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Short Communication

The relative importance of climate change and shrub encroachment on nocturnal warming in the southwestern United States

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ABSTRACT: Many regions of the world are affected by a major land cover change resulting from the encroachment of woody plants and the conversion of grasslands into shrublands. In the southwestern United States, such a change in vegetation cover has been found to increase the winter nighttime temperature, thereby contributing to a positive feedback between shrub encroachment and microclimate in areas encroached by cold-sensitive shrubs. Temperature measurements show that winter minimum temperatures are on average ~2 K higher in shrubland than in adjacent grassland sites. It is unclear how the nighttime warming induced by shrub encroachment compares with regional climate trends. We address this question by analysing both the historical and future regional temperature trends in central New Mexico. The estimated regional increase in minimum winter temperature ranges from 1 to 4 K per century using observations and climate models. Thus, the warming resulting from shrub encroachment is equivalent to a change in regional climate over a time period of century scale, which suggests that shrub encroachment has an overall important effect on the regional climate.

KEY WORDS shrub encroachment; land cover change; regional climate change; minimum temperature

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1. Introduction

Over the past 150 years, the southwestern United States (as well as many other drylands worldwide) have undergone major changes in vegetation cover resulting from the encroachment of woody plants into desert grasslands (Van Auken, 2000; Knapp *et al.*, 2008). This transition has an impact on soil moisture dynamics as well as on the energy exchange between the land surface and the atmosphere (Dugas *et al.*, 1996; Bhark and Small, 2003; Kurc and Small, 2004). The conversion from semiarid grassland to shrubland in the northern Chihuahuan desert shrubland is typically associated with an increase in the bare soil fraction (D'Odorico *et al.*, 2012) and has (on average) a pronounced nocturnal warming effect of ~2 K in wintertime (He *et al.*, 2010). This effect is potentially very important in the winter season when *Larrea tridentata*, a woody species native to North America's southwestern deserts and one of the two predominant encroaching woody species in the region, remains non-dormant and is thus sensitive to freeze-induced mortality (Pockman and Sperry, 1997; Medeiros and Pockman, 2011). Therefore, a positive feedback between shrub encroachment and winter minimum temperatures may further promote shrub establishment in this region (D'Odorico *et al.*, 2010). Similar feedbacks have been reported for other grassland-to-woodland transitions, where nocturnal warming induced by the encroachment of woody plants favours the survival of cold-sensitive trees and shrubs, thereby further enhancing their encroachment (D'Odorico *et al.*, 2013). This feedback process is particularly affected by minimum temperatures because they are directly associated with episodes of freezing-induced mortality. The nocturnal warming induced by shrub encroachment in the southwestern United States is particularly intense in cold winter nights (D'Odorico *et al.*, 2010). It is still unclear how in this region the warming resulting from the grassland to shrubland conversion compares with the temperature increase induced by large-scale drivers of global and regional climate change.

Climate change studies indicate that the global temperatures are expected to keep increasing for the next several decades as a result of fossil fuel emissions as well as abiotic and biotic feedbacks (IPCC, 2007). These warming trends vary geographically with time of the day and season, and are particularly strong for nighttime temperatures. In fact, over the last 50 years nocturnal temperatures have increased twice as much as daytime temperatures (Houghton *et al.*, 2001). Moreover, cold extremes exhibit a more rapid warming (by about 25% over landmass

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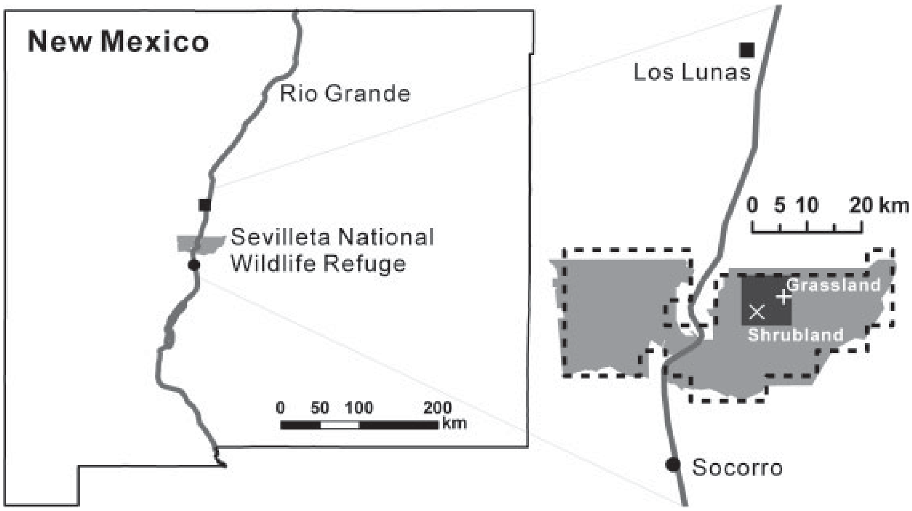

Figure 1. Locations of the SNWR (light grey shaded area) in New Mexico, the shrubland (white plus symbol) and grassland (white cross symbol) sites at SNWR, and Los Lunas (black square symbol) and Socorro (black circle symbol) USHCN stations located along the Rio Grande (grey line) valley. Also shown are the areas of PRISM grid cells encompassing the McKenzie Flats (dark grey shaded area) and the SNWR (area indicated by the dashed line).

and 30-40% globally) than warm extremes (Kharin *et al.*, 2007). In most of North America, warming is expected to exceed the global mean (IPCC, 2007), especially in the southwestern United States (Leung *et al.*, 2004; Seager *et al.*, 2007), which have become warmer and drier more rapidly than the rest of the continental United States since the mid-1970s (Williams *et al.*, 2010). These regional climate trends in the deserts of the southwestern United States have never been compared with changes in nocturnal microclimate that could result from shrub encroachment. Such a comparison will provide new insights into the importance of the warming induced by changes in vegetation with respect to the regional effects of climate change. Here, we use historical records, regional climate model (RCM) simulations and temperature measurements at adjacent grassland and shrubland sites in the northern Chihuahuan desert to compare the nocturnal warming resulting from land cover change with the background temperature trends in the regional climate.

2. Methods

The concurrent temperature measurements used in this study were from adjacent shrubland (34.3349°N, 106.7442°W, elevation: 1593 m) and grassland (34.3623°N, 106.7019°W, elevation: 1622 m) sites in the McKenzie Flats area of the Sevilleta National Wildlife Refuge (SNWR), located in the northern Chihuahuan desert, New Mexico (Figure 1). SNWR has undergone an abrupt change in vegetation cover with an encroaching front of *L. tridentata* shrubs into a desert grassland (Bhark & Small 2003, Báez & Collins 2008). Thus, this area provides an ideal location to monitor the microclimate conditions in adjacent sites with woody and herbaceous vegetation located within a distance of a few kilometres (~5 km). Temperature measurements between 2007 and 2010 (at 3 m above ground) were obtained from the Ameriflux network (ameriflux.ornl.gov). All data were recorded as 30-minute averages. Only days on which daily minimum temperature observations were available for both the shrubland and grassland sites were used (>90% of all observations).

The longest temperature record for the SNWR is available at the Deep Well Station (34.3592°N, 106.7358°W, elevation: 1600 m), which is located in the grassland area of the McKenzie Flats. The meteorological tower is operated by the Sevilleta Long Term Ecological Research (LTER, http://sev.lternet.edu) and data are available from 1987 onwards. We used the data from December 1989 onwards after the temperature sensor moved to a height of 2.5 m above ground level. A total of 23 winters from 1990 to 2012 were used here to study the local climate warming at SNWR in recent decades.

Long-term historical temperature records in the southwestern United States were obtained from the US Historical Climatology Network (USHCN) version 2 serial monthly dataset (Menne *et al.*, 2009). We analysed the temperature data from Los Lunas (34.7675°N, 106.7611°W, elevation: 1475 m) and Socorro (34.0828°N, 106.8831°W, elevation: 1398 m) from 1894 onwards, which are the closest USHCN stations to the SNWR (48 km north and 31 km south, respectively) along the Rio Grande valley (Figure 1). The USHCN dataset uses a 'pairwise' homogenization algorithm (Menne and Williams, 2009) to effectively minimize the impacts of urbanization and other factors on the historical temperature record (Menne *et al.*, 2010). Nevertheless, the areas (<1 km in radius) around those two stations are mainly covered by non-urban land use types identified on the 2001 National Land Cover Database (NLCD2001, Homer *et al.*, 2007). Thus, the warming due to urbanization is not expected to affect the analysis of temperature trends based on these two stations from the USHCN.

Table 1. The average increase in the minimum winter temperature over a 70-year period from current (1969–1999 or 1969–2000, depending on the model combinations) to future (2039–2069 or 2039–2070) using the output of 11 AOGCM and RCM combinations from NARCCAP. These temperature changes are calculated using temperature values obtained as means of the 4 grid points closest to the encroaching front at SNWR.

Models	AOGCM	CCSM	CGCM3	GDFL	GDFL	HadCM3	CCSM	HadCM3	CGCM3	GDFL	CCSM	CGCM3
	RCM	CRCM	CRCM	ECP2	HRM3	HRM3	MM5I	MM5I	RCM3	RCM3	WRFG	WRFG
Temperature change (K)		1.5	3.0	3.0	2.2	2.7	2.4	3.8	3.0	2.2	2.3	1.6

The full names of the abbreviations of the AOGCMs and RCMs are: CCSM, Community Climate System Model version 3; CGCM3, Canadian Global Climate Model version 3; GDFL, Geophysical Fluid Dynamics Laboratory Climate Model version 2.1; HadCM3, Hadley Centre Climate Model version 3; CRCM, Canadian Regional Climate Model; ECP2, Experimental Climate Prediction Center Regional Spectral Model, updated version; HRM3, Hadley Regional Model 3; MM5I, MM5 – PSU/UCAR Mesoscale Model; RCM3, Regional Climate Model version 3; WRFG, Weather Research and Forecasting Model with Grell convective scheme. The daily minimum temperatures are calculated using surface temperatures of every 100 seconds for GDFL/ECP2, every 2 minutes for CCSM/MM5I and HadCM3/MM5I, every 5 minutes for GDFL/HRM3 and HadCM3/HRM3, every 15 minutes for CCSM/CRCM and CGCM3/CRCM, every hour for CCSM/WRFG and CGCM3/WRFG, and every 3 hours for CGCM3/RCM and GDFL/RCM3. Because of missing data, the following months are excluded in the calculation: CGCM3/RCM3: December 2068; CCSM/WRFG: December 2053; CGCM3/WRFG: December 2040, December 2045, December 2050, December 2055, December 2060, December 2065.

A gridded climate dataset based on station data and the Parameter-elevation Regressions on Independent Slope Model (PRISM, Daly *et al.*, 2002) available from 1895 onwards, was used to estimate the historical climate warming in the SNWR area for a time period of over one century. PRISM calculates a climate-elevation regression for each digital elevation model (DEM) grid cell and improves the spatial interpolation, particularly in complex terrain (Daly *et al.*, 2008). With a resolution of 2.5′ for monthly climate data, in New Mexico each PRISM grid cell covers an area of about 21 km^2. In this study, we examined both the area around the encroaching front on the McKenzie Flats (transition between shrubland and grassland, 4 grid cells), and also the entire SNWR (53 grid cells, Figure 1).

Future climate change scenarios were based on model simulations from the North American Regional Climate Assessment Program (NARCCAP, Mearns *et al.*, 2009). NARCCAP provides high spatial resolution (50×50 km^2) climate simulations for North America for both past (1970s–1990s) and future (2040s–2060s) conditions under the Special Report on Emissions Scenarios (SRES) A2 emission scenario (Nakicenovic and Swart, 2000). A2 is a high emission scenario, which refers to the case of a diverse world with relatively self-reliant economic regions, slow technological development and large population. NARCCAP uses a number of model combinations based on four atmosphere–ocean general circulation models (AOGCMs) coupled with six RCMs. The results from 11 available combinations were processed and analysed to reduce the bias caused by individual models. We used 4 grid cells closest to the McKenzie Flats, the location of which slightly varies in the different model combinations due to different domain settings and projections. Monthly mean minimum temperature was obtained using the daily minimum temperature output, which was calculated from instantaneous surface temperatures at different time intervals ranging from every 100 seconds to 3 hours from 06:00 UTC to 06:00 UTC in different model combinations (see the caption of Table 1 for details). The monthly minimum temperature data were excluded in this study if one-third or more (10 days or more) data were missing within 1 month (<1% of all winter months).

Because of the sensitivity of *L. tridentata* shrubs to freezing temperatures, we focused on winter minimum temperature. The winter of a year is defined as the January and February of that year and December of the previous year. Specifically, we used the average minimum temperature of the coldest month (hereafter referred to as ‘minimum winter temperature’) in one winter, to study the changes in winter minimum temperature.

3. Results

3.1. Winter minimum temperature change caused by shrub encroachment

Data recorded at the shrubland and grassland sites from 2007 to 2010 show that the shrubland has a higher minimum temperature than the adjacent grassland throughout the year (Figure 2). On average, in 2007–2010 the daily minimum temperature in winter months in the shrubland was 1.8 K warmer than in the grassland. The daily minimum temperature occurred during nighttime or near dawn in both the shrubland and the grassland during the 12 winter months, except for five cases in which daily minimum temperature was observed during daytime. Therefore, such higher daily minimum temperature is closely associated with the nighttime warming in the shrubland. The differences in the minimum winter temperature between shrubland and grassland in the winters of 2008, 2009 and 2010 were 2.5 K, 2.6 K and 0.7 K, respectively.

3.2. Historical minimum winter temperature change

The minimum winter temperatures for the grassland site at SNWR and the nearest USHCN stations in central New Mexico are shown in Figure 3. General warming trends occurring over the last two decades in the grassland areas at SNWR are consistent with the longer temporal trends in central New Mexico: both Socorro (0.009 K year^{-1}) and Los Lunas (0.014 K year^{-1}) have been experiencing an increase in winter minimum temperature. Because of the lack of long-term observations in the investigation area, we use PRISM to analyse the historical climate change in the SNWR over a time scale of more than one century. In the McKenzie Flats, the minimum winter temperature shows

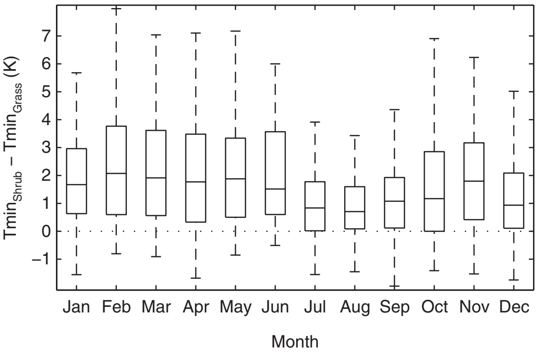

Figure 2. Box and whisker plot for differences of minimum temperatures between shrubland and grassland for 2007 to 2010.

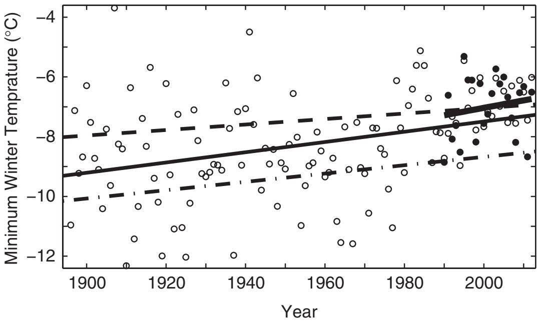

Figure 3. Historical minimum winter temperature for the grassland site and Mckenzie Flats area at SNWR and at two UHSCN stations in central New Mexico. Shown are the observations from Sevilleta LTER at the Deep Well Station (closed circles and corresponding solid grey trend line, data from 1990 to 2012), PRISM data for McKenzie Flats (open circles and corresponding solid black trend line, data from 1896 to 2012). Data from the two USHCN stations are shown as trend lines for Los Lunas (dash-dot line) and for Socorro (dashed line, data from 1894 to 2013).

clearly a warming trend over the past 116 years (Figure 3). The estimated increase in the minimum winter temperature in the McKenzie Flats is 0.025 K year^{-1}, which is slightly larger than the minimum temperature increase in the whole SNWR (0.013 K year^{-1}).

3.3. Future minimum winter temperature change from regional climate simulations

Simulations by all climate model combinations from NARCCAP show an increase in minimum winter temperatures in the future. However, the magnitude of the increase varies among the different model combinations (Table 1), ranging from 1.5 to 3.8 K over a period of 70 years. The median of temperature changes from past to future conditions is very close to the mean value. On average, there is a 2.5 K increase in the minimum winter temperature in the area around SNWR over the same 70-year period (1970s–1990s to 2040s–2060s).

4. Discussion

In the SNWR area, the long-term warming trend in minimum winter temperature is estimated to range between 0.015 and 0.017 K year^{-1} in the historical PRISM data (Table 2). Using the first and third quartiles of 11 NARCCAP model combinations to exclude extreme values, the future warming trend in climate model outputs is slightly higher, varying from 0.031 to 0.043 K year^{-1} (Table 2). The minimum winter temperature trend at the Deep Well Station for the past two decades is stronger than the long-term trend in the PRISM data for the SNWR, which could be associated with the large difference of the time period used in the estimation. In fact, grid point to site comparison indicates that the monthly average minimum temperature in winters from PRISM correlates well with the temperature measured at the Deep Well Station ($r = 0.9135$, $p < 0.0001$) and also with the two USHCN stations (Los Lunas: $r = 0.8733$, $p < 0.0001$; Socorro: $r = 0.9134$, $p < 0.0001$). Despite the simplicity of the linear regression trend (Karl *et al.*, 2000) and the dependency of such trend on the time period used to fit the regression line (Easterling and Wehner, 2009) and on the model resolution (Rind, 1988), these estimates compare well with other studies. For example, estimates by the Intergovernmental Panel on Climate Change (IPCC, 2007) suggest a 0.03–0.035 K year^{-1} increase over the 21st century in winter temperatures for the southwestern United States under the A1B scenario. An increase of 0.028–0.043 K year^{-1} in monthly minimum temperature for January, February and March was reported for the western United States by Barnett *et al.* (2008) over the second half of 20th century, whereas the average global predicted trend is 0.054 K year^{-1} over land for the 21st century in the A2 scenario (Kharin *et al.*, 2007).

In addition to the mean winter minimum temperature, the occurrence of extreme cold events is another factor that is closely associated with the survival and productivity of shrubs due to freezing intolerance. In 2007–2010, the grassland site in SNWR recorded only 3 days with temperature lower than −15 °C, a critical value at which the juveniles of *L. tridentata* start experiencing mortality, based on laboratory cold treatment experiments (Medeiros and Pockman, 2011). In contrast, such extreme cold events did not occur in the shrubland during the same time period. Moreover, at SNWR, 89% of the winter days in 2007–2010 had temperatures below freezing (i.e. <0 °C) in the grassland, compared with 80% in the shrubland. At the Deep Well Station, the occurrence of both freezing and extreme cold events showed large fluctuations from year to year without a clear tendency. For the recent 23 years, the number of days when daily minimum temperature dropped below −15 °C varied between 0 to 5 days per winter, whereas the percentage of winter days that experienced freezing temperatures varied between 72 and 96%. Although the impacts of climate change on freezing and extreme cold events are not evident, shrub encroachment does show a role in decreasing the occurrence of both events in the SNWR.

The NARCCAP simulations use a high emission scenario, A2, and therefore may overestimate the warming trend. The NARCCAP RCM simulations are only driven by fossil fuel emission without accounting for the effects of land use change. Thus, these simulations may

Table 2. Comparison between the increase in minimum winter temperature due to shrub encroachment and the estimated historical and future regional warming trend at the SNWR. The corresponding years indicate the number of years for climate change to cause a warming effect of the same magnitude as the increase in temperature induced by shrub encroachment.

	Temperature change induced by shrub encroachment					
Data source	Site	Distance (km)	Time period		Temperature difference (K)	
Flux towers	Shrubland minus grassland	5	Average of 2008–2010		2.0	
	Climate change					
	Site/grids	Spatial scale (km^2)	Time period		Warming rate (K year^{-1})	Corresponding years[a] (years)
			Start time	End time		
Meteorological tower	Grassland		1990	2012	0.025	80
PRISM	Mckenzie Flats	∼85	1896	2012	0.017	118
PRISM	SNWR	∼1150	1896	2012	0.015	133
NARCCAP	4 grid points	10 000	Average of 1970s–1990s	Average of 2040s–2060s	0.031–0.043[b]	47–64

[a] Calculated as the observed temperature differences in shrubland and grassland in SNWR divided by the warming rate obtained from historical data or climate modelling.

[b] In NARCCAP, the range of warming rate is calculated as the first and third quartiles of 11 model combinations.

underestimate temperature trends in the regions impacted by shrub encroachment and the associated warming effect. The NARCCAP outputs used in this study consist of 4 grid cells, each covering a 2500 km^2 area, which is much larger than the PRISM data also used in this study. Therefore, the mountainous regions east and west of the Rio Grande valley could affect the land surface properties of each grid cell. For example, the altitude of the grid cells used in the analysis ranges from 1706 m to 2169 m, whereas altitudes at McKenzie Flats range from 1550 to 1650 m. Therefore, NARCCAP results represent the overall regional climate change trend in central New Mexico, rather than the condition of the area close to shrub encroachment front.

The impact of shrub encroachment on regional climate entails an increase in minimum winter temperatures of about 2 K, which is comparable to the changes in temperature associated with regional climate warming over a time period of about one century, based on historical trends and model predictions of climate warming for the 21st century in the SNWR area (Table 2). This effect of shrub-induced warming could have important implications for the process of shrub encroachment. As climate warming is one of the many interactive drivers of shrub encroachment in the southwestern United States (Van Auken, 2000), the nighttime warming caused by the presence of shrubs could also contribute to the shift from grass to shrub dominance. In addition, as the effect of shrub-induced warming has the same magnitude as the background climate warming trends measured at decade-to-century time scales, it should be accounted for in a regional assessment of (nocturnal) climate warming. While many other cases of warming caused by vegetation cover change, such as the tundra-woodland transition (Chapin *et al.*, 2005) and deforestation (Lewis and Wang, 1998) , have been well investigated and understood, this study addresses an often overlooked case of land cover change (i.e. shrub encroachment in hot drylands) that has seldom been investigated in the context of its effects on local climate.

Some areas of the southwestern US are also affected by other changes in land cover conditions that are known for having an impact on the local climate. Most notably, urbanization in the Los Angeles, Tucson, Phoenix and Albuquerque areas has been reported to induce a warmer microclimate (Roth *et al.*, 1989; Baker *et al.*, 2002; Hawkins *et al.*, 2004; Imhoff *et al.*, 2010), known as ‘urban heat island effect’. The intensity of urban heat islands in general depend on a number of factors such as seasonality and city size (Oke, 1982; Memon *et al.*, 2008), but in hot arid and semiarid areas it is overall similar in magnitude (e.g. 3–4 K in Phoenix, Hsu, 1984; 4–5 K in Mexico City, Jauregui, 1997; 2–3 K in Houston, Streutker, 2003) to the effect of shrub encroachment. This shift in vegetation cover, however, affects a much more extended region of millions of hectares in southwestern North America (Van Auken, 2000) and therefore plays a more important role in shaping the local climate.

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