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# Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas

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## Abstract

**We present evidence that land use practices in the plains of Colorado influence regional climate and vegetation in adjacent natural areas in the Rocky Mountains in predictable ways. Mesoscale climate model simulations using the Colorado State University Regional Atmospheric Modelling System (RAMS) projected that modifications to natural vegetation in the plains, primarily due to agriculture and urbanization, could produce lower summer temperatures in the mountains. We corroborate the RAMS simulations with three independent sets of data: (i) climate records from 16 weather stations, which showed significant trends of decreasing July temperatures in recent decades; (ii) the distribution of seedlings of five dominant conifer species in Rocky Mountain National Park, Colorado, which suggested that cooler, wetter conditions occurred over roughly the same time period; and (iii) increased stream flow, normalized for changes in precipitation, during the summer months in four river basins, which also indicates cooler summer temperatures and lower transpiration at landscape scales. Combined, the mesoscale atmospheric/land-surface model, short-term trends in regional temperatures, forest distribution changes, and hydrology data indicate that the effects of land use practices on regional climate may overshadow larger-scale temperature changes commonly associated with observed increases in $CO_2$ and other greenhouse gases.**

*Keywords*: cooling effect, forest distribution change, hydrologic change, land use/land cover change, long-term stream flow trends, long-term temperature change, mesoscale climate modelling

## Introduction

It is well recognized that increases in greenhouse gas emissions caused by human activities may affect terrestrial ecosystems (Bazzaz 1990; Melillo *et al.* 1990; Neilson 1993; VEMAP Members 1995). Many scientists now reason that land use practices such as deforestation (Meher-Homji 1991), intensive grazing (Balling 1988, 1990; Bryant *et al.* 1990), and agriculture (Pielke & Avissar 1990; Pielke *et al.* 1991; Burke *et al.* 1991; Baron *et al.* 1997a,b) may affect regional climate, ecosystems, and water resources to a similar or greater extent than would climate change driven by global changes in atmospheric chemistry ($CO_2$, etc.) alone. Land cover effects on climate arise because vegetation characteristics such as albedo, roughness length, leaf area, and fractional coverage affect temperature, humidity, wind speed, and precipitation (Pielke & Avissar 1990; Pielke *et al.* 1991; Copeland *et al.* 1996a).

Most modern landscapes in the western U.S. are diverse mosaics of heavily modified areas (e.g. urban areas, roads, agriculture, and mining) with surrounding areas used for forestry or grazing embedded within a region containing natural areas (e.g. open space, parks, wilderness). There is increased public awareness that climate change, perhaps exacerbated by land use practices, can influence local and regional economies by affecting crop, range, and forest productivity, water quality and quantity, and recreation and tourism (Melillo *et al.* 1990; Copeland *et al.* 1996a; Watson *et al.* 1996). However, our ability to assess potential vulnerabilities of natural areas due to adjacent land use practices and to evaluate climate model

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sensitivity experiments or 'scenarios' has been hampered by: (i) poor resolution of general circulation models (GCMs); (ii) poor understanding of two–way interactions between atmospheric and land surface processes; and (iii) insufficient observations of landscape-scale temperature, hydrologic, and vegetation change in natural areas.

GCM simulations typically have a coarse horizontal resolution on the order of 200–500 km. Studies evaluating GCM experiments (Grotch & MacCracken 1991; Kittel *et al.* 1998) show high biases in their simulations of current climate and poor agreement in surface climate responses to altered forcing, making it difficult to use global climate model results directly for regional and local vulnerability assessments (Pielke *et al.* 1996). Consequently, these models cannot adequately simulate climate variables, especially precipitation, at regional scales and most notably in mountainous regions. Because regional landscapes consisting of spatially varying vegetation cover, topography, and surface hydrology have a strong influence on regional climate (Pielke & Avissar 1990; Pielke *et al.* 1991), very high-resolution (mesoscale) atmospheric models that incorporate land surface–atmosphere interactions are needed to evaluate climate sensitivity across such landscapes. Consideration of mesoscale atmospheric dynamics is particularly important when changes in vegetation community structure are to be evaluated in the context of climate change scenarios. This is because monitoring is commonly undertaken at sites embedded within heterogeneous landscapes and so are subject to climate forcing that is modified by such landscapes.

Understanding interactions between atmospheric processes, such as mesoscale circulations, cloud formation, and precipitation generation, and land surface processes, such as heat and moisture fluxes from live and dead vegetation, is critical when evaluating changes in terrestrial and hydrological systems (Pielke *et al.* 1997). For example, increased leaf biomass contributes to greater transpiration, soil water loss, and increased interception of precipitation leading to decreased surface runoff. Higher leaf biomass also results in a lower albedo and increased surface absorption of solar radiation potentially increasing air temperature and vapour pressure deficit. Together, these may influence establishment, competitive advantage, and survivorship of certain tree species and may change vegetation patterns locally or, through changes in mesoscale circulation patterns, in natural areas several kilometres or even several hundred kilometres away.

We present evidence that land use practices in the plains of Colorado influence regional climate and vegetation in adjacent natural areas in the Rocky Mountains in predictable ways. In addition, we evaluate climate trends suggested by the RAMS simulations with three independent sets of data: (i) climate records from 16 long-term weather stations; (ii) the distributions of seedlings and mature trees of five species of conifers in Rocky Mountain National Park, Colorado; and (iii) discharge data normalized by precipitation inputs during the summer months for four river basins as an indicator of basin transpiration response to temperature trends.

## Materials and methods

We used the Colorado State University Regional Atmospheric Modelling System (RAMS, Pielke *et al.* 1992), a high-resolution, mesoscale atmospheric model coupled with a land surface model implemented for this study with a grid interval of 6.25 km. The simulation domain was for a region of northcentral Colorado which includes both plains and mountains (Fig. 1). Recent improvements in the simulation of the atmospheric hydrological cycle (e.g. clouds, rain, ice crystals) were included (Walko *et al.* 1995).

The land surface submodel (Tremback & Kessler 1985) explicitly calculated heat and moisture fluxes through eight soil levels and from the soil to the atmosphere. Vegetation was implemented as a single canopy where physical and physiological vegetation parameters (e.g. albedo, roughness, vegetated fraction, stomatal control) were functions of vegetation type (values were taken from Biosphere Atmosphere Transfer Scheme, Dickenson *et al.* 1993). Leaf area was undifferentiated between vegetation types. This model configuration provided a crucial link between global forcing and local surface–atmosphere processes allowing realistic climate simulations over complex landscapes.

RAMS simulations consisted of three land use scenarios covering the period from 31 July to 2 August 1992, a common summertime weather pattern. These three days were characterized by a large high pressure system in the central United States which minimized large scale dynamical influences thereby isolating regional effects. Moisture was supplied to the region by low level flow from the Gulf of Mexico. This situation is prevalent in north-eastern Colorado summers and represents typical conditions where irrigation is highly active, plant productivity is high, and base stream flow is low.

The first scenario represented the natural, pre-European settlement state of vegetation (Fig. 2a; Küchler 1964, 1975). The second scenario (Fig. 2b) represented current land cover patterns in which large regions of the grasslands (55.0% of the grasslands or 38.9% of the study region) have been transformed into dry-land crops (wheat) or irrigated (mostly corn) agricultural lands (Loveland *et al.* 1991). In the third scenario (Fig. 2c), we increased the irrigated area by 85% at the expense of both grassland and dryland cropping. This represented

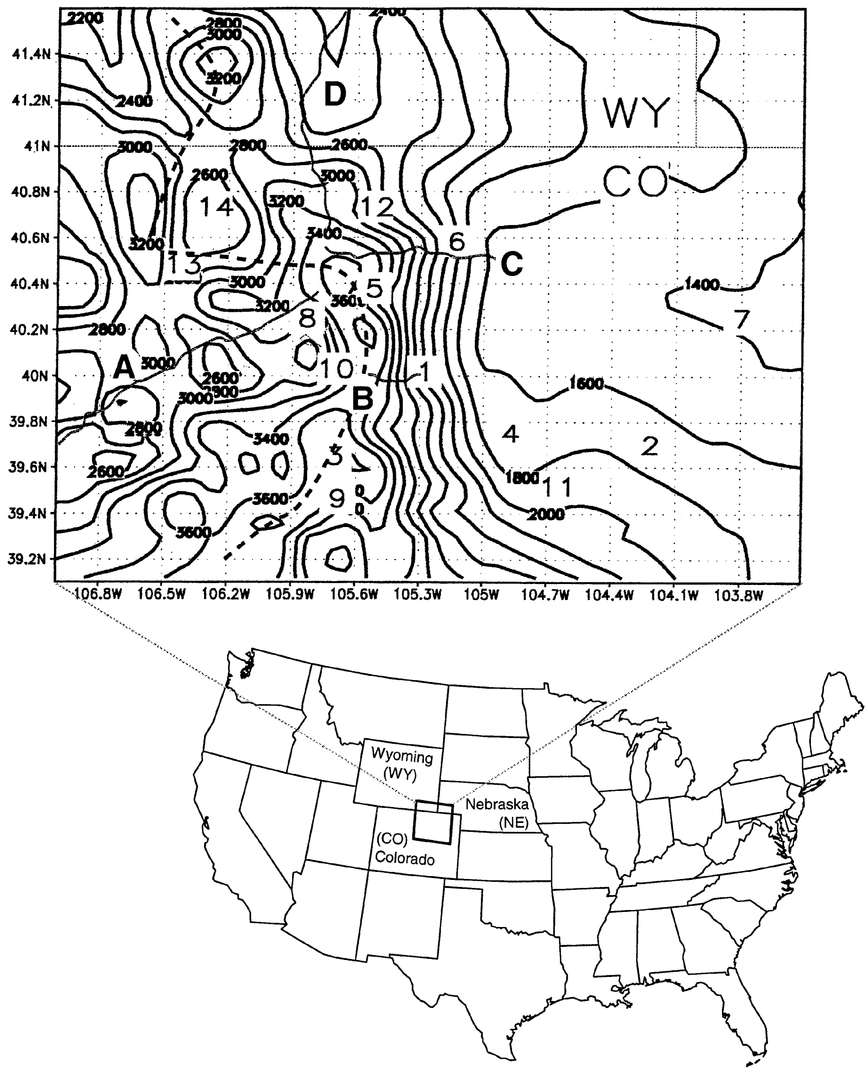

**Fig. 1** Map of the study area (modelling domain), weather station locations as numbered in Table 1 (three stations, Wray, Holyoke, and Stratton, were just outside the modelled domain but were included in table for completeness), Denver (#4) and Niwot Ridge (#11) were added for orientation, and major river basins depicted in Fig. 5.

an idealized future increase in cropland and suburban watered landscapes consistent with population projections in the region (Stohlgren 1997). The RAMS simulations provided a map of the differences in summer temperature between runs with current and natural patterns of vegetation (Scenario 2 minus Scenario 1) and between those with increased irrigated vegetation and natural vegetation (Scenario 3 minus Scenario 1).

We evaluated long-term (> 45 years) and short-term (< 45 years) trends in mean maximum July temperature in °C $y^{-1}$ for 16 Colorado weather stations in the study area (Fig. 1). We report slopes of linear regressions of monthly mean July temperature on year. Long-term trends were based on the complete record, while short-term trends were selected to show maximum trends or recent changes in the slope. The average temperature of the preceding and subsequent year was used where the record was incomplete.

We measured forest vegetation structure at ecotones, the boundaries between vegetation communities, in Rocky Mountain National Park, Colorado. Tree species (and typical elevation zones) included: ponderosa pine (*Pinus ponderosa*; 2320–3170 m), Douglas-fir (*Pseudotsuga menziesii*; 2370–3213 m), lodgepole pine (*Pinus contorta*; 2380–3480 m), Engelmann spruce (*Picea engelmannii*; 2530–3710 m), subalpine fir (*Abies lasiocarpa*; 2530–3710 m), and limber pine (*Pinus flexilis*; 2620–3560 m). At ecotones, dominant species often are at their physiological limit and so may be sensitive indicators of climate change (Stohlgren & Bachand 1997). We measured changes in forest and environmental characteristics across 14 forest ecotones (120–480 m long, 20 m wide) in the middle elevations (2530–3080 m) of the Park (Stohlgren *et al.* 1997). We located two replicate ecotone transects from lodgepole pine to spruce/fir; three replicate transects each from lodgepole pine to limber pine, Douglas-fir, and ponderosa pine; and three transects from Douglas-fir to ponderosa pine. In the 584 10 m × 10 m plots, forest

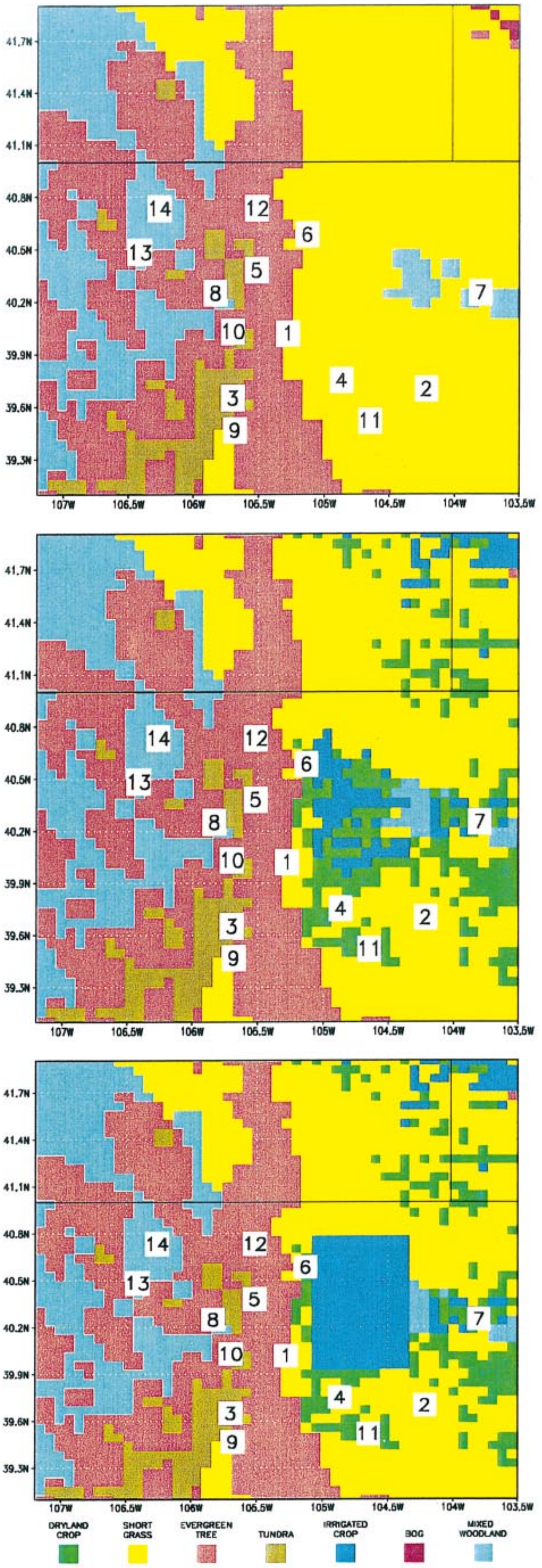

**Fig. 2** Land use scenarios used in RAMS simulations: (a) natural, pre-European settlement vegetation; (b) current vegetation patterns where major areas have been transformed into dry or irrigated agricultural lands; and (c) as in (b), but with an increase in the area of irrigated vegetation by 85% to represent a hypothetical future increase in irrigated croplands and urban landscapes.

dominance was expressed as basal area of tree species by life-stage. The life stages included small seedlings (< 20 cm tall), large seedlings (20–100 cm tall), saplings (> 100 cm tall, < 2.5 cm diameter at 1.4 m; d.b.h.), and trees (> 2.5 cm d.b.h.). Environmental factors included elevation, slope, aspect, intercepted photosynthetically active radiation, summer soil moisture, and soil depth and texture (see Stohlgren & Bachand 1997 and Stohlgren *et al.* 1997 for details). We used canonical correspondence analysis (ter Braak 1986, 1987, 1991) to assess recent changes in the distributions of tree species along environmental gradients by comparing seedling distributions to mature tree distributions along the 14 ecotones (Stohlgren *et al.* 1997).

We evaluated summer (June, July, August) stream discharge at four high-elevation gauging stations in the study area that had long-term records: the Colorado River, Boulder Creek, Big Thompson River, and Laramie River. High elevation stations were selected over lower sites because they have fewer upstream water diversions. We combined gauging station records with upstream water ditch flow data to obtain total basin runoff. To remove effects of trends and interannual variation in precipitation inputs, we normalized the runoff data by precipitation at the closest long-term climate station. We used linear regressions to test for significant trends in runoff as an indicator of basin transpiration response to temperature trends.

## Results

Results of the mesoscale climate model comparison between natural and current vegetation scenarios showed that areas east of the Continental Divide may experience cooler summer temperatures due to current land use practices, with the centre of the cooling (– 0.6 °C) occurring in the Fort Collins area (Fig. 3a). The model also simulated areas of warming on the western slope of the Colorado Rockies and in the eastern plains. These were of smaller extent and magnitude than areas of regional cooling. The cooling effect intensified in magnitude and spatial extent under the scenario of increased irrigated vegetation (Fig. 3b), with large areas on the eastern slope and western plains cooler by 0.5–0.9 °C. The locations of the centres of warming and cooling were consistent in

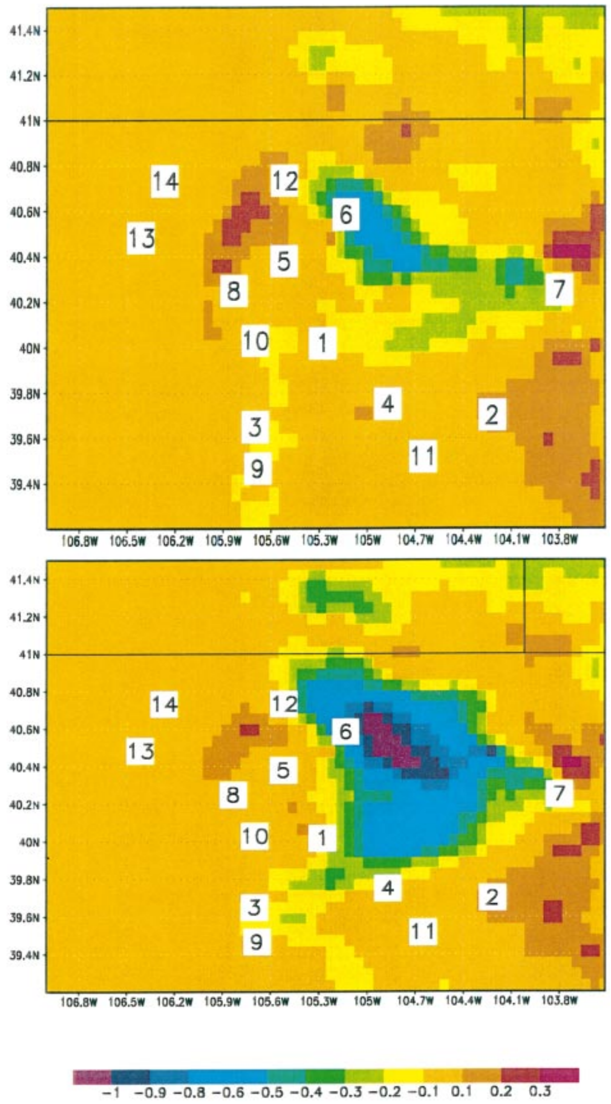

**Fig. 3** Output from RAMS simulations: (a) differences in afternoon (12–6 LST) average temperature between the current and natural patterns of vegetation (Fig. 2b minus 2a); and (b) differences in afternoon temperature between increased irrigated vegetation cover and natural vegetation (Fig. 2c minus 2a). Sites were numbered as in Fig. 1.

both of these model runs. The magnitude of change for warmer areas in the eastern plains was only 0.1–0.2 °C (Fig. 3b).

Corroborating evidence of regional cooling in summer is available from analysis of both long- and short-term trends in weather records. Four of 16 weather stations in the study area showed significant long-term decreases in July mean temperatures, and 8 stations had negative long-term trends (Table 1). Short-term trends provided more compelling evidence of a recent cooling effect, with all the stations except Grand Lake 1NW showing negative slopes for July temperatures. Some of these negative trends exceeded 2 °C/decade. Furthermore, the larger magnitude of these short-term trends indicates that rates of change have been much greater in the most recent past.

Additional evidence of regional cooling comes from data on forest seedling distributions. Data from the 584 10 m × 10 m plots showed 10,602 small seedlings, 6995 large seedlings, 679 saplings, and 5040 trees. We found no small seedlings of ponderosa pine, but small seedlings (typically $< 10$ years old) of the other five dominant species of conifers were distributed in lower-elevation, historically drier sites than mature trees of the same species (Fig. 4). The two environmental parameters correlated most closely with the species and life-stage distribution patterns are elevation (related to temperature) and growing season soil moisture (which integrates water availability, soil moisture holding capacity, and water losses through evaporation and transpiration). This suggests that environmental conditions at sites where seedlings of the five tree species have become established are cooler and wetter now than in the past.

Variability was high as expected for hydrological data, but the slopes of the regression equations were positive for the past half-century (Fig. 5), ranging from 0.140 $m^3 s^{-1}$ per cm summer precipitation for the Colorado River to 0.343 $m^3 s^{-1}$ per cm summer precipitation for the Laramie River. While the slopes were not statistically significant from zero, the trend in increasing runoff relative to precipitation inputs was consistent for the four major rivers in the study area. The slope for Boulder Creek was significantly positive (slope = 0.19 $m^3 s^{-1}$ per cm summer precipitation, $P < 0.033$, $r^2 = 0.075$) when run for the month of August.

## Discussion

The results of the mesoscale climate model simulations (Fig. 3) were consistent with coarser resolution RAMS simulations (60-km interval grid) for the coterminous United States that indicated that land use change caused July temperatures to decrease in the vicinity of the southern Rocky Mountains and increase in the eastern central Great Plains (Copeland *et al.* 1996a). Those coarser-resolution simulations also showed July precipitation to increase over the mountains of Colorado and decrease over the eastern Colorado plains under current landscapes compared to natural vegetation cover.

Both the local (plains) and remote (mountains) afternoon cooling effect suggested by RAMS simulations were rooted in changes in physical processes and interactions that occurred when dry, natural vegetation was replaced by irrigated and dry croplands, pasture, and landscaping. The main physical changes between natural and human-modified vegetation were decreased albedo, increased

**Table 1.** Long-term (> 45 years) and short-term (< 45 year) trends in mean July temperature in °C $y^{-1}$ for 16 Colorado weather stations in the study area (See Fig. 2a). Trends were evaluated through 1995 or 1996 depending on data availability. Statistical significance, P, of trends is reported (ns = not significant). Spicer is missing 1959 data, Red Feather is missing 1960 and 1961 data. Stations are numbered as in Figs 1 and 2. Holyoke, Statton, and Wray stations are just outside the modelled domain

| Station | Long-term trend (°C $y^{-1}$) | | Short-term trend (°C $y^{-1}$) | |
|---|---|---|---|---|
| 1. Boulder | –0.021 since 1931 | $P < 0.01$ | –0.065 since 1954 | $P < 0.001$ |
| 2. Byers | –0.010 since 1945 | NS | –0.016 since 1954 | NS |
| | | | –0.022 since 1963 | NS |
| 3. Cabin Creek | | | –0.079 since 1968 | $P < 0.001$ |
| | | | –0.226 since 1980 | $P < 0.001$ |
| 5. Estes Park | 0.007 since 1945 | NS | –0.068 since 1980 | $P < 0.2$ |
| 6. Fort Collins | 0.007 since 1945 | NS | –0.079 since 1974 | $P < 0.001$ |
| | | | –0.129 since 1984 | $P < 0.001$ |
| 7. Fort Morgan | 0.016 since 1945 | $P < 0.2$ | –0.122 since 1974 | $P < 0.001$ |
| | | | –0.251 since 1984 | $P < 0.01$ |
| 8. Grand L. 1NW | 0.006 since 1940 | NS | 0.041 since 1958 | $P < 0.01$ |
| | | | –0.101 since 1980 | $P < 0.05$ |
| 8. Grand L. 6SSW | –0.004 since 1948 | NS | –0.020 since 1962 | $P < 0.2$ |
| | | | –0.080 since 1977 | $P < 0.01$ |
| 9. Grant | | | –0.021 since 1964 | $P < 0.2$ |
| | | | –0.251 since 1984 | $P < 0.01$ |
| Holyoke | –0.036 since 1935 | $P < 0.001$ | –0.048 since 1954 | $P <0.002$ |
| | | | –0.131 since 1974 | $P < 0.001$ |
| 10. Parker | 0.008 since 1945 | NS | –0.080 since 1978 | $P < 0.05$ |
| 12. Redfeather | 0.022 since 1945 | $P < 0.05$ | –0.100 since 1979 | $P < 0.05$ |
| 13. Spicer Mt. | –0.030 since 1931 | $P < 0.001$ | –0.040 since 1951 | $P < 0.001$ |
| | | | –0.086 since 1980 | $P < 0.1$ |
| Stratton | –0.036 since 1935 | $P < 0.001$ | –0.075 since 1963 | $P < 0.001$ |
| | | | –0.162 since 1978 | $P < 0.001$ |
| 14. Walden | –0.005 since 1938 | NS | –0.025 since 1964 | $P < 0.1$ |
| | | | –0.073 since 1976 | $P < 0.02$ |
| Wray | –0.003 since 1935 | NS | –0.058 since 1963 | $P < 0.01$ |
| | | | –0.174 since 1974 | $P < 0.001$ |

roughness length, and increased soil moisture in irrigated regions. The lower surface albedo of the human-modified vs. natural surfaces increased total solar inputs, and greater surface roughness increased mechanical turbulence and so allowed greater surface exchange with the atmosphere. Together, these changes increased total energy and moisture fluxes from the surface to the atmosphere. This summer enhancement of transpiration and soil evaporation over irrigated areas resulted in a larger portion of solar inputs being partitioned into latent heat rather than sensible heat. Because the land surface transferred less heat directly to the atmosphere but more moisture, regions of cooler, moister air resulted which diminished the daytime plains-to-mountain circulation. This upslope circulation serves as a connection between the weather and climate of the plains and mountain regions and brought the colder, moister air to higher elevations. The elevated moisture fluxes increased convective available potential energy and atmospheric instability at higher elevations and enhanced daytime cloud cover in some regions. Increased cloudiness would further reduce daytime temperatures. Previous RAMS simulations showed that this increase in moisture and energy can increase the intensity of summer thunderstorms throughout the region (Copeland *et al.* 1996b).

The regional cooling effect suggested by the 16 weather stations (Table 1) was far more widespread than we had anticipated (three stations, Wray, Holyoke, and Stratton, were just outside the modelled domain but were included in Table 1 for completeness). Other investigators also have reported a cooler, wetter climate at high elevations in the Colorado Front Range (e.g. Niwot Ridge) and a warmer climate in the adjacent plains in the past 40 years (Greenland 1989; Kittel 1990; Williams *et al.* 1996). Station temperature data alone are not conclusive, however, because local microclimate effects and anomalies can be significant. This is illustrated by stations only tens of kilometres apart that have significant and opposite long-term trends. Nonetheless, taken together, most stations in the study area revealed a recent regional cooling (Table 1).

We found that the regional cooling effect also was evident in forest distribution patterns (Fig. 4). In the

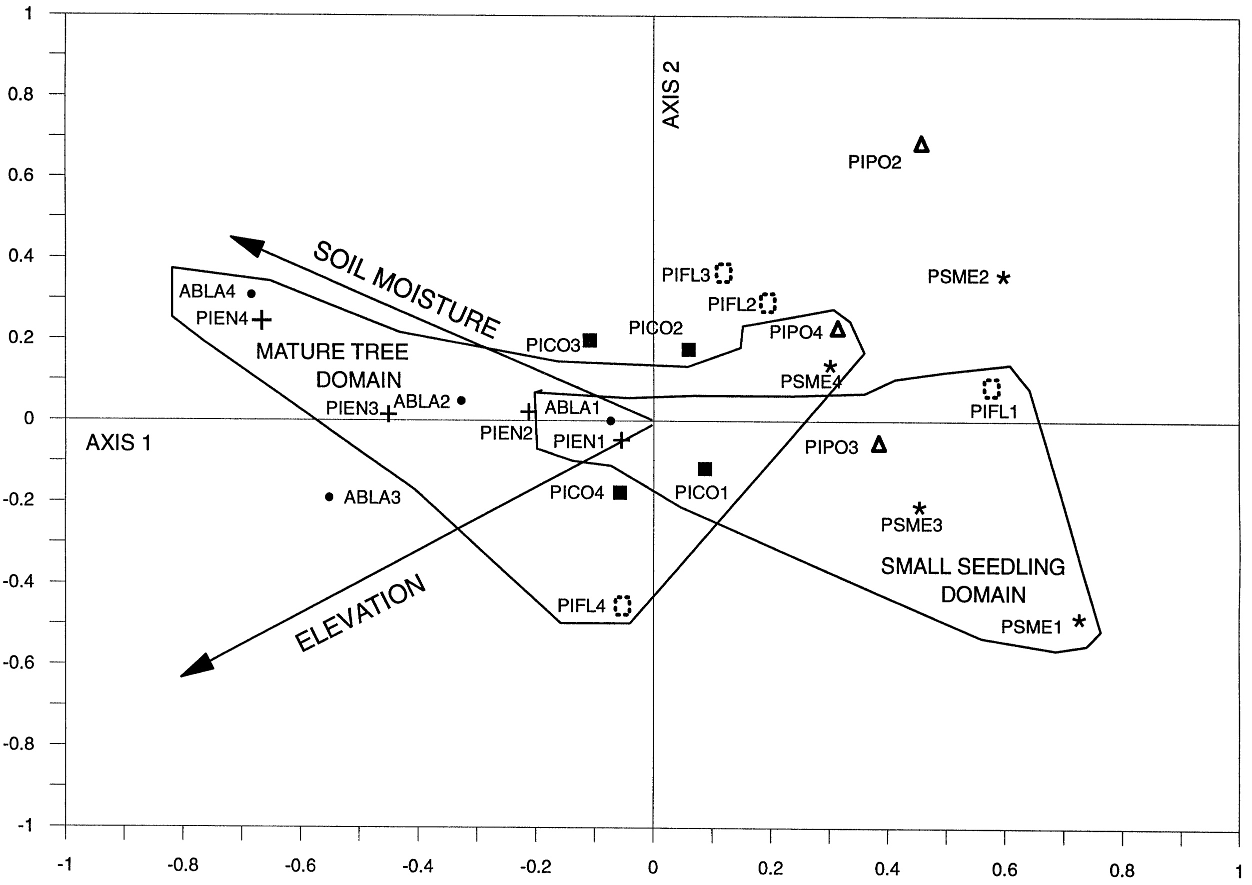

**Fig. 4** Canonical correspondence analysis (CCA) results. Centroids for each tree species' life stage are plotted by their CCA axes 1 and 2-values to show their respective domains in CCA axis space and with respect to dominant soil moisture and elevation gradients. Polygons encompassing either mature trees or small seedlings also are plotted. Forest species codes are: PIFL , limber pine; PIEN, Engelmann spruce; ABLA, subalpine fir; PICO, lodgepole pine; PSME, Douglas-fir; and PIPO, ponderosa pine followed by, 1 for small seedlings, 2 for large seedlings, 3 for saplings, and 4 for mature trees.

past, it has been difficult to assess vegetation change at landscape scales because most studies have focused on relatively small, homogeneous, stable environments (Stohlgren & Bachand 1997). By focusing on ecotones, our study design allowed a direct comparison of tree species distributions by life-stage (Stohlgren *et al.* 1997). Some of the changes in seedling distributions might be attributed to microsite conditions in forest openings, or to succession, particularly of spruce and fir seedlings into lodgepole pine forests or finding few ponderosa pine seedlings due to fire suppression. However, the consistent elevational shift in the seedling distributions of five dominant conifers toward lower elevations suggests a consistent regional cooling effect, and large seedlings and saplings of the six conifer species showed similar trends (Stohlgren *et al.* 1997).

We reasoned that if temperatures were cooler in the summer, then transpiration in a basin would be lower, and that this would be reflected in higher stream flow. This is suggested by the upward trend in stream discharge (normalized for summer precipitation) for all four rivers draining the Front Range study area (Fig. 5). High episodic, seasonal, annual variation in stream flow make it difficult to detect statistically significant trends in mountain watersheds. Stream flows are also complicated by watershed-scale processes such as herbivory, fire, insects outbreaks, or land use change. However, August discharge (normalized for August precipitation) for Boulder Creek showed a similar upward trend indicating a strong response to cooler temperatures, since the influence of spring snowmelt is usually gone by mid-July (Baron 1992). Together, the upward trends in stream flow consistently indicate decreasing transpiration losses in these high elevation watersheds, suggesting lower summer air temperatures. Greater runoff also may have resulted from lower spring and early summer temperatures which would have delayed snowmelt into midsummer.

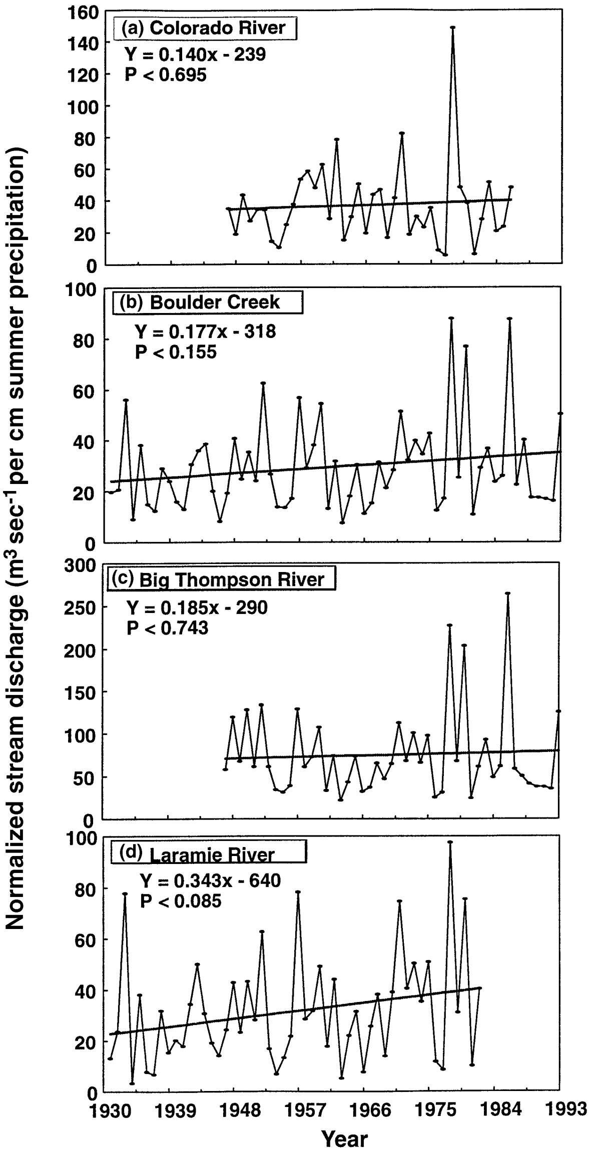

**Fig. 5** Summer stream discharge (from the U.S. Geological Survey Water Resources for Colorado Historical Surface Water Data Retrieval Server), normalized by summer precipitation inputs, from four river basins in the study area (a) Colorado River; (b) Boulder Creek; (c) Big Thompson River; (d) Laramie River; also see Fig. 1).

There are several caveats to the present research. First, RAMS simulations (Fig. 3a,b) generated regionally smoothed responses and were of limited duration. The run's high resolution was still not fine enough to match model outputs with point measurements of weather or vegetation. Short model runs may not reflect a longer-term climatological response. Second, local differences in observed climate trends cannot be ignored. For example, the two stations near Grand Lake have short-term trends that are significant and opposite (Table 1). This local variation along with patchy distribution of climate stations, especially at higher elevations, can make it difficult to discern regional patterns in climatic trends. Thus, we can not directly compare point data (i.e. average temperature data from weather stations; Table 1) to RAMS simulations (smoothed temperature maxima; Fig. 3) and the trends observed may be complicated by local or regional factors other than land use change. Third, the canonical correspondence analysis of forest distributions by life-stage (Fig. 4) integrates the effects of many other parameters and processes not measured here (e.g. light, competition, herbivory, resource use efficiency, disturbance history, dispersal mechanisms). Finally, hydrological runoff integrates snowmelt, seasonal precipitation, ground water storage, and evapotranspiration, making it difficult to partition water storage seasonally and annually into the various components.

Despite these caveats, the agreement of RAMS simulations, short-term regional temperature trends, forest distribution data, and stream discharge indicates that land use practices in the adjacent Great Plains may have a significant impact on the regional climate of the Colorado Front Range. The cooling trend at higher elevations indicated by the forest, temperature, and hydrological data coincided with the period of maximum alteration of natural vegetation at lower elevations along the Front Range and well into the plains, including human population growth of roughly 3%/year since 1950, associated expansion of rural and urban irrigated landscaping, and increased cropland irrigation. While land use practices such as irrigated agriculture have replaced natural vegetation in the region for over 100 years, the most significant changes along the Front Range have taken place in the past 30–40 years (Stohlgren 1997). We believe that the cumulative effects of land use may have exceeded a threshold whereby any long-term global warming trend to date could be overshadowed by a stronger, regional cooling effect forced by the alteration of natural vegetation (Table 1, Figs 3a, 4, and 5). An alternate explanation is that the regional cooling is coincidental but unrelated to land use in the plains, perhaps as a result of a changing south-west monsoon climatology. However, the mesoscale climate simulations suggest a mechanism by which changes in land surface properties influence climate of adjacent regions. Altered atmospheric-surface energy and moisture fluxes drive changes in mesoscale and regional circulation patterns that establish the distribution of temperature and precipitation in both the mountains and plains. The mechanisms in the RAMS simulations are logically simulated from a realistic portrayal of atmosphere–surface processes and mesoscale dynamics and are at a scale that allows validation with watershed and landscape-scale field observations.

There are several potential consequences of suggested regional climate changes arising from local land use change. In the Rocky Mountains, cooler summer temperatures and increased frequency and intensity of severe thunderstorms may influence recreational activities and tourism that feed local economies (Beniston & Fox 1996). Increased air pollution along the Front Range and increased moisture in the summer air could exacerbate air quality problems, especially visibility, in Rocky Mountain National Park (Baron & Denning 1993; Uliasz *et al.* 1996). Even slightly cooler temperatures and increased moisture in mid-summer may increase growth of grass understorey vegetation, and thus fuel availability, in lower-elevation, ponderosa pine forests thereby increasing the potential for lightning- or human-induced wildfires.

Additional research is planned to: (i) increase the length and resolution of the RAMS simulations; (ii) link climate, terrestrial, and hydrological models for the region to evaluate the joint land surface–climate response to altered regional and global forcing (Pielke *et al.* 1993; Baron *et al.* 1997a,b); and (iii) correlate weather data with tree ring records to further corroborate the results of this work. In addition to the influence of regional land use changes on regional climate, there is increasing evidence that local climate may be subject to climate change brought about by changes in vegetation and leaf area index associated with land use practices in other far-removed parts of the world (including deforestation, agriculture, and grazing; McGuffie *et al.* 1995; Chase *et al.* 1996). Understanding observed local trends in climate, vegetation, and hydrological patterns thus requires an integrated regional analysis of ecological, hydrological, and climatic dynamics that considers altered climate forcing driven by both regional and global anthropogenic changes to the land surface and atmospheric chemistry.

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