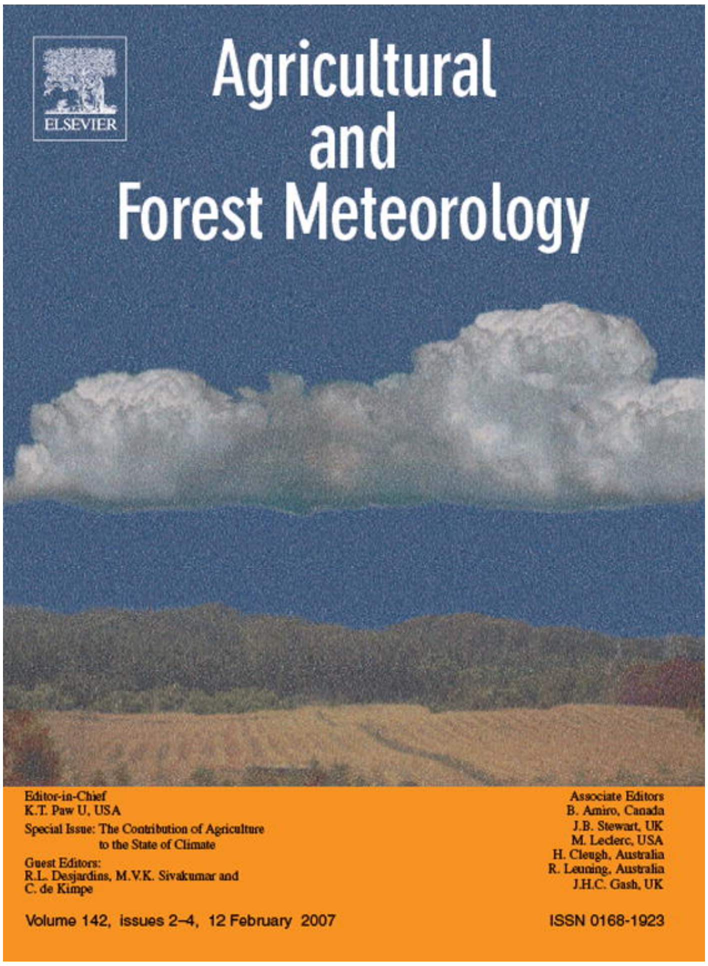

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A new paradigm for assessing the role of agriculture in the climate system and in climate change

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Abstract

This paper discusses the diverse climate forcings that impact agricultural systems, and contrasts the current paradigm of using global models downscaled to agricultural areas (a top-down approach) with a new paradigm that first assesses the vulnerability of agricultural activities to the spectrum of environmental risk including climate (a bottom-up approach). To illustrate the wide spectrum of climate forcings, regional climate forcings are presented including land-use/land-cover change and the influence of aerosols on radiative and biogeochemical fluxes and cloud/precipitation processes, as well as how these effects can be teleconnected globally. Examples are presented of the vulnerability perspective, along with a small survey of the perceived drought impacts in a local area, in which a wide range of impacts for the same precipitation deficits are found. This example illustrates why agricultural assessments of risk to climate change and variability and of other environmental risks should start with a bottom-up perspective.

Keywords: Climate change; Climate models; Climate impacts; Ecosystems, managed and natural; Mesoscale atmospheric circulations; Agroforestry

1. Introduction—the current paradigm

The approach generally used to investigate the role of agriculture in climate is to view climate as an external forcing. Crops respond to weather averages and extremes as represented by temperature and precipitation. This perspective views climate as long-term weather statistics. Farmers use quantities such as growing degree days and length of growing season to translate this weather information to information that they can act on.

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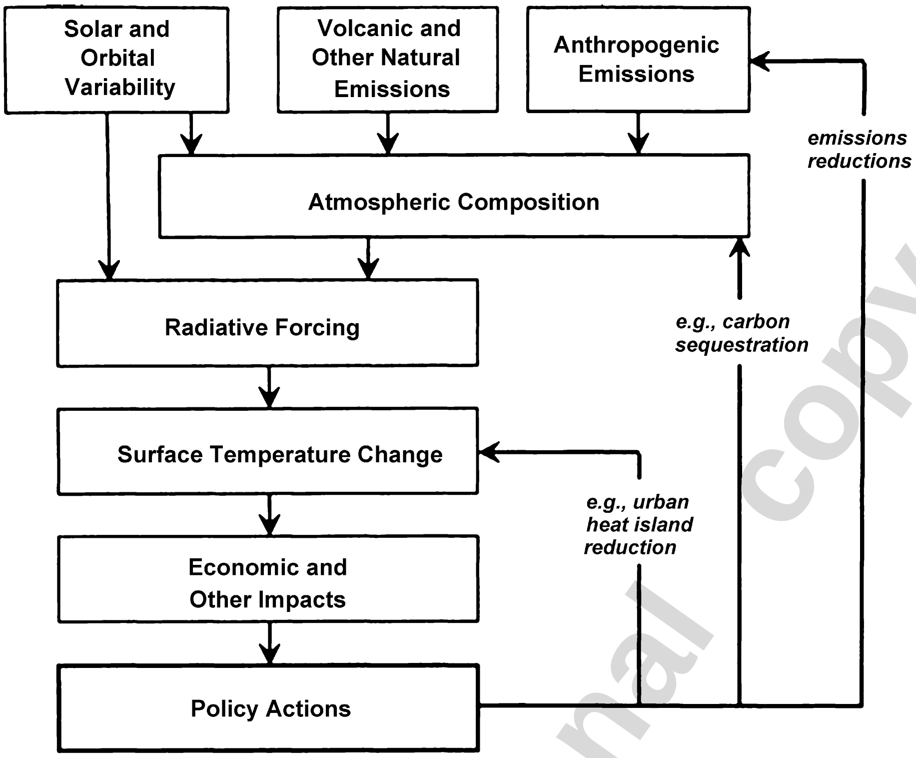


Fig. 1. Conceptual framework showing how radiative forcing fits into the climate policy framework (from National Research Council, 2005).

This view of climate as an external forcing is well represented in international and national reports on climate change, as illustrated by Houghton et al. (2001), and the National Assessment Synthesis Team (2001). The IPCC and U.S. National Assessment reports start from a large global perspective and work to downscale to regional and local impacts. The assumption is that if we can know atmospheric composition changes, we can predict the climate (i.e., the long-term weather statistics) decades into the future.

Houghton et al. (2001; their Fig. 3 in p. 8), illustrates the starting point for the global models applied to investigate human-caused climate change. Radiative forcing is the driving effect used to forecast the resultant response of the climate. As seen in their figure; however, there are large uncertainties in this global-averaged

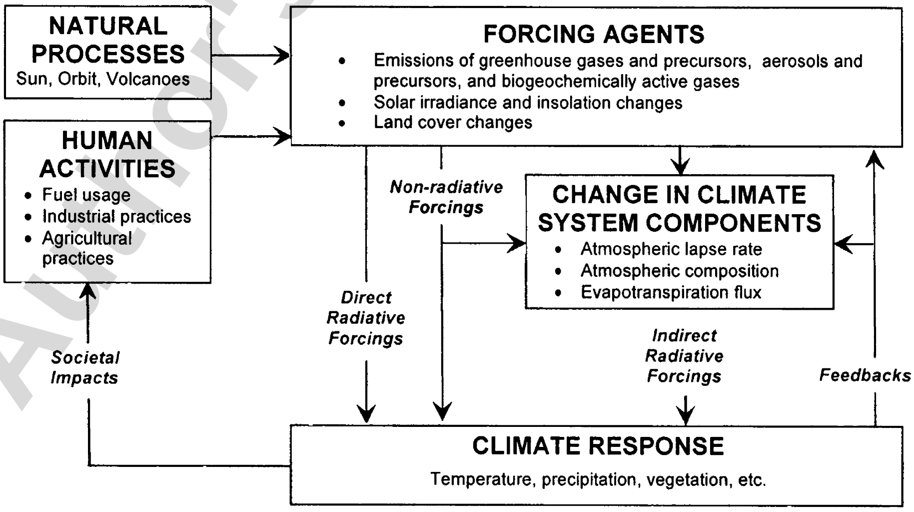


Fig. 2. Conceptual framework of climate forcing, response, and feedbacks under present-day climate conditions. Examples of human activities, forcing agents, climate system components, and variables that can be involved in climate response are provided in the lists in each box (from National Research Council, 2005).

forcing. Several of them are listed as having large uncertainties and of a "very low level" of scientific understanding. Regional variations in this radiative forcing are not considered in this paper.

Fig. 1 (from National Research Council, 2005) illustrates how global forcing is translated to regional and local agricultural impacts (represented by "other impacts" in Fig. 1). Starting with the global atmospheric or global atmospheric-ocean models, this is a *top-down perspective* where the large-scale forcing dictates the environmental impact. Typically, regional dynamic or statistical models are used to downscale the global model information to scales that can be used by the agriculture community. This is the procedure used, for example, by the U.S. National Assessment where regional agricultural impacts were defined for much of the 21st century based on this downscaling.

However, it is becoming increasingly recognized that climate is much more than long-term weather statistics and is a system that involves nonlinear physical, chemical, and biological interactions between the land, atmosphere, oceans, and continental ice sheets (Rial et al., 2004; Pielke, 2001a). The National Research Council (2005, their Fig. 1-1) illustrates this more complete description of the climate system. In this framework, agriculture is a component of the climate system. The involvement of agriculture in the climate system includes effects beyond its role in the emission and absorption of radiatively active gases (Fig. 2). The consequence of this broadening of our view of climate as centered on agricultural issues is the focus of this paper.

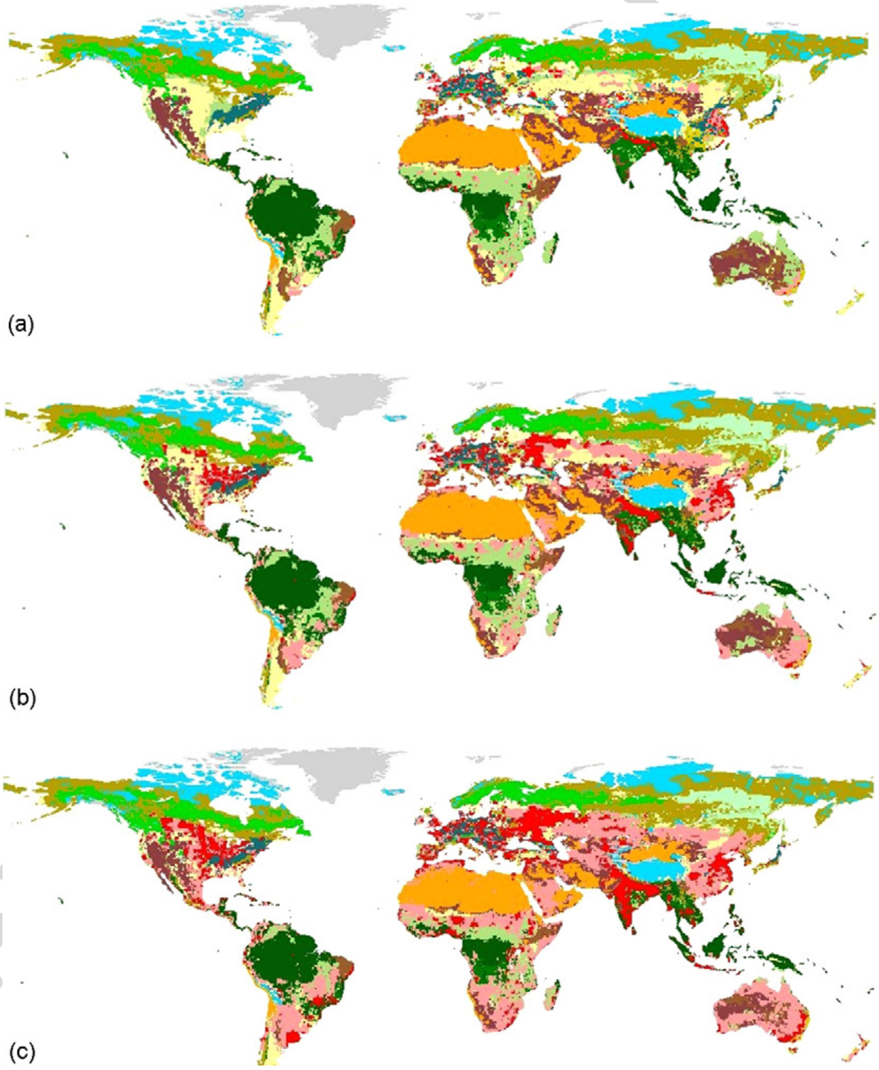


Fig. 3. Global estimate of land use and land cover for: (a) 1700, (b) 1900, and (c) 1990. The human-disturbed landscape includes intensive cropland (red) and marginal cropland used for grazing (pink). Other landscape includes, for example, tropical evergreen and deciduous forest (dark green), savannah (light green), grassland and steppe (yellow), open shrubland (maroon), temperate deciduous forest (blue), temperate needleleaf evergreen forest (light yellow), and hot desert (orange) (from Klein Goldewijk, 2001).

Table 1
Annual land clearing rate for 1999–2000 for countries clearing over 100,000 ha per annum

Country	Annual land clearing rate (ha)
Brazil	2,226,000
Indonesia	1,312,000
Sudan	959,000
Zambia	851,000
Mexico	631,000
Australia	564,800
Dem. Republic of the Congo	532,000
Myanmar (Burma)	517,000
Nigeria	398,000
Zimbabwe	320,000
Argentina	285,000
Peru	269,000
Cote d'Ivoire	265,000
Malaysia	238,000
Cameroon	222,000
Venezuela	218,000
Colombia	190,000
Bolivia	161,000
Ecuador	137,000
Angola	124,000
Paraguay	123,000
Ghana	120,000
Botswana	118,000
Madagascar	117,000
Nicaragua	117,000
Papua New Guinea	113,000
Thailand	112,000

From Australia Conservation Foundation (2001).

2. Expanding the concepts of climate forcing

2.1. Regional climate system

The global landscape has undergone enormous changes as human populations have grown. Fig. 3 illustrates the magnitude of this conversion from the natural to current landscape. India, for example, has transformed from a large forested subcontinent to vast areas of agriculture today. Western Europe and the mid-west of the United States bear little resemblance to their original landscape. As population has grown in the 20th century in the lower latitudes, this conversion has continued. Table 1 documents the rate of this conversion during the period from 1990 to 2000. O'Brien (2000) also summarizes the vast extent of these changes.

In this section, we present a brief historical overview of human impact on the natural environment and discuss recent research that has shown the influence on regional climate and climate change due to the conversion to an agricultural landscape. While there have been extensive studies of the role of agriculture as a source or sink of carbon dioxide and methane as influencing atmospheric concentrations of these greenhouse gases, there has been comparatively little discussion of its role as an integral part of the climate system in which the agricultural landscape influences weather directly both where the conversion has occurred and, through teleconnections, to locations that are far removed from the landscape conversion. In addition, we show that non-agricultural landscape change and other anthropogenic disturbances also influence agriculture.

2.2. Advertent and inadvertent land management

2.2.1. The historical context

The conceptualization of human-induced environmental change as part of habitat, economy, and culture has a long tradition. Count Buffon (1707–1788) can be regarded as the first western scientist to be concerned directly and intimately with the human impact on the natural environment (Glaken, 1963). In his role as curator of the French Royal Gardens and Museum, he produced many works, mainly concerned with natural history and Earth sciences. Count Buffon was also very involved with the domestication of plants and animals; one of the major transformations in nature brought about by human actions (Glaken, 1963). Studies of the streams of the French and Austrian Alps, undertaken in the late 18th and early 19th centuries, significantly deepened the realization of the human capacity to change the environment. Fabre and Surell studied the flooding, siltation, erosion, and diversion of watercourses brought about by deforestation in the Alps (Goudie, 1990). A recent study by Schneider et al. (2004) quantifies this effect. Comparable observations were made by the French historian, Volney (1804). He reported on several pertinent climate and hydrological observations made in Canada. Considerable interest in conservation, climatic change, and extinctions arose among European colonialists of North America, who witnessed some of the consequences of western-style economic development in tropical lands (Grove, 1990).

However, the extent of human influence on the environment was not explored in detail on the basis of sound data until George Perkins Marsh published *Man and Nature* (Marsh, 1864), a book acclaimed to be the most important landmark in the history of the role of humans in changing the face of the Earth (Goudie, 1990). In *Man and Nature*, Marsh dealt with human influence on the woods, waters, and sands. The following extract illustrates the breadth of his interests and the ramifying connections he identified between human actions and environmental changes:

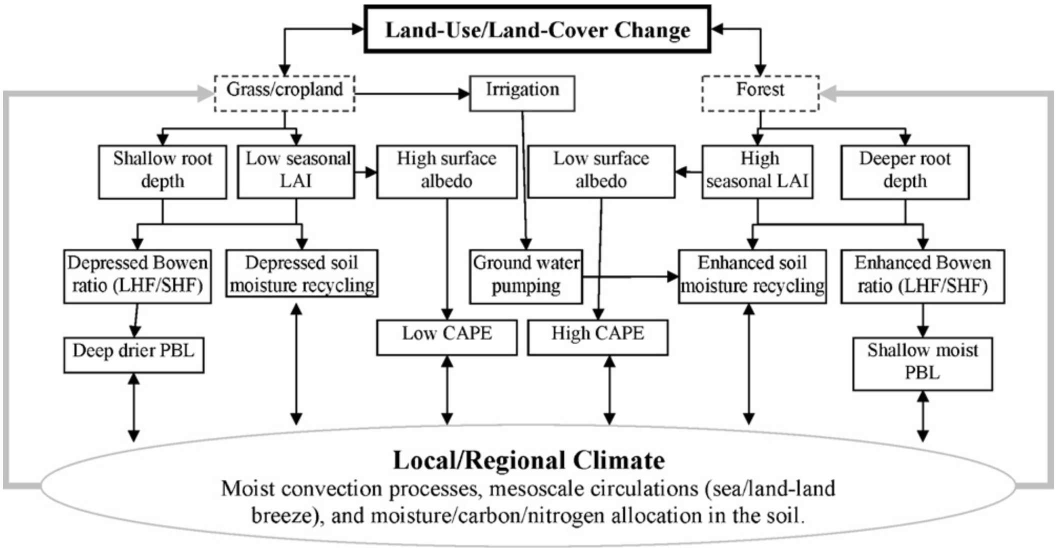


Fig. 4. Hypotheses of the influence of land-use/land-cover change on regional climate.

> “Vast forests have disappeared from mountain spurs and ridges; the vegetable earth accumulated beneath the trees by the decay of leaves and fallen trunks, the soil of the alpine pastures which skirted and indented the woods, and the mould of the upland fields, are washed away; meadows, once fertilized by irrigation, are waste and unproductive, because the cisterns and reservoirs that supplied the ancient canals are broken, or the springs that fed them dried up; rivers famous in history and song have shrunk to humble brooklets; . . . the entrances of navigable streams are obstructed by sandbars, and harbors, once marts of an extensive commerce, are shoaled by the deposits of the rivers at whose mouths they lie; the elevation of the beds of estuaries, and the consequently diminished velocity of the streams which flow into them, have converted thousands of leagues of shallow sea and fertile lowland into unproductive and miasmatic morasses” (Marsh, 1965, p. 9).

From a physical science standpoint, such large-scale anthropogenic landscape modification is important because it alters various physical properties of the land surface (e.g., albedo, surface roughness, leaf area index, and rooting depth), that have been shown to influence climate over a range of spatial and temporal scales (Pielke and Avissar, 1990; Pielke et al., 1998; Niyogi et al., 1999; Adegoke and Carleton, 2000; Adegoke et al., 2007; Oleson et al., 2004). In addition, agriculture-related land-cover conversion affects landscape heterogeneity, that observational and modeling studies show could affect the development of small cumulus clouds and potentially induce mesoscale circulations (Segal et al., 1988). In the following sections, we discuss specific examples of these impacts of land-use change on local and regional climate (Fig. 4).

2.3. Irrigation impacts on surface energy partitioning and summer climate in the U.S. high plains

The initial evidence of the role of irrigation in modifying surface climate trends came from observational studies (Marotz et al., 1975; Barnston and Schickedanz, 1984; Alpert and Mandel, 1986; Pielke and Zeng, 1989). Barnston and Schickedanz (1984), for example, 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. These studies were followed by regional-scale climate model investigations of the effect of irrigation on various PBL properties (De Ridder and Gallèe, 1998; Segal et al., 1998; Adegoke et al., 2003). Segal et al. (1998) used the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) (Grell et al., 1993) in their study of irrigated areas in North America. Their model results suggest an increase in the continental average rainfall for the present irrigation conditions compared with those of past irrigation. De Ridder and Gallèe (1998) used a European regional numerical model (Modele Atmospherique Regional) and reported a reduction in the diurnal amplitude of temperature and wind speed when a semiarid surface is replaced by a partly irrigated one. The potential for moist convection also increased with surface moisture availability in their simulations. The primary thermodynamic impact of irrigation is the repartitioning of the sensible and latent heat fluxes at the affected sites. Thus, an increase in irrigation or surface wetness reduces sensible heat flux while increasing physical evaporation and transpiration (Pielke, 2001b). The resulting additional moisture flux can enhance the moist static energy within the convective boundary layer (CBL) and consequently become thermodynamically more conducive to an increase in rainfall (Betts et al., 1994; Segal et al., 1998).

In Nebraska, as in much of the U.S. high plains, corn is the dominant crop cultivated during the warm season months (Williams and Murfield, 1977). Irrigated corn, which represented about 10% of total corn-producing areas during the early 1950s, now comprises nearly 60% of the total corn-producing areas in Nebraska (National Agricultural Statistics Service, 1998). This rapid land-use change was achieved largely by converting rain-fed corn areas to irrigated areas. To investigate the likely impacts of this agriculture-related land-use change on surface energy partitioning and summer climate, we conducted a modeling study consisting of four land-use scenarios over the 15-day period from 1 to 15 July 1997. The first scenario (control run) represented current farmland acreage under irrigation in Nebraska as estimated from 1997 LANDSAT satellite and ancillary data. The second and third scenarios (OGE wet and dry runs) represented the land-use conditions from the Olson global ecosystem (OGE) vegetation dataset, and the fourth scenario (natural vegetation run) represented the potential (i.e., pre-European settlement) land cover from the Küchler vegetation dataset. In the control and OGE wet run simulations, the topsoil of the areas under irrigation, up to a depth of 0.2 m, was saturated at 0000 UTC each day for the duration of the experiment (1–15 July 1997). In both the OGE dry and natural runs, the soil was allowed to dry out, except when replenished naturally by rainfall. The 'soil wetting' procedure for the control and OGE wet runs was constructed to imitate the center-pivot irrigation scheduling under dry synoptic atmospheric conditions, as observed in Nebraska during the first half of July 2000 (i.e., when little or no rainfall was recorded throughout the state). The observed atmospheric conditions from NCEP reanalysis data (Kalnay et al., 1996) were used to create identical lateral boundary conditions in the four cases (see Adegoke et al., 2007, for additional details on the experimental design).

A key finding of this study is that mid-summer 2 m temperature over Nebraska might be cooler by as much as 3.4 °C under current conditions. The domain-average difference between the control and OGE dry runs computed for the 6–15 July 2000 period was 1.2 °C. The cooling effect and the surface energy budget differences identified above intensified in magnitude when the control run results were compared to the potential natural vegetation scenario. For example, the near-ground domain-average temperature was 3.3 °C cooler, the surface latent heat flux was 42% higher, and the water vapor flux (at 500 m) 38% greater in the control run compared to the natural landscape run. Important physical changes between the natural shortgrass 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 (PBL) energy budget. For example, the simulated increase in the portion of the total available energy being partitioned into latent heat rather than sensible heat resulted directly from the 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 convectively available potential energy (CAPE), promote atmospheric instability, and enhance daytime cloud cover (Alapaty et al., 1997; Stohlgren et al., 1998; Pielke, 2001b; Douglas et al., 2006; Holt et al., 2006).

2.4. Simulated impacts of anthropogenic land-cover change on the mesoscale climate of the Florida Peninsula

Mankind has dramatically transformed the land cover on the Florida Peninsula. Much of the land-cover change on the Peninsula resulted from the advent of large-scale agricultural production during the 20th century. Today, agricultural production is a mainstay of the Florida economy. During 2002, Florida ranked first in the United States for cash receipts of citrus crops, and either first or second for several fresh fruit and vegetable crops, including tomatoes, strawberries, snap beans, squash, sweet corn, bell peppers, watermelons, radishes, and avocados (FDACS, 2002). By some estimates, more than half of the fresh vegetables consumed by Americans during the core winter months are harvested in south Florida (Hansen et al., 1999). As Fig. 5 shows, the extent of natural wetlands within the Everglades and the Kissimmee River Basin has been reduced significantly by agricultural development.

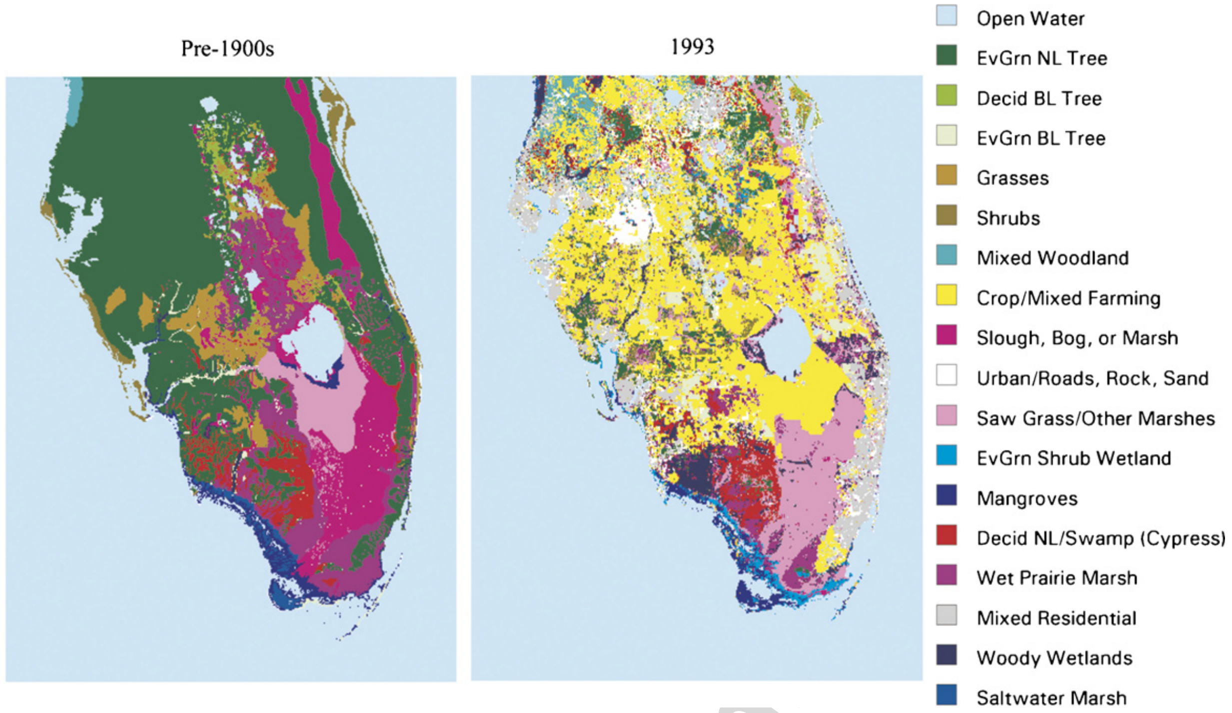


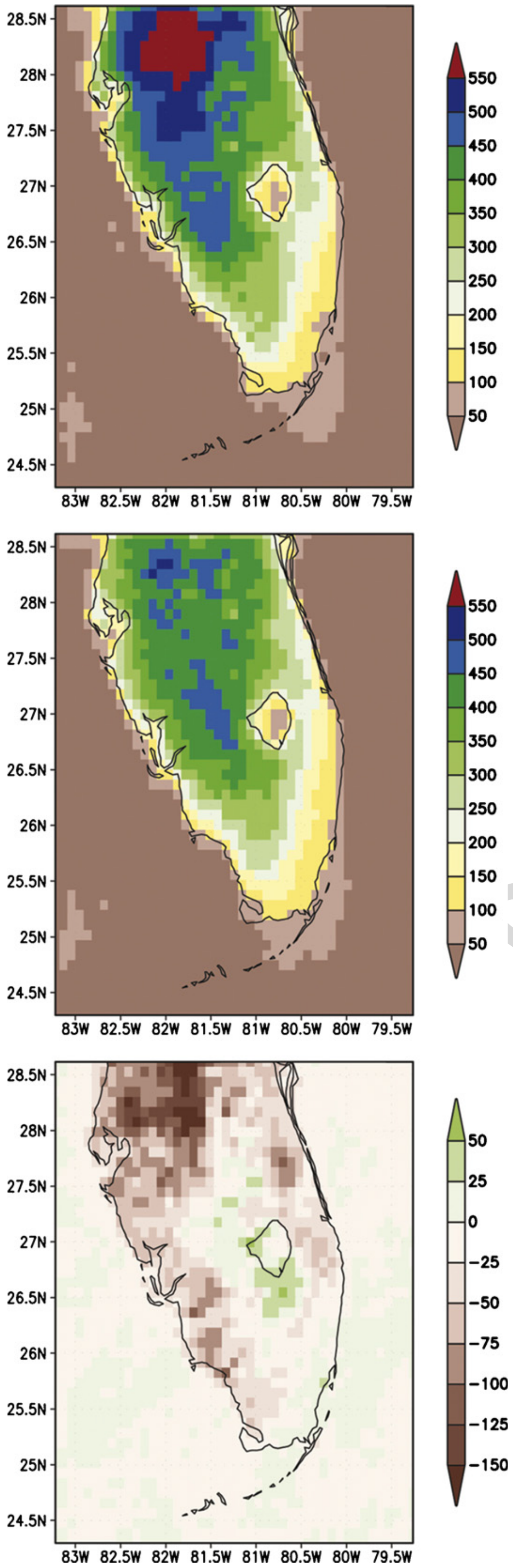
Fig. 5. U.S. Geological Survey land-cover classes for pre-1900s natural conditions (left) and 1993 land-use patterns (right) for Florida in the SE United States (from Marshall et al., 2003).

Across the remainder of the Peninsula, large areas of natural pine forestland were cleared to make way for agriculture during the 20th century.

Marshall et al. (2003, 2004a,b) presented the results of studies that were designed to explore the impacts of changes in land cover on the mesoscale climate of the Florida Peninsula. In these studies, the land-surface parameterization of the regional atmospheric modeling system (RAMS) was configured with the two separate land-cover datasets illustrated in Fig. 5. Pairs of simulations of recent weather were produced, wherein one member of each pair used the current land cover, while the other used the natural land cover. The results with a given pair of simulations were compared in order to ascertain the impact of anthropogenic land-cover change on the regional climate.

Marshall et al. (2004a) produced pairs of simulations with the RAMS model for the July–August periods of three recent years (1973, 1989, and 1994) in order to ascertain the impacts of land-cover change on several aspects of warm season weather, with a particular focus on the sea breezes and their associated rainfall. Their results suggest that the replacement of the wetlands along the central axis of the peninsula (particularly along the Kissimmee River Basin) by agricultural land resulted in a weakening of the sea-breeze circulations during the 20th century. This weakening, in turn, resulted in a reduction in regional-average rainfall during the warm season. In simulations with the natural land cover, the interior axis of wetlands served to generate a divergent mesoscale wind, which reinforced the convergence associated with the sea-breeze fronts along both the east and west coasts of the Peninsula. When these wetlands were drained, the reinforcement associated with the mesoscale divergence was lost. The impact on the distribution of warm-season rainfall is shown in Fig. 6. The top panel shows the 2-month total rainfall for the period July–August 1994 when natural land cover was used in the RAMS model, and the middle panel shows the total when current land cover was used. The bottom panel provides the difference field (current minus natural total). Along the coasts, where the sea-breezes are located on typical afternoons during the warm season, rainfall was reduced when current land cover was used in the simulation. Along the Kissimmee River Valley, where the divergence present in the natural land-cover case was lost when the current land cover was used, rainfall increased. When averaged over the model domain, the regional-scale rainfall was decreased by more than 10% when current land cover was used in the simulations.

These results were remarkably similar for all three warm season periods that were simulated (results not shown here). The results were also consistent when the model configuration was subjected to a number of important sensitivity factors, including the



parameterizations for radiative transfer and cumulus convection. In essence, these results provide evidence that the advent of agricultural production on the Florida Peninsula may have contributed to a significant decrease in warm-season rainfall across the region during the 20th century.

Marshall et al. (2003, 2004b) extended their studies to assess the impacts of land-cover change on the peninsula on cool season weather, and in particular, the possible impacts on the occurrence and severity of agriculturally damaging freezes in south Florida. Using the same experimental design described above, three recent freeze events that resulted in significant damage to crops in south Florida were simulated. These freeze events occurred on 26 December 1983, 25 December 1989, and 19 January 1997. The latter event was poorly forecast. The lack of implementation of freeze protection measures resulted in severe crop damage, with the near-total loss of crops in the fresh vegetable production area immediately south of Lake Okeechobee. Economic losses were near US $300M, and nearly 100,000 migrant farm workers became unemployed. The RAMS simulation of this event with agriculture (i.e., the current land cover) specified for those areas reproduced the freeze event. Temperatures near ground level fell below 0 °C for more than 5 h. However, when natural land cover was specified, with wetlands present at these locations, freezing conditions did not develop.

Physically, these results are not surprising. In this situation, the larger-scale meteorological conditions were barely supportive of freezing temperatures near ground level. With standing water present on the surface, the loss of infrared radiation during the night hours would be less than with dry land present. The model results suggest that the presence of standing water could have been sufficient in this case to altogether prevent the development of what was otherwise a devastating agricultural freeze.

Interestingly, agricultural development in the wetlands of far south Florida was accelerated during the 20th century in order to relocate crops from areas farther north, precisely for the purpose of escaping the risk of damaging freezes. These results suggest the ironic possibility that in the attempt to escape that risk, the advent of agricultural production in south Florida may have increased the risk of damaging freezes in this

Fig. 6. Accumulated convective rainfall (mm) from the model simulations of July–August 1994 with pre-1900 land cover (top), 1993 land use (middle), and (bottom) the difference field for the two (1993 minus pre-1900 case) for Florida, in the SE United States (from Marshall et al., 2004a).

region. In a broader sense, these results provide a unique example – with significant socioeconomic implications – of how agriculture and regional climate are part of a coupled physical system. Similar manifestation of changes in the climate system with the transformation of the forestland to croplands is seen in different parts of the globe including the Amazon (Werth and Avissar, 2002). The widespread land-use change in the Amazon and parts of southeast Asia also result in biomass burning as a means of clearing the landscapes. This indirect effect of the agricultural and farming practices on the climate systems is discussed in the following section.

3. Aerosol effect on clouds and precipitation

Changes in cloud-precipitation processes due to anthropogenic activities are vital information for the agricultural community. Over the last decade, it has become increasingly recognized that carbonaceous and mineral aerosol emitted from agricultural practice modulates cloud-precipitation process and associated hydrological cycle (Ramanathan et al., 2001; Fig. 7).

The burning of forest, grasslands, and agricultural field after the harvest or for development of agricultural land are traditional practices in many of the tropical regions. Emerging space-born satellite monitoring system and extensive studies have uncovered that biomass burning is much more extensive than previously believed (Levine, 1991). The presence of a greater concentration of hygroscopic aerosols increases the concentrations of cloud condensation nuclei (CCN) and, narrows the size spectra of cloud droplets. As a result, clouds with smaller droplet sizes reduce the efficiency of the collision and coalescence process of liquid droplet that is the vital rainfall generation process (see the detailed review in Hobbs, 1993). Measurements from the advanced very high resolution radiometer (AVHRR) sensor captured that biomass-burning smoke reduces the droplet effective radius below the drizzling threshold over the Amazon Basin (Kaufman and Fraser, 1997) and across Sumatra, Indonesia (Rosenfeld and Lensky, 1998). Rosenfeld (1999) used the tropical rainfall measuring mission (TRMM) visible/infrared-microwave-radar ensemble sensors to document that biomass-burning events shut off the warm rain process in deep cumulus convection over Kalimantan Island, Indonesia. On the other hand, heavy absorbing aerosols, such as smoke and mineral dust, could contribute to large diabatic heating in the boundary layer that (i) evaporates the shallow cloud or (ii) stabilize the boundary layer which suppresses cloud development (Ackerman et al., 2000). Koren et al. (2004) found that smoke from the biomass burning diminished the trade cumuli that typically appear in the morning over the eastern Amazon Basin.

While a smoke plume from biomass burning is directly linked to agricultural practices, mineral aerosol from dust storms can be indirectly attributed to poor agriculture practices. Thousand years ago, an emergence of irrigation in the Middle East (18th century BC) substantially increased the yield of crops. After a long-time period;

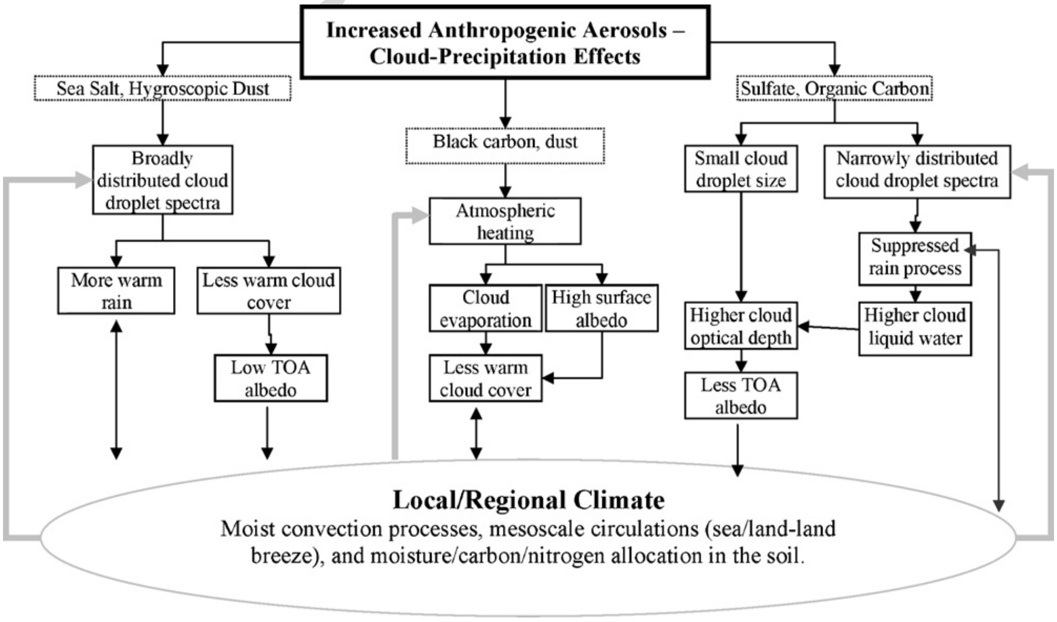


Fig. 7. Hypotheses chart of aerosol–cloud interaction.

however, excess irrigation and high evaporation transformed the productive alluvial plains into an unproductive salt desert, which now covers a large part of Iraqi (Dale and Carter, 1955). Overgrazing is another major cause of desertification worldwide (e.g., National Research Council, 1992). N'Tchayi et al. (1997) showed that a frequency of dust occurrence from 1957 to 1987 is positively correlated with rainfall anomalies over the Saharan region. Rosenfeld et al. (2001) found that dust storms contain many finer particles coated with sulfate that can inhibit precipitation over the Sahel, and hypothesized that desertification has a detrimental impact on the rainfall due to increased CCN from enhanced dust emissions.

Dunion and Velden (2004) examined the Saharan air layer and tropical cycle activity using the multispectral geostationary operational environmental satellite (GOES), and found that the Saharan dust layer could weaken Atlantic tropical cyclone activity. Matsui et al. (2004) compared the TRMM-derived cloud-top and column droplet effective radius to judge whether warm rain exist or not, and statistically show that warm rain processes are shut off elsewhere downwind of continents due to a high concentration of aerosols and strong boundary layer caps.

To summarize, historical agricultural activities have directly and indirectly increased the amount of carbonaceous and mineral aerosol emissions, which can modulate the local/regional hydrological cycle by suppressing the warm rain process. Therefore, it could have a detrimental feedback to agricultural productivity.

4. Direct/diffuse solar irradiance change due to aerosols

The agricultural landscape can also interact with the climate system via a biogeophysical pathway. For instance, there is growing evidence there is a generally positive trend for aerosols and cloudiness (Stanhill and Cohen, 2001; Schwartz, 1996) and that the radiation reaching the Earth's surface is diminishing. Understanding the changes in the radiation at the 'top of atmosphere' (TOA) have been important for climate change studies.

Recent assessments including the National Research Council (2005) report on the radiative forcing of climate change conclude that changes in surface radiation and their interaction with the land surface could have an even more critical effect on the surface energy balance and hence regional climate. The interaction between aerosols, clouds, and the terrestrial environment can modify the redistribution of radiative forcing, and also affect the integrated climate via biogeochemical pathways. In this section, we discuss the nature of these changes and the interaction with the agricultural landscape in potentially altering regional climate.

4.1. Diffuse radiation feedback with the terrestrial biosphere

A number of studies (Roderick et al., 2001; Gu et al., 2002, 2003; Law et al., 2002; Farquhar and Roderick, 2003; Reichenau and Esser, 2003; Niyogi et al., 2004, 2006a) have conducted analyses of the effect of changes in surface radiation on terrestrial biosphere response. These leaf and canopy scale measurements show that the photosynthesis (carbon assimilation) rate increases with increasing irradiance, until the irradiance reaches a threshold 'photosaturation level'.

Radiation levels from direct light can reach photosaturation levels (typically above 500 W m^{-2}) more routinely, as compared to diffuse radiation which is often too small. The implication of this is as follows. The total canopy photosynthesis is a sum of the photosynthesis from sunlit and shaded leaves. When the diffuse radiation increases on the shaded leaves, the total canopy photosynthesis increases (and will continue to do so until the diffuse radiation exceeds the photosaturation level).

This feature, which was first seen at leaf and canopy scales, has been observed at landscape and regional scales. Thus an increase in the diffuse radiation (or changes in the diffuse to direct radiation ratio: DDR) can alter the photosynthesis (carbon assimilation) and transpiration (water vapor flux) rates of the landscape (Fig. 8). The reason for the consistent increase in the CO_2 fluxes with increasing diffuse radiation fraction appears to be that a larger fraction of the vegetation canopy participates at a higher level in its interaction with the radiative flux (Campbell and Norman, 1998).

4.2. The cloud versus aerosol feedback on diffuse radiation changes

Diffuse radiation can increase because of higher cloudiness and/or increasing aerosol loading such as from biomass burning. Are there any differences on the landscape feedback whether the DDR change is cloud or aerosol induced? Niyogi et al. (2004) addressed this question by providing the first multi-site analysis using direct measurements of net ecosystem CO_2 exchange (NEE) from the AmeriFlux network over forests, grasslands, and agricultural fields (C3 and C4 crops).

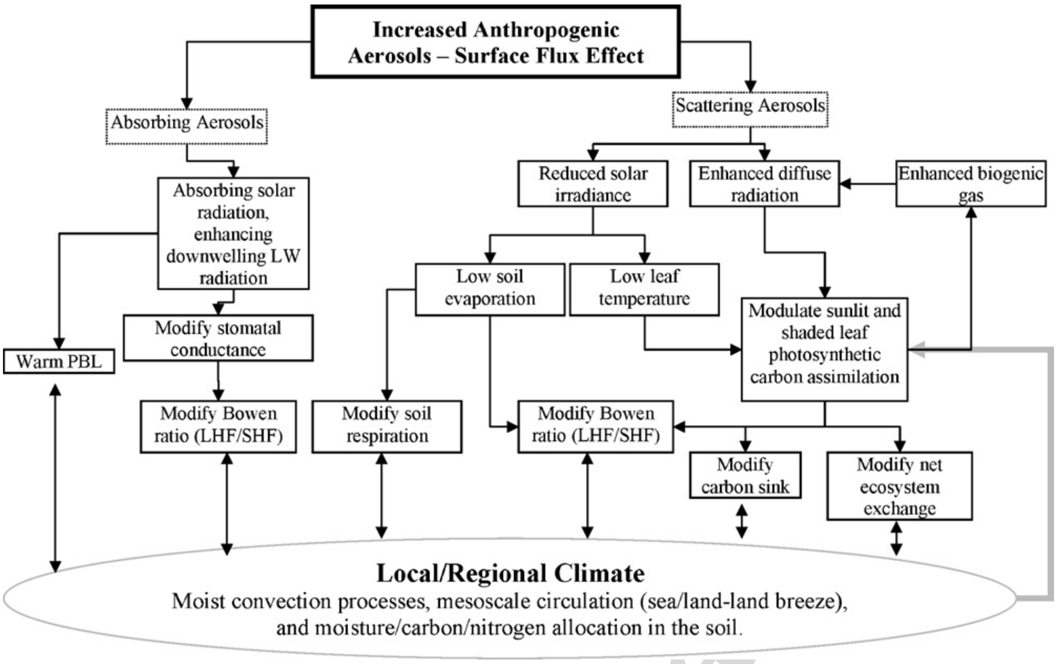


Fig. 8. Hypotheses chart of aerosol–surface flux interaction.

Their results indicated that aerosols can routinely influence surface radiative fluxes and hence the terrestrial CO_2 flux and regional carbon cycle. In addition, although larger cloud cover leads to an increase in the DDR, there is a concurrent decrease in the total radiative flux, which can reduce the rate of carbon assimilation. However, under 'clear' sky conditions and high aerosol loading, the total radiative flux still remains relatively large, as seen from their dataset (e.g., Garrison, 1995; Jacovides et al., 1997). The aerosol loading effect could be more important than the effects of clouds in terms of its role in modulating the regional terrestrial carbon cycle.

Niyogi et al. (2004) also indicates that the effect of aerosols, and global dimming or DDR increase, would be different depending on the landscape. For forests and croplands, increasing aerosol loading resulted in increasing NEE, while for grasslands this translated in lowered NEE. The main reasons for these differences are related to the canopy architecture and the photosynthesis pathways. The changes in land use associated with the conversion of grasslands to productive agricultural landscapes could have an equally important dynamic feedback on the biogeographical climate forcing of the region as compared to the changes from forests to agricultural croplands. Thus, aerosols appear to be more important than clouds in altering the biospheric responses, and the agricultural landscapes could interact in a complex manner on reallocating the carbon and biogeochemical fluxes.

4.3. Role of aerosols on radiative energy redistribution

Aerosols are abundant in the environment as both natural dust particles as well as anthropogenic residues of combustion or other energy production-related activities. The direct effect of aerosol loading in the environment is on atmospheric radiation. Ramanathan et al. (2001) showed that aerosol layers in the atmosphere caused divergence in the heating and cooling rates of the lower troposphere over the Indian Ocean. The impact of aerosols on the redistribution of the radiation at the top of the atmosphere is relatively well understood, but its effect on the tropospheric lapse rate and surface temperatures is relatively unknown.

Transpiration is implicitly linked with photosynthesis and the carbon exchange over terrestrial landscapes, including, of course, agriculture. Therefore, changes in the photosynthesis rates and the regional NEE could also translate into changes in regional water loss via changes in transpiration. Chang (2004) and Niyogi et al. (2006a) sought to address this hypothesis. Since transpiration measurements are relatively rare at field scales, the analysis had to be performed using latent heat flux measurements that are routinely available from sites such as AmeriFlux.

Their results indicate that aerosol loading can alter the surface latent heat flux and the redistribution of the radiative energy reaching the surface. Interestingly, the relation between aerosol loading and latent heat flux changes was not as significant as compared to that seen for NEE. This was expected, as latent heat flux is known to depend on various environmental factors such as soil moisture, air temperature, vapor pressure deficit, vegetation type, etc. Additionally, in their study the majority of the results indicated that the effect of increasing aerosol loading would cause a relative decrease in the surface latent heat flux.

There are two potential reasons for the energy redistribution with increasing aerosol loading: (i) an increase in transpiration as a response to increased DDR, and a corresponding smaller decrease in soil evaporation, and (ii) an increase in the surface albedo as a feedback of soil moisture, and possibly wavelength shifts between the incoming and reflected radiation. Both these effects could be verified with observations (Niyogi et al., 2006a), and provide evidence that the integrated climate change assessment would need to consider the role of aerosols as a modulator of biogeochemical forcing (via NEE changes), radiative redistribution of the surface energy flux (via Bowen ratio changes), and a potential for warming or cooling as a feedback to the aerosol loading.

The uncertainty of the aerosol loading could be more significant on the agricultural systems, where the leaf area index (LAI) changes are seasonal and there can be complex radiation – temperature – and moisture interactions that may be difficult to generalize as compared to forests or grasslands. This is important in that with increasing LAI, it can be hypothesized that the photosynthesis and transpiration will be radiation dominated instead of temperature dominated. Therefore, the question can be posed whether the magnitude and type of aerosol loading and as they interact with the wavelength spectra of the sunlight also matters in understanding the aerosol – surface radiation – terrestrial biosphere feedback. There are still no conclusive field analyses for this question.

However, it is apparent that aerosols directly modulate global irradiance by increasing diffuse radiation by scattering and absorption of solar radiation, which is determined by the aerosols' chemical composition and particle size distribution and shape.

Synthesis of past observations and modeling studies; however, do indicate some results to be probable, and are listed below. First, the effect of aerosols on the land surface appears to be responsive to both radiation as well as temperature and humidity changes. This would suggest that sulfate aerosols, which would contribute to increase DDR, would have a different feedback on the vegetation as compared to the carbonaceous aerosols, which are prone to absorbing radiation and altering the atmospheric temperature.

Synthetic studies such as Yu et al. (2002), can be used as guidance on the role of sulfate versus carbon aerosol loading and the relative changes possible within the DDR, air temperature, relative humidity, and surface energy balance and NEE changes.

Aerosols can diminish surface radiation, inhibiting sensible and latent heat flux, and induce feedbacks such as the enhanced stratification and changes in relative humidity (Niyogi et al., 2006c). It is expected that the modifications to the surface energy distribution can affect the PBL structure and evolution resulting from the direct impact of aerosols on atmospheric radiation which, in turn, affect aerosol life cycle, the distribution, concentration, and the chemical and physical properties of aerosols. Changes in relative humidity and thus liquid water content can affect chemical oxidation reactions on the surfaces of aerosols, and can lead to changes in the chemical production of other chemical species. The surface–atmosphere interaction can also affect surface and PBL relative humidity and its effects on the optical properties of aerosols through hygroscopic growth.

Second, the aerosol size distribution could affect the biospheric response with the larger aerosols contributing to scattering the light and thus increasing the transpiration and photosynthesis rates, while very fine aerosols could deposit on the leaf surface and reduce the potential for carbon and water vapor exchange. This needs to be studied further and will have important ramifications with regards to understanding and reproducing the effects of aerosol versus temperature effects on regional productivity, and integrated climate change assessment.

Note that even though we have discussed biomass burning as one significant source of aerosols impacting the landscapes, there is increasing evidence that large-scale animal feeding operations (AFOs) also lead to significant ammonia-to-ammonium particulates formation. These aerosols would also cause changes in the DDR and would provide a feedback between animal agricultural production and climate changes.

5. Biological effect of increased CO_2

While the radiative effect of increased CO_2 has been extensively studied (Houghton et al., 2001), the influence of the effect of this increased CO_2 on agricultural and other vegetation as it influences weather has received much less scrutiny (Fig. 9). Eastman et al. (2001) explored this issue using a coupled atmospheric-biogeochemical model applied to

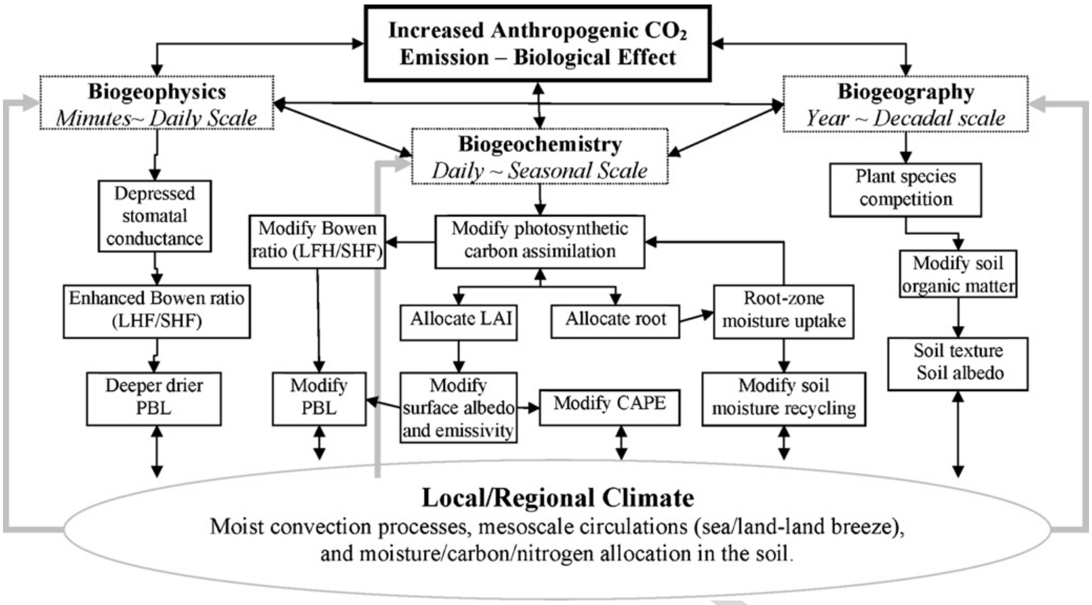


Fig. 9. Increased CO_2 on biological activity as it influences weather.

the central Great Plains of the United States for a growing season (210 days). The relative importance of land-use change, the radiative effect of doubled CO_2, and the biological effect of doubled CO_2 on maximum and minimum temperatures, precipitation and above ground biomass growth were investigated. Table 2 summarizes the results averaged for the 210-day time period and for the region modeled.

This study shows that, on this time scale, the biological effect of increased CO_2 dominates the radiative effect of increased CO_2. The biological effect alters climate through the effect of higher concentrations of CO_2 on stomatal conductance (each stoma is more water-use efficient) and on carbon assimilation (the grasses, in particular, grow more in the CO_2-enriched environment). For example, when higher CO_2 exists, the model produces lower maximum temperatures but higher minimum area-averaged temperatures than occurs otherwise due to the biological forcing. In contrast, the radiative effect of increased CO_2 has its main influence by raising the nighttime minimum (since less longwave radiation is lost at night; the *greenhouse gas effect*) but with little influence on the maximum temperature. The biological effect of increased CO_2 also has a greenhouse gas effect at night, but it is due to water vapor increases from the greater transpiration during the previous day, not the CO_2. The biological effect of increased CO_2 is comparable in magnitude to the large land-use change effect! The important role of the biological effect of increased CO_2 on long-term weather has been further substantiated by Narisma et al. (2003) for Australia and by Niyogi and Xue (2006) for different vegetation types. Betts (2001), Cox et al. (2000) and Friedlingstein et al. (2001) have shown this biological effect to be important on the global scale.

6. Other regional effects

Other agricultural issues have not been explored. One example is the role of nitrogen deposition on these lands, and how the effect on plant growth feeds back to the atmosphere (Rhome et al., 2003; Niyogi et al., 2006b).

Table 2
Regional atmospheric modeling system/general energy mass transfer model (RAMS/GEMTM) coupled model results

	Natural vegetation	2 × CO_2 radiation	2 × CO_2 biology
Contributions to maximum daily temperature (°C)	−1.191	0.0141	−0.747
Contributions to daily precipitation (mm)	−0.035	0.0078	−0.046
Contributions to minimum daily temperature (°C)	−0.017	0.097	0.261
Contributions to LAI	0.198	0.001	0.578

Changes in the 210-day growing season domain-averaged central Great Plains maximum daily temperature, minimum daily temperature, precipitation, and leaf area index (LAI) from the control simulation with current landscape and atmospheric concentrations of CO_2 (due to: natural vegetation, 2 × CO_2 radiation, and 2 × CO_2 biology) (adapted from Eastman et al. (2001).

As shown in Holland et al. (2005a), nitrogen emissions from industrial and vehicular traffic are transported long distances by the wind. When this material deposits, it can serve as fertilizer that can invigorate plant growth. Similar to what was found with the biological effect of increased CO_2, we should expect an altered climate in response to this inadvertent anthropogenic forcing. Even if the direct effect on the crops themselves is small, since crops are often deliberately fertilized with nitrogen, atmospheric deposition of nitrogen could affect adjacent unfarmed land, resulting in climate effects over the cropland. Moreover, as discussed by Holland et al. (2005b) the ‘‘cycles of nitrogen, carbon and other key nutrients are inextricably linked. Their interactions are likely to provoke key non-linearities in the evolving Earth system.’’

7. Global teleconnections

While land covers less than 30% of the Earth’s surface, its effect on global climate can be disproportionally large (Pielke, 2001b). Thunderstorms, for example, predominantly occur over land (by a 10:1 ratio). As illustrated in Fig. 10, the preponderance of cloud-to-ground lightning strikes over land is clearly evident. This preference for deep convection over land is because energy for deep cumulus clouds, or CAPE, is typically larger over land.

It has also been shown (Riehl and Malkus, 1958; Riehl and Simpson, 1979) that much of the energy transported upwards in the tropics and then poleward, occurs because of these thunderstorms which are the starting point for the major, global-scale, circulation cells such as the Hadley and Walker cells. These studies demonstrated that 1500–5000 thunderstorms, which they refer to as ‘‘hot towers’’, are the conduit to transport heat, moisture, and wind energy to higher latitudes. Since these thunderstorms occur mostly over land, any change in their spatial patterns due to land-use/land-cover change, including vegetation, or anthropogenic aerosols would be expected to have global climate consequences. Indeed, this human-caused change in thunderstorm patterns caused by the diverse regional climate forcings identified in this paper may have a greater effect on the climate system than the radiative effect of doubled CO_2.

Fig. 11a and b shows recent trends in 300 mb zonal winds from the NCEP/NCAR and ECMWF40 Reanalyses respectively (Kalnay et al., 1996; Simmons and Gibson, 2000; Kållberg et al., 2004). Regions of statistically significant trends are contoured. What is clear from these figures is that significant wind shifts (i.e., changes in circulation patterns and intensity) have occurred to various degrees all over the globe in recent decades.

Shifts in the major circulation patterns occur on all temporal scales and, therefore, significantly affect the weather of agricultural systems. Two teleconnection patterns, El Niño/southern oscillation (ENSO), and the North Atlantic oscillation (NAO), for example, have

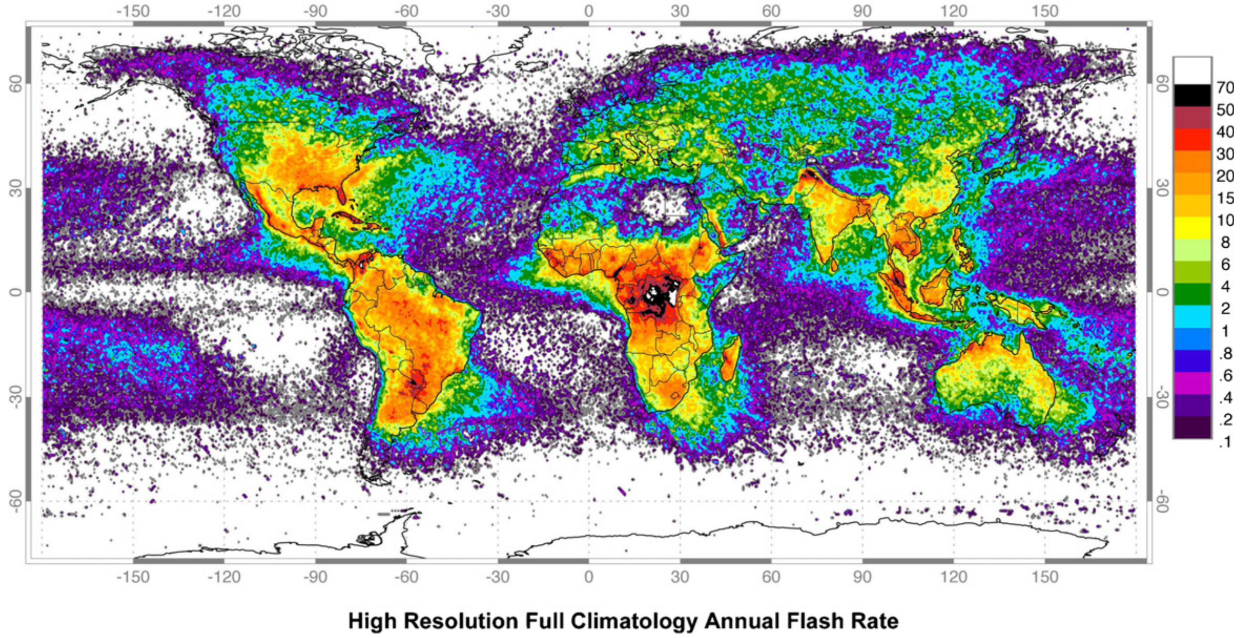


Fig. 10. Global distribution of lightning April 1995–February 2003 from the combined observations of the NASA OTD (April 1995–March 2000) and LIS (January 1998–February 2003) instruments (from http://thunder.nsstc.nasa.gov/images/HRFC_AnnualFlashRate_cap.jpg).

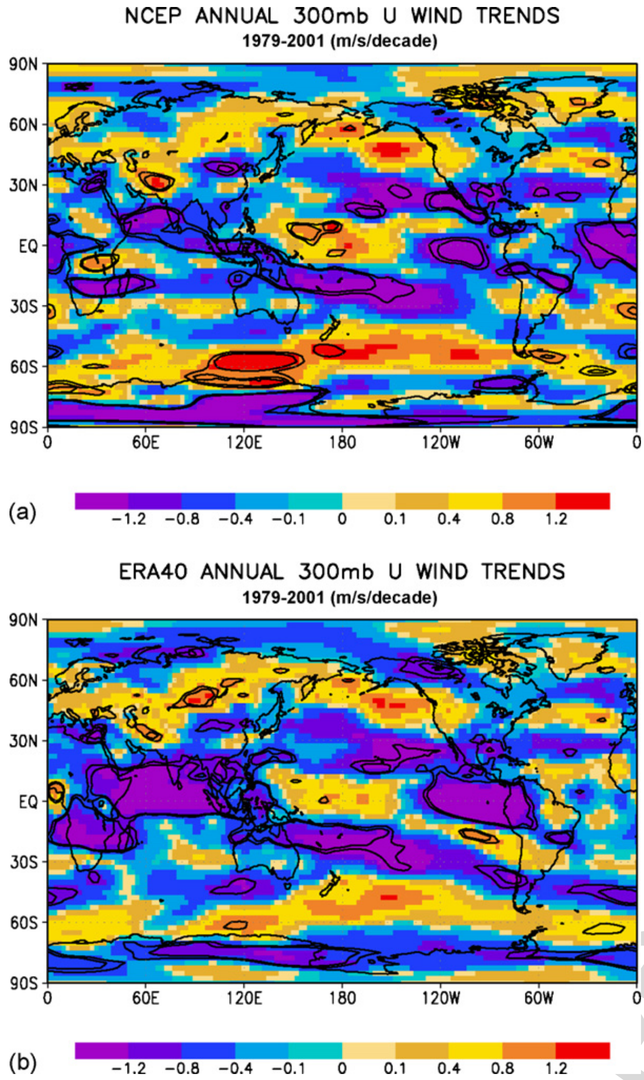


Fig. 11. (a) and (b) show recent trends in annual, 300 mb winds from the NCEP/NCAR and ECMWF-40 reanalyses, respectively. Significant trends at the 90 and 95% levels are thickly contoured (see http://www.ecmwf.int/publications/library/ecpublications/_pdf/era40/ERA40_PRS17.pdf for a description of the 40-year European reanalysis project).

been directly linked to a large portion of the observed northern hemisphere winter warming signal (Palecki and Leathers, 1993; Hurrell, 1996; Corti et al., 1999).

There is accumulating evidence that land-cover changes, including those due to agriculture, may have significant effects on these circulation regimes and may have some role in explaining the observed wind shifts shown in Fig. 11. Chase et al. (1996, 2001) noted, using general circulation model experiments, that agricultural and other land modifications result in large and significant changes in large-scale circulations such as the major jet streams, Hadley cells, and monsoon. These shifts in circulation allow the effects of land-cover change on agriculture, and on other regions, to be experienced far from regions where the land-cover changes occur and therefore can be considered surface-induced teleconnection patterns. Other examples are given in Chase et al. (2005). Results from more recent experiments have supported the idea that human agricultural land-cover changes can have strong and quite distant effects (Zhao et al., 2001; Feddema et al., 2005).

These modeling results illustrate that surface global average temperature, and even regional average temperature, are inadequate metrics to characterize agricultural impacts, both because they are external large-scale values, and because they do not characterize the actual effect of climate on agriculture. Of more relevance to agriculture are variations in circulation that result from changes in regional tropospheric temperatures and precipitation, and, thus, the weather patterns that an agricultural region experiences.

8. Consequences of diverse and complex climate forcings and feedbacks

Sections 1–7 illustrate that agriculture is an active component of the climate system. It alters the heat, moisture, winds and other weather from what would have occurred with the natural landscape. The influence of agricultural land also extends beyond where the actual conversion of landscape occurred. Moreover, the forcings and feedbacks are multi-dimensional and nonlinear (Rial et al., 2004). This makes the prediction of future climate in agricultural lands a daunting challenge.

9. A new paradigm focused on vulnerability

From the discussion in this paper and other papers (e.g., Pielke, 2002), it is clear that existing model simulations have used only subsets of the climate forcings and feedbacks to predict future climate (Houghton et al., 2001 for the IPCC; NAST, 2000 for the U.S. National Assessment). Indeed, as the diverse types of climate forcings are recognized (National Research Council, 2005) and the interactions between local, regional, and global scales becomes more recognized, skillful forecasts of the future climate becomes an increasingly challenging task (Pielke, 2001c). Addressing this challenge requires a greater focus on assessing key societal and environmental vulnerabilities (Foley et al., 2005; Sarewitz et al., 2000; Pielke and Bravo de Guenni, 2004; Steffen et al., 2004; Sarewitz and Pielke, 2005; Pielke, 2004).

This section discusses a redirection of the paradigm from a perspective driven by global model predictions

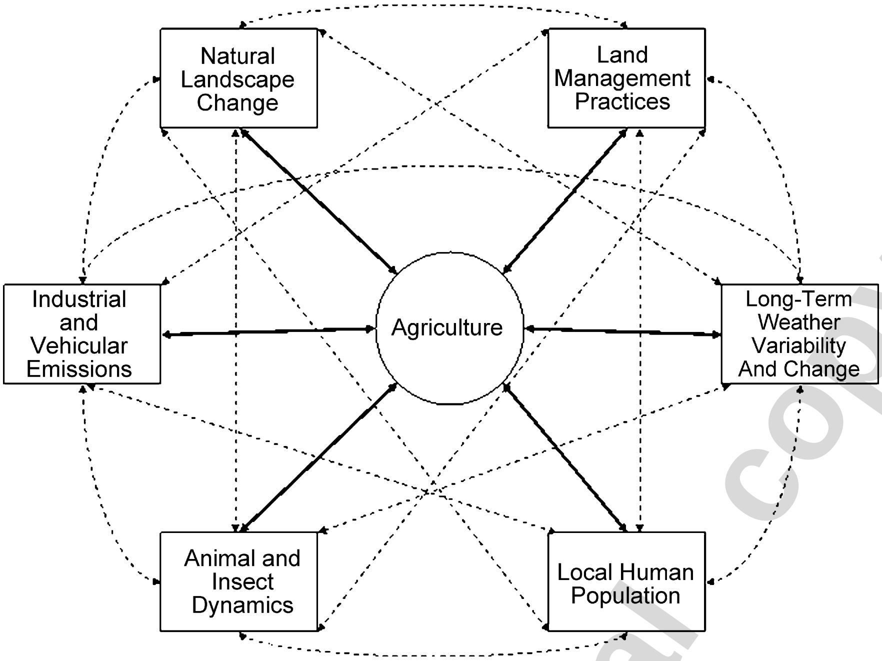


Fig. 12. Schematic of the relation of agricultural vulnerability to the spectrum of the environmental forcings and feedbacks. The arrows denote nonlinear interactions between and within natural and human forcings (adapted from Pielke, 2004).

that are downscaled to agricultural impacts (*a top-down approach*) to an affected party view (*a bottom-up approach*) where risks and thresholds to change are assessed first. Global-scale model predictions, also referred to as projections, cannot by itself be the primary basis on which to plan for the future. Rial et al. (2004) present examples demonstrating that the Earth's climate system is highly nonlinear, that inputs and outputs are not proportional, that change is often episodic and abrupt, rather than slow and gradual, and that multiple equilibria are the norm. This limits the value of global models as forecast tools. Peters et al. (2004) shows that spatial nonlinearities result in critical environmental thresholds, such that what may be an appropriate mitigation response for one spatial scale of a disturbance may be inappropriate for a different spatial scale.

However, this new direction in Earth science has not been clearly recognized by many, particularly in the atmospheric science and science policy communities. For example, many, if not most climate change policy studies still focus on global mean surface temperature change as the metric to link to economic impact due to anthropogenic changes in atmospheric composition (Houghton et al., 2001). Yet climate impacts, and certainly agricultural impacts, extend far beyond a global mean temperature and include other anthropogenic climate forcings, as discussed in Sections 2–7, such as land-use change (e.g., Pielke, 2001a,b; Marland et al., 2003), the multiple forcings associated with aerosols (e.g., Andreae et al., 2004; Niyogi et al., 2004) as well as complex feedbacks (National Research Council, 2003).

The perspective adopted by many in the atmospheric modeling and climate policy communities is that the global models provide skillful projections of the future, and we are just seeking to confirm them with selected observations. However, there are issues with the robustness of climate change models, as has been documented in the peer-reviewed literature (e.g., Pielke, 2002; Chase et al., 2004). The resistance within the atmospheric modeling community to more rigorous model testing and the general lack of effective dialog within and between disciplines has constrained advances in our understanding. Rial et al. (2004) conclude, "It is imperative that the Earth's climate system research community embraces this nonlinear paradigm if we are to move forward in the assessment of the human influence on climate."

A new *vulnerability* paradigm was proposed in Pielke and Bravo de Guenni (2004) to address the shortcoming of emphasising global model projections as the primary basis for determining the likely impacts of future climate. The vulnerability paradigm, as applied to agriculture and other aspects of the Earth system, is a more inclusive approach than prediction. Key vulnerabilities include risks, for example, to regional and global food, water, and energy supplies.

The environmental and human-caused threats extend well beyond climate.

The framework for vulnerability assessments (Fig. 12) is place-based and has a bottom-up perspective, in contrast to the GCM-focus which is a top-down approach from a global perspective. The vulnerability focus is on the resource of interest, agricultural production, in the case of Fig. 12 (adapted from Pielke, 2004). The challenge is to use resource specific models and observations to determine thresholds at which negative effects occur associated with this resource. Changes in the climate, represented in Fig. 12 by weather and land-surface dynamics, *represent only one threat*; the climate itself may also be significantly altered by changes in agricultural practices and of other land management, and there are multiple, nonlinear interactions between the forcings as shown by the dashed lines in the figure. The GCM models could only capture a portion of the threat to agriculture.

One approach to assess vulnerability is to ask the agricultural impact community their current effects due to existing climate conditions, and their thresholds for deleterious effects. Also what adaptation and/or mitigation could be performed to reduce this vulnerability?

We have tested this approach for a specific community located in Larimer County, Colorado, where agriculture is a major local industry. Selected examples of this community were polled in early summer 2004 using a five-category scale with respect to their impact of a long-term precipitation drought in this area. The four groups that provided input responded as shown in Fig. 13. Despite very similar long-term temperature and precipitation in this area, the impacts on the different sectors were quite diverse. The major problem was the uneven distribution of the available water which in Colorado is based on water rights which is a property right based on seniority. This example illustrates that access to water involves more than climate, and involves laws and regulations that are complex in their own right (Hobbs, 2003a,b).

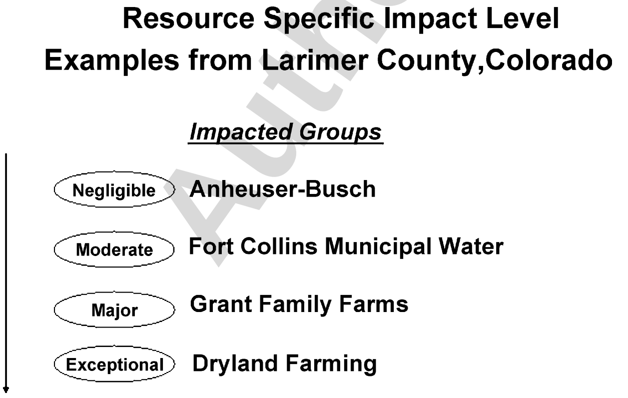


Fig. 13. Resource specific impact level examples from Larimer County, Colorado.

With a bottom-up perspective, the distribution of agricultural and other impacts across a community would be assessed, and objectively confirmed, as a more accurate assessment of the local impacts. Then the fundamental question becomes on seeking ways to mitigate and/or adapt to the threats to these local resources. This is a more societally beneficial approach than seeking to downscale to the local region from a global climate model.

10. Conclusions

The human disturbance to the climate that influences agriculture is multi-dimensional and acts across all time scales, ranging from short-term weather events, such as damaging freezes, to seasonal average weather, such as growing season precipitation, to multi-year effects, such as in the viability of specific types of crops. This complexity makes the skillful prediction of the future climate very challenging. Currently, forecast skill beyond several months does not exist, and even on that time scale, skill is possible only for certain conditions such as a strong El Niño, as concluded in the American Association of State Climatologist policy statement on climate change and variability (http://www.ncdc.noaa.gov/oa/aasc/aascclimatepolicy.pdf). Therefore, there is a need to adopt a new paradigm which focuses on the vulnerability of agricultural resources to the spectrum of climate change and variability threats. This approach also permits the consideration of the relative threats posed by non-climatic environmental risks, such that policymakers can make more informed decisions as to what mitigation and/or adaptation procedures can be used to reduce the threat and increase the resiliency of the agricultural system.

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