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Impacts of regional land use and land cover on rainfall: an overview

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Abstract This paper documents the diverse role of land-use/land-cover change on precipitation. Since land conversion continues at a rapid pace (e.g. see Table 1 in Pielke *et al.* 2006b), this type of human disturbance of the climate system will continue and become even more significant in the coming decades. The regional alteration of landscape also has global climate effects through teleconnections as concluded in NRC (2005); a conclusion which is bolstered by studies such as that of Chase *et al.* (2000) and Fedemma *et al.* (2005).

Key words land–atmosphere interactions; land-use/cover change; numerical modelling; rainfall/runoff; regional climate

INTRODUCTION

The role of landscape change in altering convective rainfall is well documented (e.g. Pielke, 2001; Pitman, 2003; Pielke *et al.* 2006a). This overview paper summarizes this topic by landscape conversion type focusing on how regional change results in changes in rainfall in the same area.

SHORT GRASS CONVERSION TO DRYLAND AGRICULTURE AND IRRIGATED AGRICULTURE

The conversion from native shortgrass grassland to cropland is manifested in biophysical effects that influence energy and water cycling. Seasonality of growing season, albedo, leaf area index, surface roughness, and moisture fluxes were altered with conversion to cropland. Cropland and grassland albedos are similar during the crop growing season (Oke, 1987), but croplands have bare soil for much of the year and native vegetation has a higher albedo than bare soil (Bonan, 2002). Dryland and irrigated crops are taller, and possess more leaf area than native shortgrass steppe (Paruelo *et al.*, 2001). Moreover, surface roughness is higher with taller agricultural plants (Chase *et al.*, 1999; Bonan, 2002). Lastly, moisture fluxes are higher in agricultural systems, especially irrigated croplands (Baron *et al.*, 1998; Stohlgren *et al.*, 1998; Chase *et al.*, 1999).

Growing season dynamics change with conversion to agriculture. With shortgrass steppe featuring a mixture of cool- and warm-season grasses, photosynthesis occurs during the entire growing season and peak biomass occurs in early summer (Paruelo *et al.*, 2001). In contrast, croplands have one dominant plant with dramatically different growing seasons and peak biomass, with dryland and irrigated crops peaking earlier and later than shortgrass, respectively (Paruelo *et al.*, 2001).

The effect on air temperature and precipitation produced with shortgrass conversion varies with the conversion, spatially and temporally. The magnitude of change from shortgrass steppe to irrigated agriculture is much more dramatic than the shift to dryland agriculture (Baron *et al.*, 1998). At relatively fine scales during short periods of the growing season, lower temperatures and higher atmospheric moisture levels are closely tied to irrigated croplands (Chase *et al.*, 1999; Segal *et al.*, 1989). At larger scales, given the same brief temporal scale, this difference produces a regional cooling effect and precipitation increase on the adjacent Rocky Mountains (Stohlgren *et al.*, 1998). At a coarse resolution (50-km grid increment) regional modelling comparison of natural and current vegetation change, Eastman *et al.* (2001) showed a 0–1°C increase in maximum temperatures over unconverted shortgrass steppe, while a 2–3°C increase occurred in areas converted to dryland crops. Precipitation changes were heterogeneous.

TALL GRASS CONVERSION TO DRYLAND AND IRRIGATED AGRICULTURE

The tall grass conversion is similar to the short grass conversion except the loss of aboveground biomass (leaf area index, LAI) is greater when the tall grass prairie was removed, and almost 100% of the original tall grass region is gone. Further studies on the role of grassland conversion include the initial evidence of the role of irrigation in modifying surface climate trends which came from observational studies (Marotz *et al*., 1975; Barnston & Schickendanz, 1984; Alpert & Mandel, 1986; Pielke & Zeng, 1989). Barnston & Schickendanz (1984) found that irrigation increased precipitation in the Texas Panhandle when the synoptic condition provided low-level convergence and uplift such that the additional moisture produced by irrigation was allowed to ascend to cloud base.

Adegoke *et al.* (2006) found that midsummer 2 m temperature over Nebraska might be cooler by as much as 3.4°C under current irrigation (control run) conditions as contrasted with natural landscape conditions. Energy budget differences were identified between current and potential natural vegetation scenarios: the surface latent heat flux was 42% higher, and the water vapour flux (at 500 m) 38% greater in the control run compared to the natural landscape run. Important physical changes between the natural tallgrass prairie of this region and the current land-use patterns include alterations in the surface albedo, roughness length, and soil moisture in the irrigated areas.

These changes are capable of generating complex changes in the lower atmosphere (planetary boundary layer, PBL) energy budget. For example, the simulated increase in the portion of the total available energy partitioned into latent heat rather than sensible heat resulted directly from enhanced transpiration and soil evaporation in the control run. Although not examined in detail in this study, elevated dewpoint temperature and moisture fluxes within the PBL can increase convective available potential energy, promote atmospheric instability, and enhance daytime cloud cover (Alapaty *et al*., 1997; Stohlgren *et al*., 1998; Pielke, 2001; Holt *et al*., 2006).

MID-LATITUDE DECIDUOUS FOREST CONVERSION TO AGRICULTURE

Asner *et al.* (2004) document that agricultural activities associated with grazing operations are an important driver for conversion from deciduous forest to grassland and pastures particularly under poor soil conditions. This conversion is surmised to have hydrological impacts by reducing the rate of spring snowmelt and cloud condensation levels and hence moisture availability, reducing moisture interception due to decreased LAI, increasing runoff and soil evaporation, and decreasing transpiration. This latter effect leads to higher soil moisture fluxes and discharge over the landscape, which causes erosion and poor soil conditions in the region. Typically, the change from forest to grasslands leads to a significant reduction in moisture flux, while a change to cropland can have variable influences on the regional moisture flux (because of crop photosynthetic pathways and transpiration rates, cropping patterns, irrigation, etc.).

Hogg *et al.* (2000) used field measurements over deciduous forest to demonstrate that the distinctive climate of interior western Canada is the feedback associated with the leaf phenology of the aspen forest. Latent heat fluxes are largest under high LAI conditions leading to cooling, but with the resultant higher concentrations of water vapour, moisture availability and precipitation increased. Xue *et al.* (1996) indicate that the LAI changes of deciduous vegetation cause regional changes and propagate high uncertainty into general circulation model (GCM) simulations. Bounoua *et al.* (2000) concluded that for the mid-latitude forest regions, the resulting impact of LAI changes was a decreased albedo, cooling of about 1.8°C during the growing season, and slight warming during winter due to snow albedo masking, decreased effective precipitation, and an increase in the low-frequency variability of weather in the northern latitudes. Baidya Roy *et al.* (2002) simulated a 300-year (1700–1990) time series of USA land use/land cover and found that changing land-use/land-cover patterns can lead to several degrees of warming or cooling at the surface accompanied by significant changes in precipitation patterns. Satellite products can detect this change following techniques similar to those discussed in Shepherd (2005) and Cai & Kalnay (2005) using blended re-analysis data sets.

TROPICAL EVERGREEN FOREST CONVERSION TO AGRICULTURE

Tropical forests, occupying approximately 800 million hectares, are being cleared at the rate of approximately 14 million hectares per year. Observational studies, spanning several decades, and numerical modelling studies both show that tropical deforestation influences cloud formation and rainfall (Sud & Smith, 1985; Meher-Homji, 1991; Cutrim *et al*., 1995; McGuffie *et al*., 1995; Costa & Foley, 2000; Lawton *et al*., 2001; Pielke, 2001; Silva Dias *et al*., 2002; Durieux *et al*., 2003; Sen *et al*., 2004; Fisch *et al*., 2004; Ray *et al*., 2006). Observational studies include Meher-Homji (1991), Pielke (2001), Durieux *et al.* (2003) and Ray *et al.* (2006). These studies report a wide range of changes in rainfall associated with deforestation (1–20% decrease), as well as the alteration of seasonality and frequency of convection. Regional-scale modelling results show that the eastern Asian summer monsoon is sensitive to deforestation in the Indochina region (Sen *et al*., 2004). Heterogeneity-induced mesoscale circulations have the potential to modify cloudiness (Souza, *et al.* 2000; Pielke, 2001; Silva Dias *et al*., 2002; Baidya Roy & Avissar, 2002; Werth & Avissar, 2002). Mesoscale numerical modelling experiments show that lowland deforestation and associated increases (decreases) in the Bowen ratio lead to elevation (lowering) of the orographic clouds forced by terrain downwind (Lawton *et al*., 2001; van der Molen, 2002; Nair *et al*., 2003; Bruijnzeel, 2004; Ray *et al*., 2006), leading to changes in the direct harvesting of cloud water by montane vegetation.

There is some indication that deforestation in a continent surrounded by oceans has more potential to impact tropical circulation compared to deforestation that is further removed from ocean sources of water vapour (van der Molen *et al*., 2006), and this needs to be validated through the use of cloud-resolving and regional modelling experiments.

BOREAL FOREST CONVERSION DUE TO FIRE

Fire in the boreal forest is an integral part of this ecosystem (Stocks, 1991). As shown in Vidale *et al.* (1997), mesoscale circulations develop in response to the spatial variations of surface sensible heat fluxes that occur due to these fires and other landscape pattern disturbances, which also include the lakes that are ubiquitous in the boreal forests. Knowles (1993) reported that cumulus clouds form preferentially downwind of recent burn areas within a boreal forest landscape. These burn areas have a lower albedo than the surrounding landscape. Such a preference also indicates that subsequent lightning strikes from deep cumulus clouds will more likely initiate fires immediately downstream of a recent burn scar, rather then elsewhere in the forest. After a period of time, as the forest regenerates, the burned area may be lighter than the surrounding unburnt landscape, as aspen and other secondary growth forest and shrubs grow.

The environment of the boreal forest, particularly in the spring, is very conducive to fires as the roots are embedded in cold, or even frozen soils, yet the air temperature and solar insolation at this time of year is high. Almost all of the net radiation received at the surface is transferred back into the atmosphere as sensible, rather than latent heat flux (Sellers *et al*., 1995). Pielke & Vidale (1995) show that one consequence of the resultant large heating of the atmosphere by the sensible heating is a particularly deep planetary boundary layer, as well as a preference for the summer polar front to often situate along the boreal–tundra ecotone boundary. The region south of the polar front in the spring (and also in the summer) is a weather location where thunderstorms occur. The spatial variations of the landscape will provide focused regions for thunderstorm development that would otherwise not occur.

URBANIZATION

While the fraction of the Earth’s surface currently classified as urban accounts for less than 2% of the available land surface, over 45% of the Earth’s population is concentrated there (Arnfield, 2003). Furthermore, future projections indicate this percentage will soon exceed more than 50% (Cohen, 2003). Observational studies over the past three decades have demonstrated that urban areas radically restructure the local energy budget and thus lead to different boundary layer structure (Shepherd, 2005; Arnfield, 2003; Oke, 1988). The anthropogenic influence also includes altering the aerosol environment. These changes likely lead to alterations in urban precipitation frequency, intensity, and patterns. Shepherd (2005) presents the most recent and complete review of urban precipitation issues.

Observational studies of urban precipitation stretches over three decades (e.g. Huff & Changnon, 1973). Studies in the USA have been mainly concentrated in three urban areas: St Louis, Atlanta, and Houston, and generally demonstrated increases in rainfall over and downwind of urban areas attributed largely to the Urban Heat Island (UHI) initiated convergence zone and to a lesser extent, increased surface roughness (Huff & Changnon, 1973; Huff, 1986; Bornstein & Lin, 2000; Dixon & Mote, 2003; Shepherd & Burian, 2003). Evidence also suggests an increase in heavy rain events (Huff, 1986). In addition, the UHI has been found to decrease the likelihood of freezing rain events in urban areas (Changnon, 2003). Bornstein & Lin (2000) also found urban influence on established thunderstorms approaching an urban area. Model studies have demonstrated significant changes to the convective boundary layer structure (e.g. Hildebrand & Ackerman, 1984; Baik *et al.*, 2001) and even influences on the behaviour of cold fronts (Gaffen & Bornstein, 1988).

A big unknown in the urban-induced precipitation problem is the role of urban aerosols. Studies like that of van den Heever & Cotton (2005) have begun to examine the relative sensitiveities involved, but as shown in Shepherd (2005), while evidence strongly points to a link between aerosols and urban precipitation modification, the details of the connection remain highly uncertain.

TROPICAL FOREST FIRES AND RESULTANT BIOMASS BURNING EFFECT ON RAINFALL

Biomass burning produces smoke plumes with large quantities of aerosols (tiny particles) which can potentially affect the regional, and even the global hydrological cycle (Ramanathan *et al.*, 2001). Aerosols serve as cloud condensation nuclei which effect the formation of cloud droplets (Cotton & Anthes, 1992); thus the extensive input of aerosols from fires could significantly affect cloud properties and rainfall. In addition to affecting cloud microphysics, aerosols absorb and scatter radiation. Increased aerosols in the atmosphere from forest fires reduce the radiative energy reaching the Earth's surface (Ramanathan *et al.*, 2001). Because surface radiative input drives evaporation, which is balanced with precipitation on a global scale, aerosol-induced reductions in surface radiation are likely to decrease global rainfall (Lohmann & Feichter, 2005).

Andreae *et al.* (2004) analysed Amazonian aircraft observations and found delays in the onset of precipitation within smoky clouds. Khain *et al.* (2005) show that while elevated aerosol concentrations initially lead to lowered precipitation efficiency due to warm-rain suppression, the delay in raindrop formation decreases the drag on updrafts by falling raindrops and increases the latent heat release by the additional water that reaches higher altitudes where freezing takes place.

Lin *et al.* (2006), based on satellite observations during the entire Amazonian biomass burning season, empirically confirmed the aforementioned results of Andreae *et al.* (2004) and Khain *et al.* (2005). Increased aerosols from fires were correlated with increased observed total (warm + ice-phase) rainfall from the TRMM-TMI sensor, even after accounting for the atmospheric stability environment through the cloud work function. Changes in cloud properties were also correlated with aerosol loading; i.e. higher cloud tops, increased presence of ice, and enhanced cloud cover.

AFFORESTATION AND REFORESTATION

Afforestation and reforestation (A&R) are proposed as possible tools to mitigate desertification (FAO, 1989) and to reduce atmospheric concentrations of CO_2 by sequestering carbon in forest biomass (UNDP, 2003). In southern South America, A&R plans commenced in Chile, Uruguay, and Argentina in the last two decades, supported through government economic incentives or subsidies (World Bank, 2000). In southwestern Australia, A&R are also seen as ways to ameliorate salinity (Walker *et al.* 2002).

Overall, conversion from grasslands or croplands to forest leads to a decrease in albedo and increases of LAI, roughness length, and rooting depth (Sellers, 1992; Pitman, 2003; Jackson *et al.*, 1996). Changes in these parameters can modify the near-surface energy fluxes, which can influence temperature and humidity (Pielke, 2001). In general, observations and modelling studies agree that A&R would decrease near-surface temperature and increase latent heat (e.g. Beltrán, 2005; Fahey & Jackson, 1997; Nosetto *et al.*, 2005; Xue & Shukla, 1996). Simulated impacts on precipitation are not so clear, and depend on geographical location, regional atmospheric characteristics, extent of the afforested–reforested area (Pitman & Narisma, 2005; Xue & Shukla, 1996) and biophysical parameters of the land-use/land-cover change (Xue *et al.*, 1996).

Observational (Jackson *et al.*, 2005) and several modelling studies (Beltrán, 2005; Xue *et al.*, 1996) demonstrated that tree plantation establishment may affect the hydrological cycle. Precipitation processes depend on local, regional, and large-scale atmospheric characteristics and therefore regional atmospheric modelling represents an important tool for studying the impacts of realistic patterns of A&R on precipitation. Moreover, model domain size, grid spacing, and parameterizations (e.g. convective schemes) may largely influence simulated precipitation (e.g. Castro *et al.*, 2005). Thus, more comprehensive regional modelling sensitivity studies are needed to assess those impacts.

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