently do not appear to have the same utility. A greater sample size of fens in the Sierra Nevada is needed to confirm the general applicability of this method. In addition, future work needs to focus on integrating fen monitoring with geochemical and/or isotopic process-level studies in order to quantify changes in groundwater recharge identified using this new approach.

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1. Introduction

Over the past 50–100 years, various measures of climate have changed in the western United States. During the twentieth century, winter and spring air temperatures increased throughout western North America (Folland et al., 2001). In California, this has translated into an increase of about 1 °C in annual average (T_{avg}), minimum (T_{min}), and maximum (T_{max}) air temperatures throughout the century (Anderson et al., 2008). T_{min} has increased faster than T_{max}, leading to a decreased range in diurnal temperatures (LaDochy et al., 2007; Anderson et al., 2008) and declines in total winter snowfall relative to total winter precipitation (Knowles et al., 2006). Since the 1950s there has been an earlier onset of snowmelt and reduced snow water equivalent of the snowpack in much of the western United States (Barnett et al., 2008; Abatzoglou, 2011; Pederson et al., 2011), particularly in mountain ranges such as the northern Sierra Nevada and southern Cascade Range of California, where relatively mild winter temperatures remain close to freezing (Cayan et al., 2001; Mote et al., 2005; Mote, 2006; Stewart, 2009). Such trends in earlier snowmelt, reduced snowpack, and declines in snowfall relative to rain in California are projected to continue into the future (Dettinger et al., 2004; Cayan et al., 2008).

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Changes in the snowpack have attracted great attention because, in the arid West, the snowpack is a crucial component of water storage for human populations (Mote et al., 2005; Kapnick and Hall, 2010). However, the snowpack is also the main source of groundwater recharge in the mountainous west (Winograd et al., 1998; Barnett et al., 2008; Earman and Dettinger, 2008, 2011; Hanak et al., 2011), because the accumulated "critical mass" of precipitation in the snowpack is required for flow to travel through the thick unsaturated zone without being entirely evaporated or transpired in the process (Earman et al., 2006). Higher minimum temperatures could reduce the residence time or longevity of the snowpack, leading to faster runoff and less groundwater recharge. This would have serious environmental implications because groundwater recharge, which maintains groundwater springs, soil moisture, stream baseflows and cool water temperatures, is important not only for human populations, but also for sensitive species and their habitats (Earman and Dettinger, 2008; Hanak et al., 2011). Research has shown that decreases in groundwater recharge can negatively impact trout and other fish populations (Hanak et al., 2011), reduce wetland habitat (Winter, 2000), cause forest die-off (Breshears et al., 2005), and increase incidence of wildfires (Westerling and Bryant, 2008).

Currently, little is known about the impact of climate change on groundwater recharge in the Sierra Nevada of California or other mountainous regions of the world (Goderniaux et al., 2009; Earman and Dettinger, 2011; Viviroli et al., 2011). There is concern that in mountain ranges with dwindling snowpacks, such as the Sierra Nevada, groundwater recharge is declining (Earman and Dettinger, 2008; Manning et al., 2012). At this time, there is no monitoring network for groundwater recharge in the mountainous western United States (Earman and Dettinger, 2008), in large part because of the difficulties and uncertainties related to monitoring recharge through time. Such a lack of comprehensive data on groundwater recharge rates, groundwater flow paths, and groundwater–surface-water interactions precludes modeling efforts to determine current groundwater resources and project future changes.

Several approaches exist for measuring groundwater recharge including water level monitoring, isotopic and geochemical analyses, geophysical methods, stream-based methods, and biological inventories. However, most of these approaches require long-term data sets, which may or may not exist for particular areas (Earman and Dettinger, 2008). In addition, approaches such as stream-based methods integrate groundwater recharge measurements over an entire watershed and, therefore, cannot pinpoint a specific area or elevation of interest. New approaches are needed that can span the timeframe of recent climate change, provide local-scale as well as regional coverage, and complement any groundwater monitoring program by providing independently derived data.

Fens are peat-accumulating wetlands that receive some drainage from the surrounding upland mineral soil and contain herbaceous vegetation similar to that found in marshes (Mitsch and Gosselink, 2007). Fens are broadly distributed in temperate and boreal regions of the world (Gore, 1983). The steady hydrologic regime of fens, which consists of groundwater flow combined with surface flows such as snowmelt and/or streamflow, allows them to remain saturated for most if not all of the growing season. Their groundwater component gives rise to unusual chemistry, which results in a highly diverse and distinct flora dominated by mosses, grasses, and sedges, but which also includes shrubs and trees (Bedford and Godwin, 2003; Cooper and Wolf, 2006). In the Sierra Nevada of California, fens can occur alone or as part of meadow complexes that contain other wetland types including dry meadows, which remain wet for only several weeks following snowmelt, and wet meadows, which stay wet for approximately 1–2 months, but ultimately dry out during the dry summer months (Benedict, 1983; Bartolome et al., 1990; Cooper and Wolf, 2006).

Fens are ideal ecosystems for studying changes in groundwater recharge, because they are groundwater discharge sites that rely upon corresponding recharge sites for their sustenance (Siegel, 1983). Fens are commonly found where a sudden break of slope causes groundwater to discharge to the land surface (Winter, 1998). Because fens are so closely tied to groundwater flow systems, changes in the supply of groundwater can be recognized by changes in fen characteristics. When the amount of groundwater flow to a fen is reduced, the elevation of the water table drops. This typically leads to desiccation, compaction, and increased microbial oxidation of the organic soil, ultimately resulting in subsidence of the fen surface (Schothorst, 1977; Price and Schlotzhauer, 1999; Whittington and Price, 2006). In cases where groundwater flow is reduced over an extended period of time, major changes in flora can occur, resulting in the loss of the moss carpet and eventual conversion of fen into wet or dry meadow or even pine forest (Bartolome et al., 1990).

Peat soils in the Sierra Nevada are generally shallow in depth ($\sim$1 m or less) with even shallower peat columns expected along the periphery (Ehrman, 1976; Cooper and Wolf, 2006). The shallow nature of these soils leaves them vulnerable to desiccation from climate warming. Drying of the peat column can occur for only so long before fen margins begin to recede. Therefore, changes in fen area may be a way to assess changes in groundwater recharge. Fens subject to desiccation and eventual shrinkage would indicate major reductions in groundwater recharge in a watershed over time. Such an approach could provide information on changes in groundwater recharge for a large geographic region, while also providing crucial information on the effect of climate change at a local scale.

The objective of this study was to determine whether fens have the potential to be effective whole-ecosystem gauges of groundwater recharge under climate change. We chose to study fens in the Sierra Nevada and southern Cascade Range of California because (1) climate change has been well documented for this region over the past 50–100 years, and (2) this region is particularly sensitive to climate change due to its relatively mild winter temperatures and, thus, vulnerable snowpacks. We report an analysis of seven fens distributed throughout the Sierra Nevada and southern Cascade Range based on 50–80 years of aerial photography. We compared the delineated areas of each fen throughout its "photo history", being careful to acknowledge seasonal vs. multi-year trends. In order to interpret the changes found, we carried out a climate analysis over the study period with measured climate data from the U.S. Department of Agriculture Natural Resources Conservation Service SNOpack TELemtry system (SNOTEL) as well as modeled data using a distributed parameter water-balance model called the Basin Characterization Model (Flint et al., 2004; Flint and Flint, 2007), which is a downscaled version of the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al., 2004). Results were used to construct a conceptual model of the relationships among hydrogeology, climate, and changes in fen areas over the past 50–80 years.

2. Materials and methodology

2.1. Study site selection

Thirty-eight fens that were identified and described by Cooper and Wolf (2006) or included in the Vital Signs Monitoring Networks of Yosemite and Sequoia/Kings Canyon National Parks (National Park Service, 2009) were evaluated for inclusion in this study. Fens were ranked according to several criteria. Firstly, any fen that may have been affected by roads, dams, or water diversions was eliminated from consideration because such anthropogenic impacts can cause major hydrologic disturbance to fens, potentially resulting in changes to fen area. Next, fens in close proximity to large rivers and lakes not directly arising from groundwater springs were also eliminated from the study. These sites were excluded because surface flows could overshadow small changes in groundwater recharge rates. Next fens were excluded if they were in close proximity to clear-cut forests, tree farms, or recently grazed areas as these disturbances might also affect the flora or hydrology of fens, potentially leading to changes in fen area. The remaining fens were located on 2005 National Agriculture Imagery Program (NAIP) aerial photographs and evaluated with respect to visibility from different angles and adequate size for identification on different scales of aerial photos.

The evaluation process identified seven suitable fen sites located within the southern Cascade Range and Sierra Nevada of California, USA (Fig. 1). The fens are distributed at elevations ranging from 1560 to 2640 m. The study region has a Mediterranean climate defined by warm, dry summers and cool, wet winters (Western Regional Climate Center, 2012). Basic site descriptions are provided in Table 1. Hypothesized groundwater flow paths, based on topography and stream flow patterns, and hydrogeomorphic position are shown in Fig. 2.

2.2. GIS database

Historical aerial photographs were retrieved from four different sources. Most of the photographs prior to 1950 were retrieved from the National Archives and Records Administration (at 900 dpi through Double Delta Industries, Inc., Woodbine, MD), but a few photographs were obtained from the collections at the University of California (UC) Berkeley and UC Davis Map Libraries (scanned at 600 dpi). Photos from after 1955 were identified and scanned by staff at the Aerial Photography Field Office (APFO) in Salt Lake City, Utah (1000 dpi). Most of the photography was at a scale of 1:15,840, with some photos at the 1:12,000 scale. Not all photos retrieved could be used due to issues with resolution. A

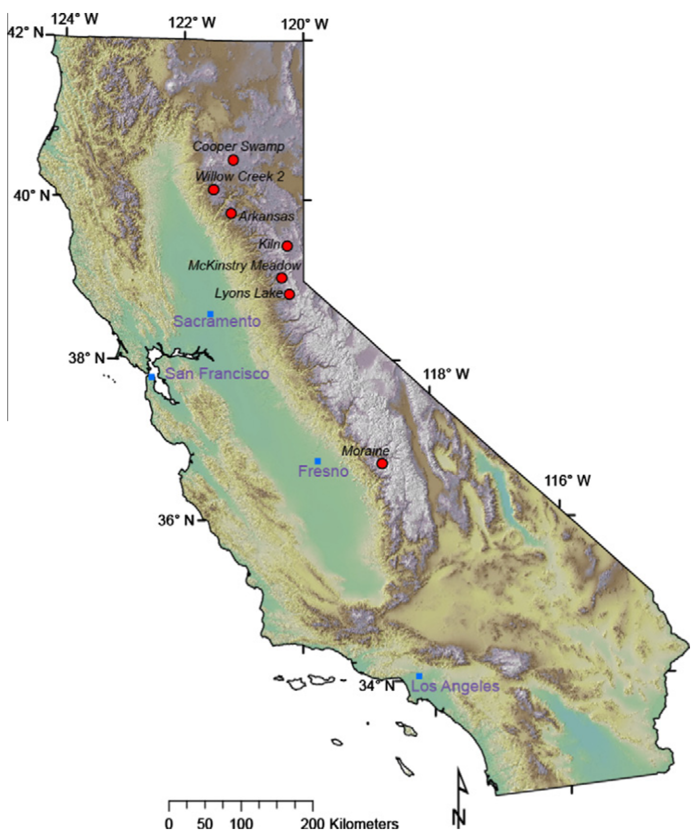

Fig. 1. Location map of fen study sites in California, USA.

Table 1
Fen study sites, locations, and characteristics.

Fen name	California county	Elevation (m)	~Peat depth[a] (cm)	Fen type[a]	Aspect	Primary rock type[a]	Latitude	Longitude
Arkansas	Plumas	1775	40	Sloping	260	Metamorphic	39°49′34.61″N	−121°10′35.22″W
Cooper Swamp	Lassen	1948	170	Basin	NA	Volcanic	40°29′33.14″N	−121°9′12.02″W
Kiln Fen	Nevada	1991	115	Sloping	20	Sedimentary	39°25′51.78″N	−120°15′31.18″W
Lyons Lake	El Dorado	2239	30	Basin	360	Plutonic	38°49′47.32″N	−120°12′56.74″W
McKinstry Meadow	Placer	2089	60	Basin	220	Plutonic	39°2′2.69″N	−120°20′26.38″W
Moraine Fen	Tulare	2640	40	Sloping	226	Plutonic	36°42′53.93N	−118°44′59.10W
Willow Creek 2	Tehama	1560	120	Lava bed discontinuity	164	Volcanic	40°7′25.36″N	−121°28′14.59″W

[a] Based on Cooper and Wolf (2006).

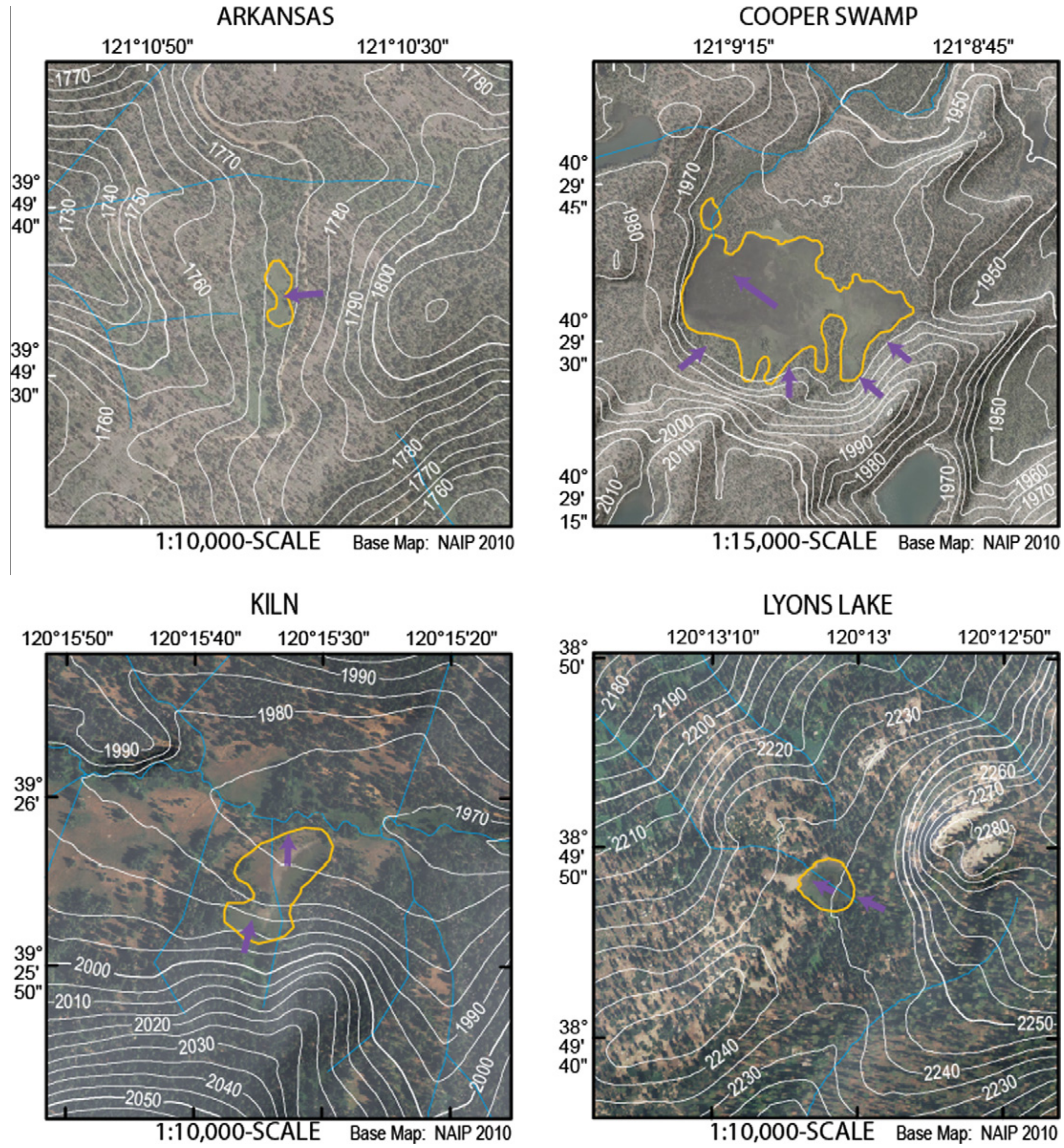

Fig. 2. Hydrogeomorphic setting of each fen within its watershed. Purple arrows indicate hypothesized groundwater flow paths, blue lines indicate streams (from the High Resolution Hydrography Dataset of the U.S. Geological Survey), and orange outlines signify fen boundaries.

great effort was made to collect aerial photographs taken during early to mid-summer (June–August), to keep seasonal variation to a minimum. Overall, a total of 57 aerial photographs were used in the analysis with a minimum of 6 and maximum of 10 photos per fen (Table 2).

Images were projected to UTM Zone 10, NAD 83 using ArcGIS 10.0 (Environmental Systems Research Institute, 2010). All photos were geo-registered using an affine transformation of 4–5 multi-temporal control points. For approximately 95% of the photos, RMSE was less than 1 m and for the remainder it was less than 2 m. Due to the fact that most of the fens studied were <0.4 ha in size and each fen was situated differently on each photo of the time series, control points were chosen to be localized around each site and to be consistent through the time series. Each photo was then projected into Albers Equal Area Conic projection.

2.3. Fen delineations

The boundaries of each fen were delineated and subsequently digitized based on vegetation communities discernible from the aerial photographs. Each fen was first viewed at a range of scales beginning at 1:4000 and then increasing to the largest scale (between 1:500 and 1:1000) that was not pixilated to the point of obscuring the image. Fens were identified as open and partially treed areas with (1) dark brownish-green coloring (or various shades of gray and black in black and white imagery) and (2) mottling of colors and clustering of vegetation, which signify a distinct moss canopy with overlying clumped sedge vegetation. Although some fen areas may have been excluded due to these "rules" (e.g., transitional peripheral areas lacking moss vegetation), this procedure enabled a highly consistent approach to be applied to all aerial photographs in the study.

For each site, multiple comparisons were made between aerial images from different years to check that major features used to delimit fen boundaries were used consistently throughout the photo record. Black and white images, the only image type available for the 1940s through the 1950s and sometimes even 1960s, were interpreted in much the same way as colored images. At each site, we procured both color and black and white images for the same year or within a couple years of each other. We then

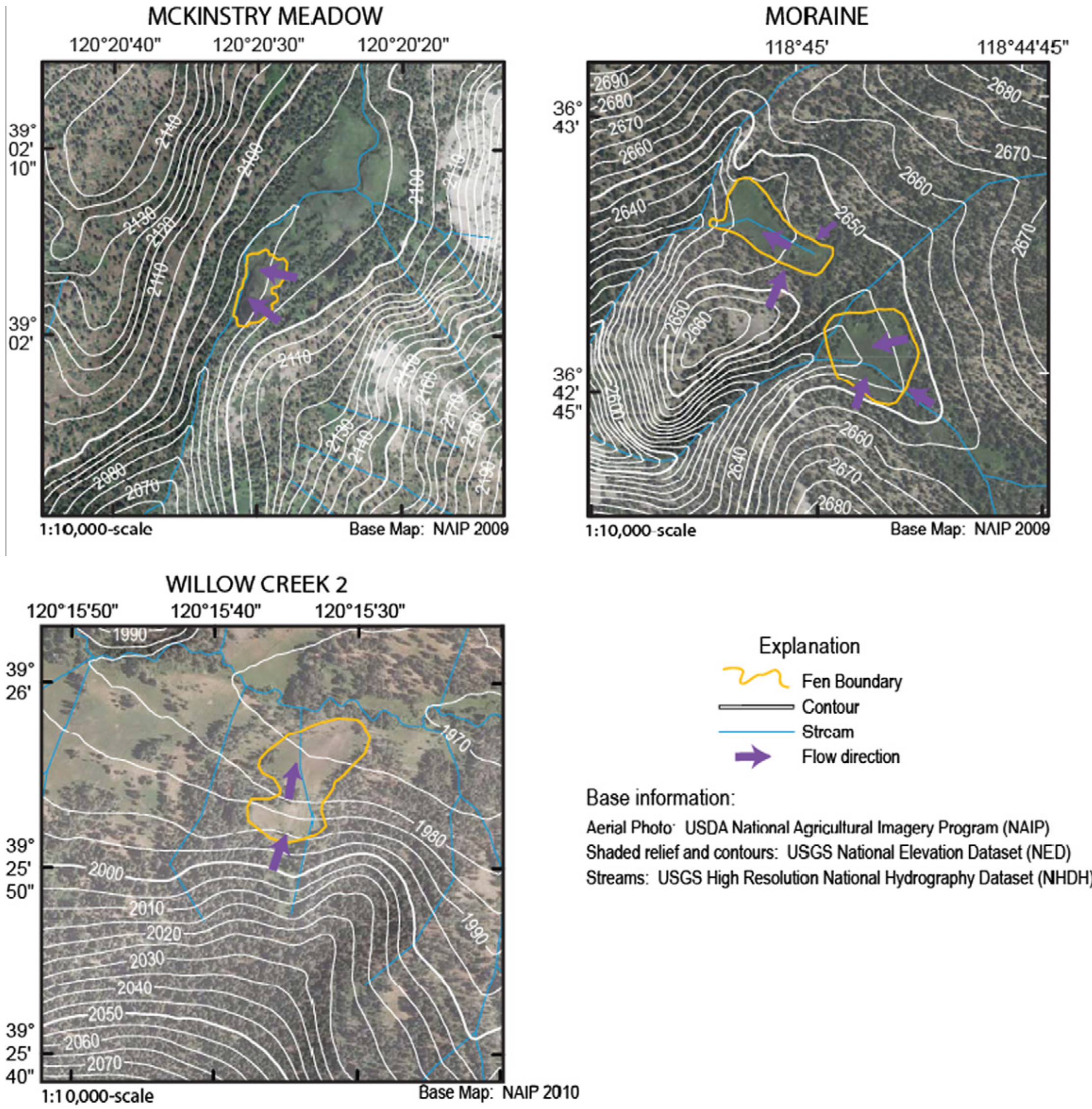

Fig. 2. (*continued*)

compared feature types between color and black and white images to make sure we were interpreting gray-scale differences on the black and white images consistently with those of color images.

Fen boundaries were most challenging to delineate during very wet and very dry years. During wet years differences in vegetation were more difficult to decipher due to standing water. In dry years, mosses turned pale or white and reflected very highly on the photos. Some photos had to be eliminated from the analysis because high amount of glare or shading by trees impacted the accuracy of the delineations. The overall objective was to delineate fen boundaries as accurately as possible while maintaining consistency between major features in each photograph despite challenges posed by shading due to trees and boulders, changes in vegetation through time, and variability in the wetness of the fen surface.

The "delineated area" for each site was determined from the digitized fen boundaries and stored inside an ArcGIS database structure. In this paper, the term "delineated area" is defined as the estimated area of a fen based on the rules described above. This term, in no way, assumes that the delineated fen area is equal in size to the peat body beneath the surface. It is well established that peat soils are the last vestige of a peatland to remain even after suitable hydrologic conditions and indicator vegetation have long since vanished (Drexler et al., 2009).

In order to ground-truth our delineations using aerial photographs, we visited both Kiln Fen in the Sierra Nevada and Cooper Swamp in the southern Cascade Range in late July 2012. We delineated all of Kiln and the northwest portion of Cooper Swamp with a hand-held global positioning system (GPS) unit (Magellan Triton 2000, approximate error: 1–3 m horizontal). Our delineations using aerial photographs were well within the error of the delineations with the hand-held unit. Greater accuracy in field delineation may have been achievable with a higher end unit such as a Real-Time Kinematic GPS instrument, however, exact delineation of each fen was not the objective of this study. The main purpose was to apply the above-mentioned set of rules to the delineations as consistently as possible so that any changes over time were discernible.

2.4. Regional climate data

A climate analysis of both measured and modeled data was carried out for each fen site in order to examine any potential causes for changes in delineated fen area through time. We looked at

Table 2
Aerial photograph records used for the analysis of each fen.

Photo year	Arkansas	Lyons Lake	Moraine	Willow Creek 2	McKinstry Meadow	Cooper Swamp	Kiln
1940			x		x		
1941						x	
1948				x			
1952		x		x			x
1954						x	
1956	x						
1962			x				x
1965					x		
1966	x	x					
1970			x				
1971		x			x		
1973						x	
1974				x			
1976		x	x		x		
1982			x				
1983					x		x
1984						x	
1986		x	x		x		
1988				x		x	
1991		x	x		x		
1992	x						x
1993						x	
1996			x				
1997	x						x
1998				x		x	
1999				x			
2000	x	x			x		x
2001			x				
2004				x		x	
2005 NAIP		x					
2009 NAIP			x		x		
2010 NAIP	x			x		x	x
Total photos used	6	8	10	8	9	9	7

linear trends and also at differences in two key recent periods, 1951–1980 and 1981–2010. The first period, 1951–1980, represents a commonly used, base period with little global temperature change, while the 1981–2010 period represents a time of rapid global warming (Hansen et al., 2010).

We examined two main climate networks for the proximity of climate stations to the fen sites. The first was the United States Historical Climatology Network (HCN), which is derived from a variety of sources including the National Climatic Data Center archives, state climatology archives, and published literature (United States Historical Climatology Network, 2012). This data set contains monthly temperature and precipitation data for the contiguous United States. It is of high quality for trend analysis because it corrects for station moves, instrument changes, urbanization effects, and time-of-observation differences. None of the HCN climate stations are located near the fens (between 23 and 49 km away) or at similar elevations.

The second network examined was the SNOwpack TELemetry or SNOTEL system (United States Department of Agriculture Natural Resources Conservation Service, 2012). The SNOTEL system has a network of more than 1200 manually-measured snow courses and over 750 automated SNOTEL stations in 13 Western States, including Alaska. Of these stations, 7 snow course sites are situated at similar elevations and within 10 km or less (mean = 4.5 km) from the fen sites. Of those stations, 6 had snow water equivalent data for the past 70 or more years. Willow Creek 2 was the only fen for which no long-term SNOTEL data were available. No other climate data were available for these sites spanning the period from 1951 to 2010.

We also used the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al., 2004) because it could provide a suite of estimated climate data for each fen location that were not available from the SNOTEL and HCN stations. The PRISM data rely on station data, including the HCN stations, to develop interpolated climate surfaces, and incorporates relatively large scale processes and features in its interpolation scheme, such as distance from the ocean, rain shadow effect, as well as adiabatic lapse rate. It is acknowledged that PRISM does not include analysis of station data to assess variability over time associated with new or terminated stations or changes in methods or locations. As a result, the use of PRISM data for spatial analysis of highly localized, long-term trends is not generally advisable. However, we decided it was more useful to use this modeled data rather than stations that were not co-located because the local topographic setting of each individual fen is likely to directly influence local air temperature via elevational gradients, topographic shading, and cold air drainage or pooling. These factors influence the snow accumulation and timing of melt and subsequent timing of recharge and seasonal groundwater availability.

The application of PRISM data to indicate changes in precipitation and air temperature over time is supported because PRISM can provide data at a local scale that is relevant to the study sites. Evidence for this can be found in an evaluation of cold air pooling. PRISM estimates of cold air pooling at locations throughout the Sierra Nevada (following Lundquist et al., 2008) were compared with air temperature measured at 282 corresponding SNOTEL locations. The analysis determined that for the period from 1896 to 2009 for December through March (the months with snow), the average minimum air temperature of sites identified as likely areas of cold air pooling was 1.6 °C cooler in the PRISM dataset than for the sites occupying locations unlikely to have cold air pooling. These results support the notion that the PRISM interpolation scheme reflects the temperature conditions at the local scale relevant to fens.

A distributed-parameter regional water-balance model called the Basin Characterization Model (BCM; Flint et al., 2004; Flint and Flint, 2007), which uses gridded climate datasets from PRISM available at 4-km that are downscaled to 270-m for model application, was used in this paper. The BCM requires inputs including digital representations of topography, soil properties, geology, and vegetation combined with monthly time-series of precipitation and air-temperature data to estimate potential evapotranspiration, snowpack, changes in soil moisture and hydrologic response in recharge and runoff. The BCM has been developed for California at a spatial resolution of 270-m, so all model inputs are downscaled to this resolution by applying a multiple regression method that evaluates spatial and elevational gradients by using inverse-distance squared weighting along northing, easting, and elevation dimensions (Nalder and Wein, 1998; Flint and Flint, 2012). Potential evapotranspiration is estimated using a method adapted from Flint and Childs (1987) wherein solar radiation is determined for the latitude and longitude of each grid cell based on the percent of sky viewed due to topographic shading. The computed solar radiation together with air temperature is converted to net radiation and soil heat flux (Shuttleworth, 1993). Potential evapotranspiration is then calculated according to the Priestley–Taylor equation (Priestley and Taylor, 1972). Snow accumulation and ablation (sublimation plus snowmelt) are estimated with an energy and mass balance model that was adapted from the Snow-17 operational model of the National Weather Service as described by Anderson (1976) and Shamir and Georgakakos (2005). Potential snowmelt is calculated from air temperature and an empirical snowmelt factor that varies by day of year (Lundquist and Flint, 2006). Snow accumulation and melt are calibrated to snow sensors and snow courses for the Sierra Nevada, as well as to areal extent of snowpack measured with the Moderate-Resolution Imaging Spectroradiometer by adjusting empirical snow accumulation and snowmelt factors (Flint et al., 2004).

The BCM provided downscaled data for monthly precipitation, minimum air temperature, potential evapotranspiration, and snowpack for all fen locations. Time series trends in climate data were evaluated with the Mann–Kendall trend test (Helsel and Hirsch, 2002). Student's *t*-tests were used to compare climate variables between 1951–1980 and 1981–2010. All statistical tests were carried out using SYSTAT version 13.00 05 (SYSTAT Software, Inc., 2009).

3. Results

3.1. Total delineated areas

Delineated areas for each fen for the entire photographic record are provided in the Supplemental material. At Arkansas, Kiln, Lyons Lake, McKinstry Meadow, and Moraine, there were decreases in delineated areas through time, with significant trends at all but Lyons Lake (Figs. 3 and 4). Reductions in delineated fen area range from approximately 10–16% (Fig. 3). For Moraine Fen, only the southern part of the site had a significant reduction in delineated area (Fig. 3). For Arkansas, there was approximately a 16% decline in delineated area over the study period. However, this pattern was determined from a total of 6 aerial photographs (the smallest record among the sites) and there was a 26-year gap between the black and white and colored images, so this result may not be as robust as the others.

Two sites, Willow Creek 2 and Cooper Swamp, did not have any appreciable differences in delineated area over the photographic record (Fig. 3). For Cooper Swamp, which was the largest of the fens, a smaller, highly distinct part of the site (Cooper NW; Fig. 4) was used for its overall assessment due to major problems with glare in the main body of the site in the early black and white photographs.

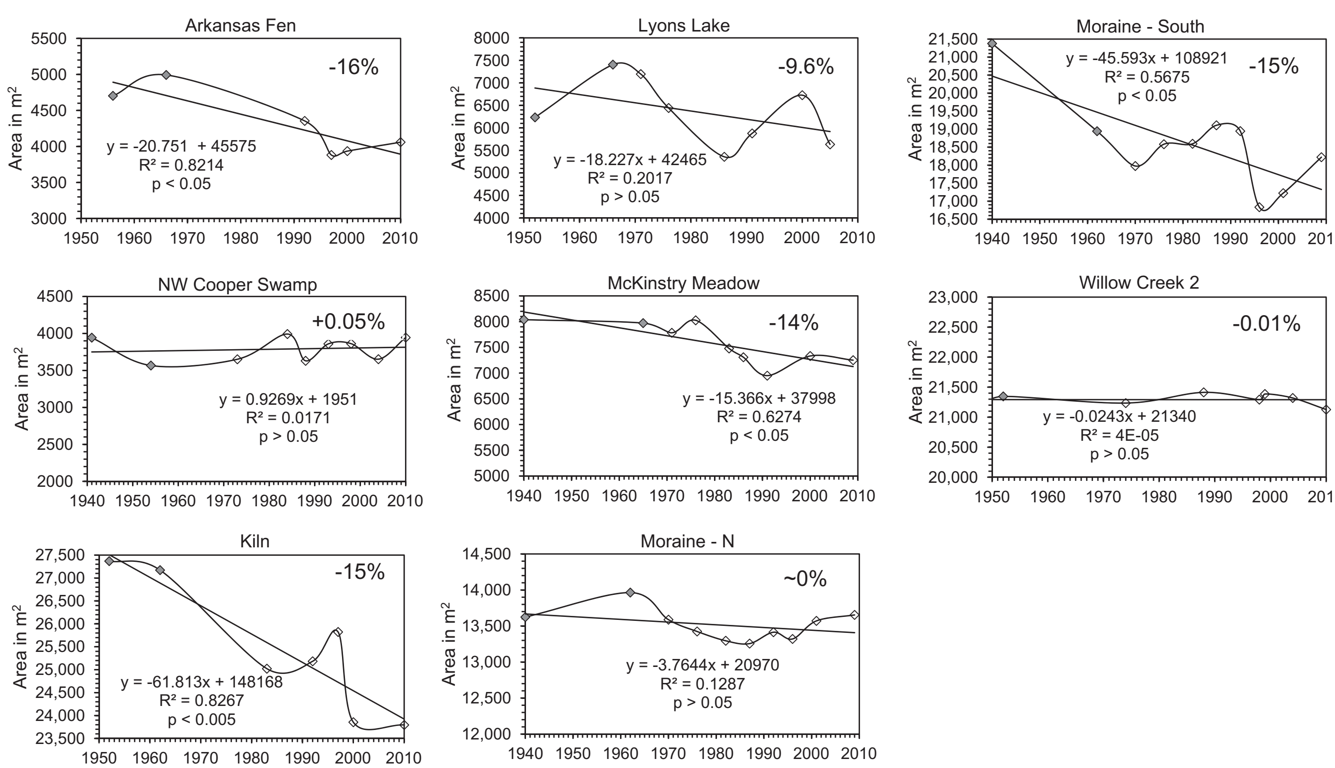

Fig. 3. Fen area delineations for the entire photo record of each fen. Solid (gray-filled) diamonds indicate fen area delineations were based on black and white photographs vs. color (open diamonds) photographs. Linear trend lines show significance of trends through time and percentages are the amount of change in area over the entire study period.

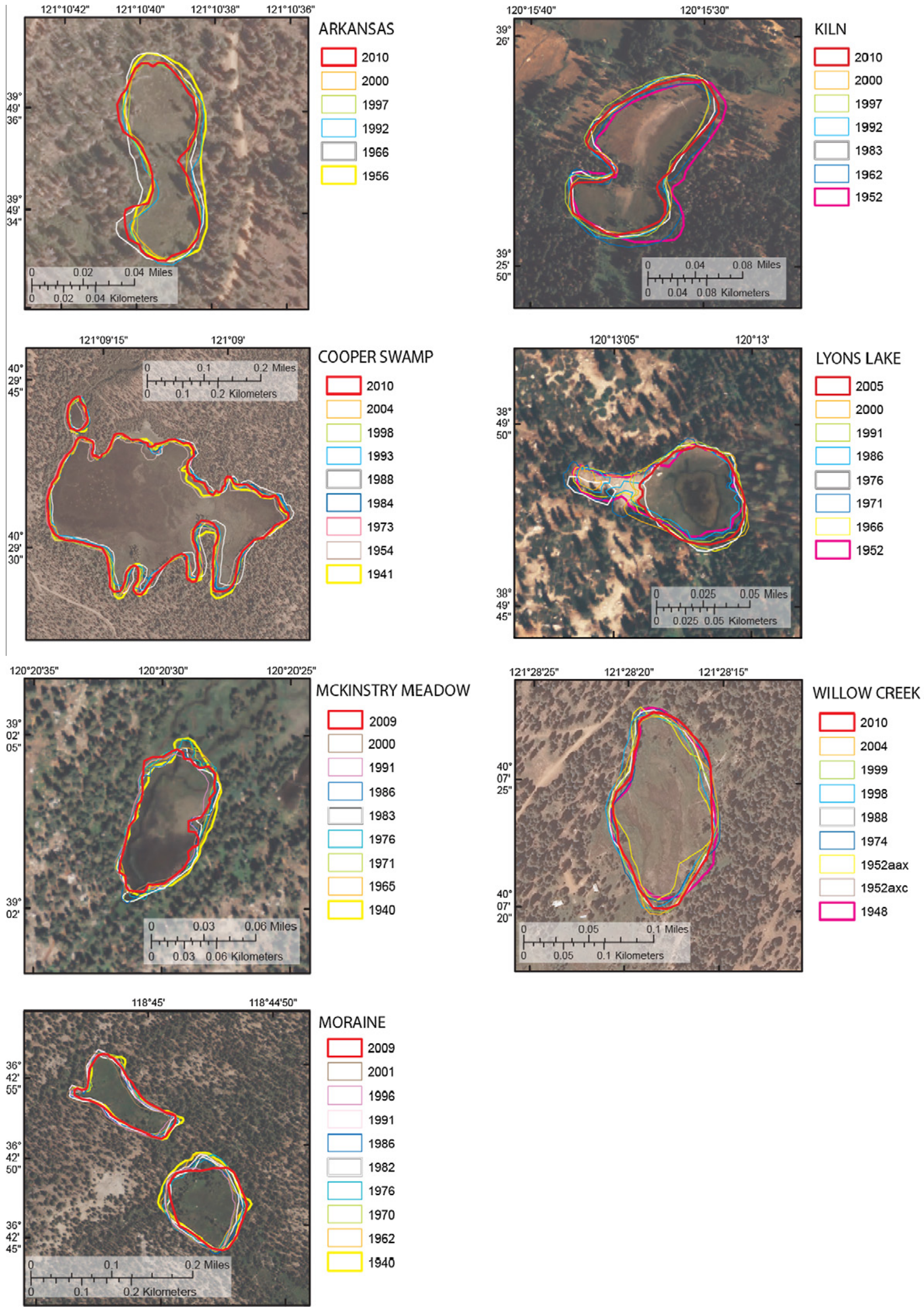

Fig. 4. Fen area delineations (shapefiles) for each year shown on top of the final image of the photographic record, which is the 2005, 2009, or 2010 NAIP image. Such overlaying of images helps to see the general pattern of change in delineated fen areas through time.

3.2. Climate data

The BCM results show that total annual precipitation has increased slightly (between 20 and 100 mm) at most of the sites between 1951–1980 and 1981–2010 (Fig. 5). This increase was too small and too variable to be statistically significant (Student's one-tailed *t*-test, $p > 0.05$). At Cooper Swamp, there was little change between the two periods and at Kiln there was a decrease between 20 and 100 mm (Fig. 5).

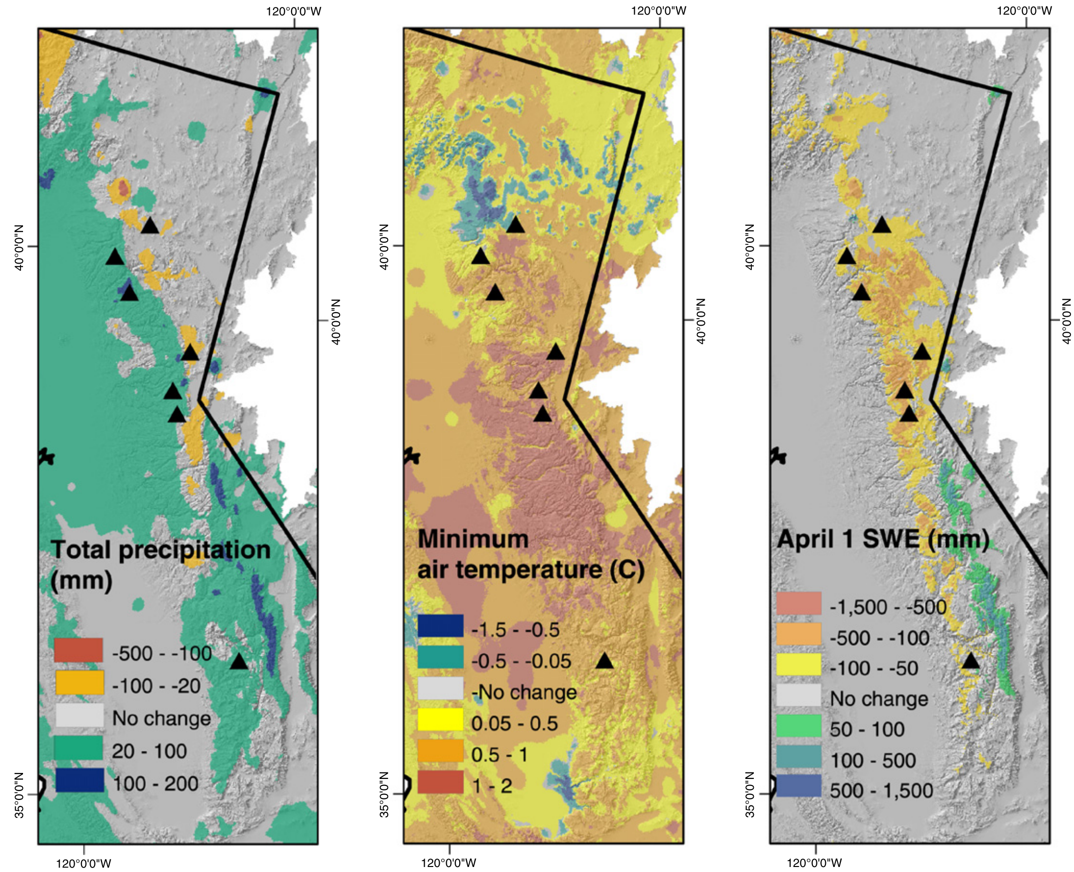

Fig. 5. Change in annual total precipitation, mean annual T_{min}, and mean April 1st snow water equivalent (SWE) between two 30-year periods: 1951–1980 and 1981–2010.

T_{min}, as estimated by the BCM, has increased between 0.05 and 2 °C at all seven sites between 1951–1980 and 1981–2010 (Fig. 5). The greatest amount of warming has occurred at the central sites vs. the northern or southern fens in the study region. At all sites except Willow Creek 2, there has been a significant increasing trend in T_{min} through the study period (Mann–Kendall tests; Fig. 6). Even at Willow Creek 2, however, there has been an increase in T_{min}, but at this site as well as Cooper Swamp, a major change has occurred only recently. At Willow Creek a sharp rise in T_{min} began in 1985, while at Cooper Swamp a similar increase started in 1990 (Fig. 6).

Increases in T_{min} have led to a decline in April 1 SWE between the periods 1951–1980 and 1981–2010. The BCM data show this trend for all fens except Moraine in the southern Sierra Nevada (Fig. 5). An analysis of the April 1 SWE data at the six SNOTEL stations closest to the fens also showed a decline between the two time periods for all sites except Willow Creek 2, for which no long-term records were available (Student's one-sided t-test, $p < 0.05$). The number of June months with zero snowpack (BCM results) showed that snowpack longevity has also decreased significantly between the periods 1951–1980 and 1981–2010 (Table 3).

With respect to potential evapotranspiration (PET) estimated by the BCM, there was little to no change between 1951–1980 and 1981–2010 (not shown) and this change was not statistically significant (Student's one-sided t-test, $p > 0.05$).

4. Discussion

In this paper we demonstrated reductions in delineated areas for five fens: Arkansas, Kiln, Lyons Lake, McKinstry Meadow, and Moraine. The decreases in delineated fen areas all showed statistically significant trends through time except at Lyons Lake, where the variability in the pattern apparently overshadowed the long-term trend. At the other two fens in the study, Cooper Swamp and Willow Creek 2, there was little to no change in delineated area through time (Figs. 3 and 4).

There are many potential explanations for the reductions in delineated fen areas. A wide range of climate factors including increases in air temperature, fluctuations in total precipitation, varying snowpack volume and/or longevity, changes in evapotranspiration, and variations in surface flows can all ultimately affect fen areal extent. However, the results of this study combined with some basic characteristics of fens suggest a combination of increasing T_{min} (which has been increasing faster than T_{avg} and T_{max} in California; LaDochy et al., 2007; Anderson et al., 2008) and decreasing snowpack volume and/or longevity as the most likely climate factors. The reasons for this are as follows. First of all, for the areal extent of fen flora to contract through time (i.e., leading to a decrease in delineated area), there needs to be a systemic change, not just yearly fluctuations. Previous work cited above and the climate analysis in this paper show that T_{min} has increased steadily through time (Fig. 6). Fig. 6 also demonstrates that the photographs used through time in the analysis, by and far, straddle or remain close to the mean change in T_{min} at the sites, precluding bias during warm or cold years. T_{min} is known to exert a strong influence over snowpack longevity (Knowles et al., 2006). Snowpack volume and its longevity in the landscape most strongly influence the amount of groundwater recharge that occurs because most of recharge in the arid West occurs beneath the snowpack (Winograd et al., 1998; Barnett et al., 2008; Earman and Dettinger, 2008; Hanak et al., 2011). The climate analyses of both BCM and SNOTEL data not only showed reductions in April 1 SWE between 1951–1980 and 1981–2010, but also reductions in snowpack longevity (Fig. 5, Table 3). Furthermore, much recent

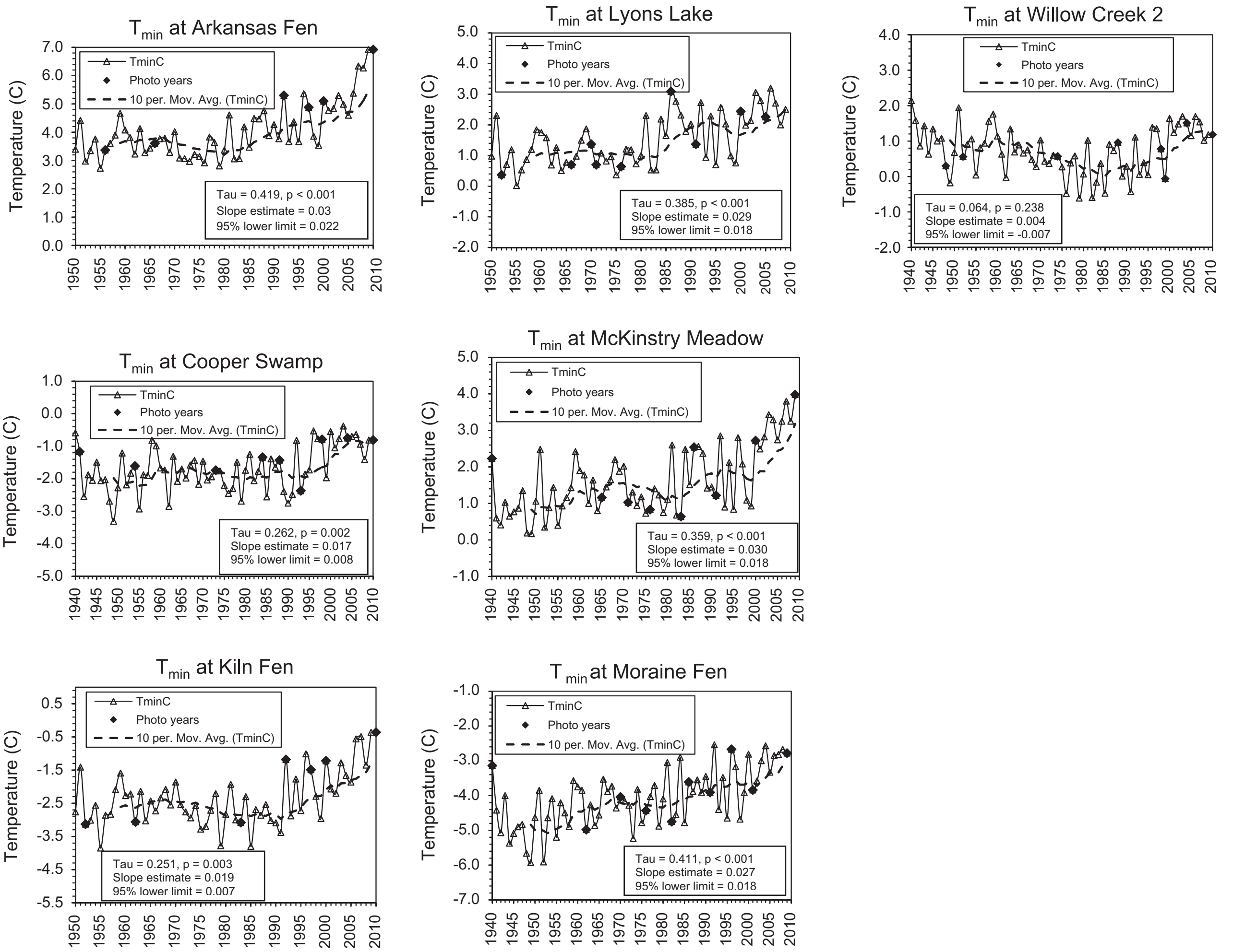

Fig. 6. BCM T_{min} estimates for 1951–2010, the years for which aerial photographs were available, a 10-year moving average, and trend analysis results (Kendall Tau statistic (Tau) for upward trend and Sen's slope estimate with a 95% lower limit) are provided for each of the fen sites.

Table 3
Number of June months with 0 mm snowpack estimated by the BCM for each fen location during 1951–1980 and 1981–2010.[a]

Fen	1951–1980	1981–2010
Arkansas	16	21
Cooper Swamp	14	19
Kiln	7	15
Lyons Lake	14	21
McKinstry Meadow	7	14
Moraine	4	9
Willow Creek 2	8	9

[a] A one-tailed t-test (positive) was significant for the fens as a group ($p < 0.05$).

work has shown that April 1 snowpack is decreasing in the arid West, with an ongoing trend of more precipitation falling as rain vs. snow (Dettinger et al., 2004; Knowles et al., 2006; Cayan et al., 2008; McCabe and Wolock, 2009; Abatzoglou, 2011; Pederson et al., 2011). All of these climate trends suggest that the amount of groundwater recharge in the study area is decreasing.

The rate of groundwater recharge is inextricably tied to the rate of groundwater discharge further downstream in a watershed. By definition, a fen is a wetland type that relies on groundwater discharge from the watershed to maintain its saturation as well as its distinct water chemistry and flora (Bedford and Godwin, 2003; Mitsch and Gosselink, 2007). All of the fens in this study exist because they are situated downstream from springs, which are groundwater discharge zones (Fig. 2). Because summer rainfall is minor compared to winter precipitation in the study area (due to the Mediterranean climate), the only hydrologic change that could potentially impact fen saturation and, thus, eventually decrease delineated fen area is a decrease in groundwater flow.

At Cooper Swamp and Willow Creek 2, there were no discernible changes in delineated area and climate change occurred on a much more recent time scale (Figs. 5 and 6). For example, at Cooper Swamp, T_{min} began an ascent starting in ~1990, whereas at Willow Creek 2 this change began in 1985 after a previous long decline in T_{min}. The BCM results showed decreases in June snowpack longevity for these sites, but a longer record of changes in snowpack volume and/or longevity may be needed to see if this is just a temporal fluctuation or indeed part of a long-term trend (Table 3). It is possible that the more recent climate signal combined with the fact that the peat column is greater than 1 m at both of these sites (thicker peat would likely retard the desiccation process) may explain why reductions in delineated fen area have not occurred. However, it is also important to consider whether climate is the sole determinant of changes in delineated area or whether another factor such as hydrogeology controls the threshold at which changes are discernible.

There are important differences in hydrogeological characteristics between the bedrock in the southern Cascade Range (Modoc Plateau), where Cooper Swamp and Willow Creek 2 are located, vs. the Sierra Nevada, where the rest of the sites are found. First of all, quaternary volcanic bedrock, present as fractured basalt, common in the Modoc Plateau can have values of saturated hydraulic conductivity (K) as high as 1 cm s^{-1}. Jefferson et al. (2006) note that lavas in the southern Cascade Range (Modoc Plateau) form a stack of mostly high permeability rock more than 1000 m in thickness, with high transmissivity of groundwater through the aquifers. In young volcanic arcs that receive large amounts of annual precipitation, high recharge rates coupled with volcanic aquifers that have high near-surface hydraulic conductivity lead to extensive groundwater systems. In Hat Creek Basin, which is located 45 km north of the Lassen volcanic highlands in fractured basalt, flows rely on very large-volume springs (Rose et al., 1996). Water temperature measurements indicate that deep groundwater circulation does not occur in this area. The aquifer residence times are inferred to be less than or equal to 200 years, but may be considerably less based on preliminary tritium measurements (Rose et al., 1996). These time frames are supported by Manga (1997) who determined that groundwater being discharged from quaternary volcanics is most likely in the range of 50–200 years and is governed by porous flow.

Hydraulic conductivities, groundwater reservoirs, and groundwater residence times in the Sierra Nevada are quite different from the southern Cascade Range. The unfractured and unweathered granite (plutonic), which is more typical of the glaciated central Sierra Nevada, has values of K as low as 10^{-9} cm/s. Weathered and fractured granite, common in nonglaciated areas, has values of K on the order of 10^{-4}–10^{-3} cm s^{-1} (Hill and Mitchell-Bruker, 2010). Fogg and Trask (2007) note that granites in the Sierra Nevada near Lake Tahoe have large downward hydraulic gradients, which is consistent with conceptual and field studies in other areas showing that areas of high relief tend to promote groundwater flow to great depths. Based on tritium values, the mean residence time for groundwater in the Merced Basin in the Central Sierra Nevada is estimated to be about 35 years for mountain block groundwater and 20 years for some of the springs at or near the interface of soil and bedrock (Conklin and Liu, 2008). However, lateral subsurface flow, more relevant to the flow systems that feed fens, typically flows faster and has a smaller reservoir at higher elevations than lower elevations due to steeper slopes and thinner soils (Conklin and Liu, 2008). Rademacher et al. (2001) dated spring waters in the Sagehen Creek Watershed in the central Sierra Nevada using chlorofluorocarbons and tritium analyses and determined that they ranged between 5 and 40 years old. More recently, Manning et al. (2012) compiled a 13-year record for groundwater age for springs in the Sagehen Creek Watershed using chlorofluorocarbons, sulfur hexafluoride, and tritium data. Piston-flow ages for the springs ranged from 10 to 50 years. In most of the springs, mean ages of groundwater increased over the study period, likely due to decreasing recharge rates in response to a declining snowpack (Manning et al., 2012).

The two fens that did not change in delineated area, Willow Creek 2 and Cooper Swamp, are situated in the southern Cascade Range. These fens lie within the basalts and lava flows of the Modoc Plateau that have extensive groundwater reservoirs with relatively long residence times compared to the Sierra Nevada. The BCM data showed that there was either little or no decrease in total precipitation at these sites (Fig. 5). However, the sites have experienced steady increases in temperature, albeit during the past 20–25 years (Fig. 6). The BCM data also showed a decrease in the longevity of the June snowpack between 1951–1980 vs. 1981–2010 (Cooper Swamp: 14 vs. 19 Junes with 0 mm; Willow Creek 2: 8 vs. 9 Junes with 0 mm) but not as great as some of the other sites (Table 3). This smaller change may be related to the more recent upturn in T_{min} compared to the other sites. It may be that extensive groundwater reservoirs act to buffer changes in fen areas, particularly if climate change is not dramatic and not sustained for a long enough period of time.

The other five fens are situated in different geologic environments than Willow Creek 2 and Cooper Swamp. Arkansas fen is located in the more layered volcanic strata surrounding Mt. Lassen, which typically have shallower groundwater reservoirs (Rose et al., 1996; Manga, 1997) and, thus, shorter groundwater travel times that would likely respond quickly to climate variation. Of the remaining fens, Kiln is in a mixed pyroclastic/granite region and the 3 southern fens (McKinstry Meadow, Lyons Lake, and Moraine Fen) are all located within the Sierra Nevada granite batholith of very low permeability. During the period from 1951 to 2010, the BCM data showed notable decreases in snowpack longevity at each of these sites and a general warming in T_{min} (Fig. 5; see also LaDochy et al., 2007; Anderson et al., 2008), but little change in total yearly precipitation or potential evapotranspiration.

A conceptual model is presented in Fig. 7, which summarizes the key hydrogeological and climate factors that influence fen delineated area. The main point of the conceptual model is that changes in climate are likely to have a much greater impact in Sierra Nevada fens than in Cascade Range fens because of hydrogeological factors. The Sierra Nevada, on the whole, has lower porosities, lower hydraulic conductivities, and smaller groundwater reservoirs than the Cascade Range. Therefore, the fens in the Sierra Nevada are much more vulnerable to changes in areal extent than those in the Cascade Range. Although this conceptual model illustrates the relationships found in this study, it is likely limited by the small sample size of the study. A greater statistical sampling is needed not only to test the validity of this conceptual model, but also to test the overall viability of using fens as gauges for changes in groundwater recharge. Integration of fen monitoring with groundwater dating studies, such as Manning et al. (2012),

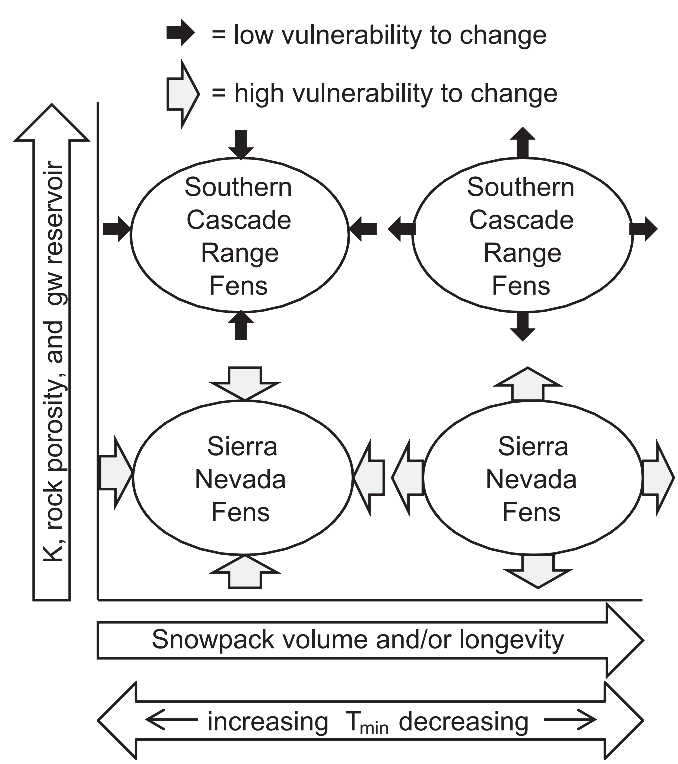

Fig. 7. Conceptual model illustrating the vulnerability of fens to increases or decreases (shaded arrows) in delineated fen area and what likely controls such changes. Long-term changes in T_{min} and snowpack volume and/or longevity, which are major determinants of groundwater recharge, are strongly associated with changes in delineated fen areas. However, underlying hydrogeology, particularly hydraulic conductivity (K), rock porosity, and size of the groundwater (gw) reservoir of the watershed as well as the fen itself, may be important as buffers to sudden changes.

would allow for quantification of changes in groundwater recharge identified using fens.

5. Conclusions

Overall, the results from this study show that fens in the Sierra Nevada have strong potential as whole-ecosystem gauges for determining long-term changes in groundwater recharge under climate change. Due to either more moderate climate change and/or hydrogeological differences, fens in the southern Cascade Range currently do not appear to have the same utility. Decreases in fen areal extent found in the Sierra Nevada fens were all between 10% and 16%. Considering the range of fen sizes, aspects, and elevations (Table 1) as well as the potential differences in the scales of groundwater flow systems at these sites, this is a remarkably consistent result. It shows that the fens reflect subtle and chronic changes in the landscape. Because fens require consistent groundwater discharge to maintain their unusual flora, they are highly sensitive to changes in groundwater recharge in the watershed. The results in this study suggest that such changes in groundwater recharge are occurring at a rate fast enough to be translatable into changes in flora (~on a decadal scale or faster), because otherwise there would not have been significant downward trends in delineated fen areas (Fig. 3). Fen monitoring via aerial photography represents a unique new approach for discerning subtle changes in groundwater recharge at both the watershed and regional scale. Future work needs to focus on applying this method to a statistically relevant sample size and integrating fen monitoring with groundwater dating to quantify changes in groundwater recharge identified using fens.

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Appendix A. Supplementary material

Figs. S1–S7. Delineated areas for each fen for the entire record of historical aerial photographs used in the study. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2012.11.056.

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