AgroEco Systems Pty. Ltd.
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Ref: 6105
Date: 22/7/2008

The Secretary,
Senate Standing Committee on Rural and Regional Affairs and Transport,
PO Box 6100
Parliament House,
Canberra ACT 2600

INQUIRY INTO LEGISLATION UNDERPINNING CARBON SINK FORESTS

Dear Ms Radcliffe,

I wish to make the following submission to this enquiry. I would be available in the morning on Thursday for a teleconference if your committee so desires - 03 59 427562.

Yours Sincerely,

Andrew G. Helps

INQUIRY INTO LEGISLATION UNDERPINNING CARBON SINK FORESTS

Submission by: **Andrew G. Helps**
Environmental Disaster Manager.

1. General Comment.

This is a complex and difficult issue that seems to be on the fast track through the Commonwealth system without the requisite amount of planning and thought. The Legislative Instrument seems to be based more on appeasing the MIS industry than developing a plan that is in the National best interest.

The issues with Carbon Sink Forests, if handled correctly, has the ability to sequester all the emissions from the power industry without the costly need for geo-sequestration and the imposition of increased power prices on the general community. The stumbling block is that Professor Garnaut did not choose to look at this issue and there is no other way for the issue to stand on its merits in the current public forum on emission reductions.

2. Specific Comment.

2.1 The Legislative Instrument signed by Minister Wong on the 2nd of July 2008 is factually incorrect in a number of its provisions:

2.1.1 By omission it restricts the most beneficial carbon sink process from the provisions of the taxation act;

2.1.2 It enshrines specific provisions for the avoidance of land clearing when land clearing is or should be totally banned in all states and territories;

2.1.3 Uses flawed terminology in bullet point 3 to require carbon sink forests to be established to avoid negative impacts on water availability. Trees use water and respire it, they do not consume it and therefore this provision is incorrectly worded;

2.1.4 Weed and feral animal plans should not be included in this legislative instrument as it is not relevant;

2.1.5 The heading in item 2 is incorrectly worded and uses flawed terminology. The heading item should read:

> *2. Carbon sink forest establishment activities should be guided by a NATIONAL Environmental Recovery Plan (NERP).*

2.1.6 Regional natural resource management plans are flawed terminology. The national environmental recovery plan would create catchment and sub-catchment plans (CERP's and SCERP's). The IGBP has published massive amounts of data on this issue and the Federal Government would be wise to study this data. These plans would be based on changes to surface Albedo resultant from the plantations and the macro, meso and microclimate changes that would flow from the establishment of a plantation.

2.1.7 Measuring the potential cumulative environmental effects of carbon sink forest activities at a catchment scale is quite pointless as the establishment of the carbon sink forest has the capability to create macro, meso and microclimate changes.

2.1.8 Interception activity (last para item 2). This para represents 20 year old science from an era when national and regional satellite data was not available. If a National Environmental Recovery Plan was in place then these interceptions would be acquitted at a National level and not a sub catchment level.

2.1.9 Item 3 is wrong. These guidelines and the requirement for a NERP, CERP's and SCERP's should become part of an amendment to a more muscular EPBC Act and the states, state agencies, corporations and individuals should have to seek an EPBC clearance for each carbon sink forest that is established so that National cumulative effects can have central point monitoring.

3. The alternative.

In late May 2008, It became apparent that the Garnaut review was focussed a particular course and was not interested in looking at alternative scenarios other than full blown emissions trading for Australia. Wether this was by political direction or a fascination with the economic issues surrounding the introduction of an emissions trading scheme is unclear.

I was approached by a well known Federal backbencher and asked to put in writing a concept for the use of carbon sink forests to offset the bulk of the national emissions from the power generation sector. I put this document together and it is attachment A to this document.

If the Rudd Labour government has a serious commitment to restoring water flows in the Murray Darling Basin and restoring some normalcy to rainfall patterns in the dryland farming areas of Southern Australia then the proposal in Attachment "A" merits serious consideration. If the project were to come to fruition then it would require some legislative support that would again mean that this current Carbon Sinks Forest legislation be better scoped to deal with the need for a National Environmental Recovery Plan.

I look forward to the opportunity to discuss this matter in more detail with the Inquiry.

Yours Sincerely,

Andrew G. Helps
Managing Director.

AUSTRALIAN ENERGY SECTOR EMISSIONS IS THERE A MORE COST EFFECTIVE SOLUTION?

1. PROCESS.

Australia is in the process of embarking on its biggest ever Research and Development (R+D) project in an attempt to develop commercial scale technologies that can geologically sequester (Geosequestration) Carbon Dioxide (CO_2) gasses from the combustion of brown and black coal to make electricity. There are a number of unknowns in this R+D process and even if the technology is proven up it will dramatically increase the price of electricity in Australia by somewhere between $60 and $120 per tonne of CO_2.

At some point in the future, the ability to sequester CO_2 will stop when suitable reservoirs reach capacity. Geosequestration does not deliver any other community benefits except storing CO_2 that may or may not become a legacy issue for future generations.

2. COST.

Capital cost for conversion of Australia power stations may be in the order of $55-70 billion and the necessary piping and compression stations will add about 25-35% to current power demand. It is interesting to note that none of the current promoters of Geosequestration have put on the table a full cumulative effects study of the technology.

3. DATA.

Latest figures from the Department of Climate Change indicate that the Stationary Energy sector will have greenhouse gas emissions of at least 429 million tonnes per year on average over the period 2008 -2012. At $60 per tonne of CO_2 (lowest recent estimate) this equates to an annual cost of $2.574 billion dollars per year for technology that is unlikely to be commercially available until 2020.

Is there better value to be had from this expenditure? Could equivalent emission savings be made by other methods that would also deliver significant other benefits for Australia. The answer may well be YES.

4. THE ENVIRONMENT.

Southern Australia is currently in its 12th year of drought conditions and it is well known that some of the effects of this drought are due to man made changes to the ecological land form over Southern Australia over the last 200 years. These man made changes are non-linear and relate to the inadvertent changes to surface albedo (light reflectance) made by the clearing of land to grow crops and improved pastures. A land surface area that is light in color reflects much more solar radiation than a darker surface area and this causes serious changes to the microclimate close to ground. Surface albedo changes have been well understood since the early 1950's and this understanding of the issues[1] has meant that it true impact on southern Australia has not been subject to the sort of R+D that it should have.

5. BRS.

The Bureau of Rural Sciences publish on the web an Integrated vegetation tool[5] for the farming areas in Australia and using this tool it is possible to define the surface albedo impacts of land clearing for farming. A key part of this critical issue is the land clearing that has gone on in coastal Western Australia. In the northern Agricultural Region centered on Geraldton, 52.2% (42,188km$^{\square}$) of the region has been modified to grow crops and improved pasture. During this modification of the land form, the surface albedo has gone from an average of 10% to a figure between 20% and 25% depending on the soil type. The five cropping regions in Western Australia comprise 318,158 km $^{\square}$ of which at least 178,965 km $^{\square}$ has modified surface albedo. Across the four southern Australian States, there is 1,299,702 km $^{\square}$ of cropping regions of which 406,094 km $^{\square}$ has extensively modified surface albedo.

6. ALBEDO.

The importance of this modified surface albedo is that it has a major direct impact on the rainfall pattern over Southern Australia and more importantly the quantum of rainfall. This impact is caused by the reduction of surface heating from solar radiation. This surface heating causes thermal convection which triggers the inflow of moisture laden colder air from the southern ocean.

For instance, in Western Australia in the winter time, colder moisture laden air is dagged inland by convection and becomes part of the constant west east system of high and low pressure systems. The 406,094 km $^{\square}$ that has modified surface albedo is now probably only dragging in about 1/3 of the moisture laden air that was dragged in prior to land clearing. There is a good body of evidence that suggests that the ecological threshold (tipping point) for this convection driven moisture laden air may well be in the region of a 40% reduction of surface albedo.

When you add to this reduction the massive changes in surface albedo that have taken place on the Eyre and Yorke peninsulas, the south east of South Australia, the Mallee and the Riverina and it is not hard to come to the conclusion that the current drought is actually about man made changes to surface albedo, climate change and changes in oscillation indexes rather than just the last two. It is interesting to note the movement of high and low pressure systems that now commonly are centered south of Tasmania rather than running through areas like Adelaide as they did in the 1940's.

7. HOW DOES ALL THIS FIT BACK INTO THE GEO-SEQUESTRATION ISSUE?

It is generally acknowledged, that the cleared cropping and improved farm land across the four southern states of Australia has, on average, about 1/3 of its land that is not suitable for intensive production either of crops or pasture. Re-planting this land to its native trees would go a long way towards restoring some of the microclimate thermal issues that are so important in bringing into the west east trade winds moisture laden air from the southern ocean. The 406,094 km $^{\square}$ of cleared crop and pasture land in the four southern states consist of 40.6 million Ha. If 1/3rd of this was re-treed, this would amount to 13.53 million Ha. At an average over the whole area of 300 trees to the Ha, a conservative average of 35kg of Carbon sequestered in each tree per year over its life time would equate to annual sequestration of 495 million tonnes of CO2e, a 66 million tonne buffer over the 429 million required to totally offset the needs of the Stationary energy sector and 2/3rd's of what is required to fully offset the agricultural sector emissions.

Current pricing is indicating that planting/fencing and initial growth support would cost in the region of $A 5000 per Ha or in current dollar terms, about 67.6 billion dollars of expenditure. Unlike Geosequestration, this expenditure would have flow on effect that would include but not be limited to:

7.1 Massive employment of low skilled labor in rural areas;
7.2 Significant reduction in soil erosion across the whole southern Australian farming system with consequential savings of soil carbon and nutrients;
7.3 Major impact on the salinity issues in Southern Australian farming systems;
7.4 Increased farm production due to the effect of trees sheltering crops and raising the temperature of the surface areas in winter cropping areas;
7.5 A significant rainfall increase potential across all rehabilitated areas within about 10 years of re-afforestation;
7.6 A significant rainfall increase potential for the major storages in the Murray Darling basin system;
7.7 A significant potential to increase stream flows in all the river and stream systems in southern Australia (The Government is looking to spend $10 billion to buy back water licences to help restore riparian flows - how much better to spend this $10 billion on restoring rainfall to its previous levels).

If the re-afforestation of this 13.53 million HA resulted in an increase in winter rainfall of only an average 100mm across the farming systems of the four southern states then this could result in an extra 15 million tonnes of winter crop yield that would be worth in the region of 4.5 billion dollars per year plus significant increased irrigation water being available for irrigated summer crops and intensive agriculture such as vineyards and dairy's.

8. FURTHER SAVINGS

Further savings of emissions from the National Greenhouse gas inventory can be made by restricting the landfilling of organics waste in the major Australian City's. In 2002, Australia's major City's dumped to landfill 5.552 million tonnes of waste organics consisting of food waste, garden waste, animal mortality and industrial food processing wastes. This waste contained;

1. Enough nitrogen and phosphorous to replace at least 655,000 tonnes of DAP chemical fertiliser;

2. Enough surplus nitrogen to replace 157,000 tonnes of chemical urea;

3. Enough potassium and Sulfur to replace 232,500 tonnes of Chemical Sulfate of Potash;

At today's prices this amount of nutrient is worth $A 1.193 billion per year. The greenhouse gas emissions associated with manufacturing and transporting all this nutrient are hidden in other parts of the National Greenhouse inventory and replacing these nutrients will lower emissions by about 4 million tonnes per year for the manufacture and transport of the chemical fertiliser and about 15 million tonnes per year by the avoidance of furtive emissions from landfill.

The 5.552 million tonnes per year of diverted landfill organics could be processed through modern 5th generation anaerobic digestion plants and would produce about 210 Mw of baseload renewables which would cut another 1.7 million tonnes from the inventory. The biohumus left over from the digestion would make about 1,100,000 tonnes per year of high quality organic fertiliser that could be co-blended with brown coal and used as potting mix for the trees that were being planted in nurseries for eventual rehabilitation of farm land.

This proposal gives a much better outcome for the Australian people and in particular the farming sector and the rural economy as a whole. It is a project that urgently needs to be carried out because the national benefits are so compelling.

References:

1. "The Climate Near The Ground" Rudolf Geiger, Harvard University press Cambridge, Mass 1965.
2. ABARE Australian Commodities March Quarter 2007.
3. Department of Climate Change - Tracking the Kyoto Target February 2008
4. Pielke Sr RA, Adegoke J, Beltran-Prezkurat A *et al* 2007. An overview of regional land use and land cover impacts on rainfall. *Tellus B* 59:587-601
5. Integrated vegetation online - http://adl.brs.gov.au/mapserv/intveg/
6. Living in an increasingly connected world; a framework for continental-scale environment science. Debra PC Peters, Frontiers in Ecology and the Environment 2008; 6 (5): 229-237

Living in an increasingly connected world: a framework for continental-scale environmental science

Debra PC Peters[1*], Peter M Groffman[2], Knute J Nadelhoffer[3], Nancy B Grimm[4], Scott L Collins[5], William K Michener[5], and Michael A Huston[6]

The global environment is changing rapidly, as the result of factors that act at multiple spatial and temporal scales. It is now clear that local processes can affect broad-scale ecological dynamics, and that broad-scale drivers can overwhelm local patterns and processes. Understanding these cross-scale interactions requires a conceptual framework based on connectivity in material and information flow across scales. In this introductory paper to *Frontiers'* Special Issue on *Continental-scale ecology in an increasingly connected world*, we (1) discuss a multi-scale framework, including the key drivers and consequences of connectivity acting across spatial and temporal scales, (2) provide a series of testable hypotheses, predictions, and an approach, and (3) propose the development of a "network of networks", which would take advantage of existing research facilities and cyberinfrastructure. This unique framework and associated technology will enable us to better forecast global environmental change at multiple spatial scales, from local sites to regions and continents.

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The interplay between fine-scale patterns and processes and broad-scale dynamics is increasingly being recognized as key to understanding ecosystem dynamics, particularly as the number and magnitude of global change drivers increases over time (Huston 1999; Rodó *et al.* 2002; King *et al.* 2004). Cross-scale interactions (CSI) are processes at one spatial or temporal scale that interact with processes at another scale, often resulting in non-linear dynamics with abrupt threshold responses (Holling 1992; Carpenter and Turner 2000; Peters *et al.* 2004a, 2007). These interactions may generate behavior that emerges at broader scales and cannot be predicted based on observations at single or even multiple independent scales (Michener *et al.* 2001). Redistribution of material, energy, and information flow within and among spatial units (ie connectivity) is one potentially powerful explanation for these cross-scale interactions. The degree of connectivity is determined both by the spatial structure of the environment and by the way in which this structure influences the change in redistribution rate – a definition similar to one used by landscape ecologists (With *et al.* 1997).

In a nutshell:

- The world is becoming increasingly connected through the flow of materials, organisms, and information, both within and among regions that may or may not be adjacent or even close to each other
- Connectivity pathways allow fine-scale processes to propagate and impact large areas; in some cases, broad-scale drivers can overwhelm fine-scale processes to alter ecosystem dynamics
- Changes in connectivity have the potential to produce rapid and dramatic changes in ecosystem dynamics unlike any observed in recorded history
- Understanding global connectivity and its consequences requires the creation of an international ecological "network of networks" for observation and experimentation, and the accompanying cyberinfrastructure for analysis and synthesis

All ecosystems around the world are connected through a globally mixed atmosphere and, historically, regional connections existed through a variety of both biotic and abiotic processes. This connectivity has been altered through human transport of propagules, toxins, and diseases, as well as anthropogenic disturbances and changes in land use (Reiners and Driese 2003; MA 2005; Herrick and Sarukhán 2007). Thus, changes in one location can have dramatic influences on both adjacent and distant areas, either at fine or broad scales. For example, the extreme drought of the 1930s in the central Great Plains of the US interacted with cultivation of marginal croplands to generate high rates of soil erosion from individual fields, which subsequently resulted in the Dust Bowl (Figure 1). This site- to regional-scale set of events spread across the continent, to affect broad-scale patterns in soil and air quality, migration patterns, human health, and the economy (Peters *et al.* 2004a).

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Beyond the Frontier: Listen to Debra Peters discussing this Special Issue on *Frontiers'* monthly podcast, at www.frontiersinecology.org.

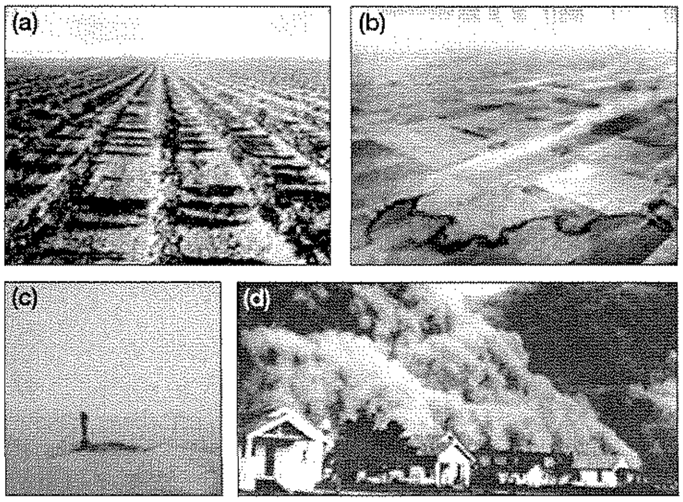

Figure 1. *Development of the US Dust Bowl, an event that propagated from the cultivation of many individual fields on marginal land in the 1920s to widespread abandonment in the 1930s during a severe drought, which led to continental-scale impacts of massive dust storms (www.weru.ksu.edu). (a) Many individual fields cultivated in the Great Plains in the 1920s (b) became highly connected following drought and strong winds in the 1930s, through wind erosion. (c) Extensive areas of soil were eroded, creating (d) massive dust storms, with effects on human health, the economy, and migration across the continent.*

Connectivity across scales can also link continents: hurricanes along the east coast of North America often originate as fine-scale thunderstorms in eastern Africa (Price *et al.* 2007). In 2003, it took only 8 months for severe acute respiratory syndrome (SARS) to spread from a single province in China to 29 countries, resulting in over 8400 confirmed cases around the globe (WHO 2003). Ozone, carbon monoxide, mercury, and other particles from degraded land in China cross the Pacific Ocean to affect air quality in North America (Jaffe *et al.* 2003). The ecological consequences of these broad-scale connections for phenomena at finer scales, from sites to regions and continents, are often unknown. Furthermore, the influence of fine-scale ecological patterns and processes at local sites on broader-scale patterns at regional to continental and global scales is poorly understood.

Here, we provide a conceptual framework to understand and predict broad-scale ecosystem dynamics based on connectivity in material and information flow, linking multiple scales of observation, from local sites to regions and continents. Although we focus on dynamics in the US, as a major part of North America, our framework applies to all continents and to inter-continental dynamics as well. We also suggest an approach to test hypotheses about interactions across scales, and to predict future dynamics. Finally, we describe how our cross-scale framework can be used to leverage existing and emerging research networks to integrate datasets and ecological knowledge.

■ Connectivity framework: a hierarchy of interacting scales

A theory of connectivity across scales is emerging, and it builds on concepts from diverse disciplines, including landscape ecology, Earth-system science, population ecology, macroecology, hydrology, and biogeochemistry. This theory provides one key to forecasting large-scale, multi-process phenomena, and is the basis for our conceptual framework. Our basic premise is that the climate system and human activities operate across multiple, and often disparate, spatial and temporal scales to influence, and be influenced by, ecological systems (Figure 2). Three major scales of climate drivers may lead to synchronicity in ecosystem responses as a result of connectivity via air masses. We use the term "driver" to refer to broad-scale processes and human activities that directly or indirectly influence ecological and socioeconomic systems. This definition allows for interactions among drivers as well as feedback mechanisms between drivers and responses. One example is seen in climatically induced shifts in vegetation that produce changes in surface-energy balance, which then feed back to alter weather patterns that affect both ecosystems and human society (eg Pielke *et al.* 2007). Observed precipitation and temperature patterns at site to regional and continental scales (Figure 3) result from a combination of three climate drivers:

(1) global circulation patterns and other broad-scale drivers, such as solar insolation, which influence long-term climatic averages, with resulting effects on ecosystem structure and function across large regions;
(2) sub-continental to continental-scale phenomena driven by patterns such as the Northern Annular Mode (NAM), the Pacific–North American pattern (PNA), and the El Niño–Southern Oscillation (ENSO); and
(3) mesoscale patterns from a few to several hundred kilometers , as weather interacts with local to regional topography and land surface properties.

However, along with these multi-scale patterns in climate, other gradients are often needed to explain regional- and continental-scale variability in ecosystem dynamics. For example, connectivity along major river systems leads to variable patterns in land use, human settlement, invasive species, and nutrient distribution in soil or sediment that overlay climate-based variations in connectivity (WebFigure 1). Human activities at local scales increasingly drive and connect ecosystem dynamics and land change at broader, regional scales (Luck *et al.* 2001; Dietz *et al.* 2007). In addition, interactions among climate, human populations, and disturbance agents, such as disease vectors, have both ecological and socioeconomic consequences (Yates *et al.* 2002).

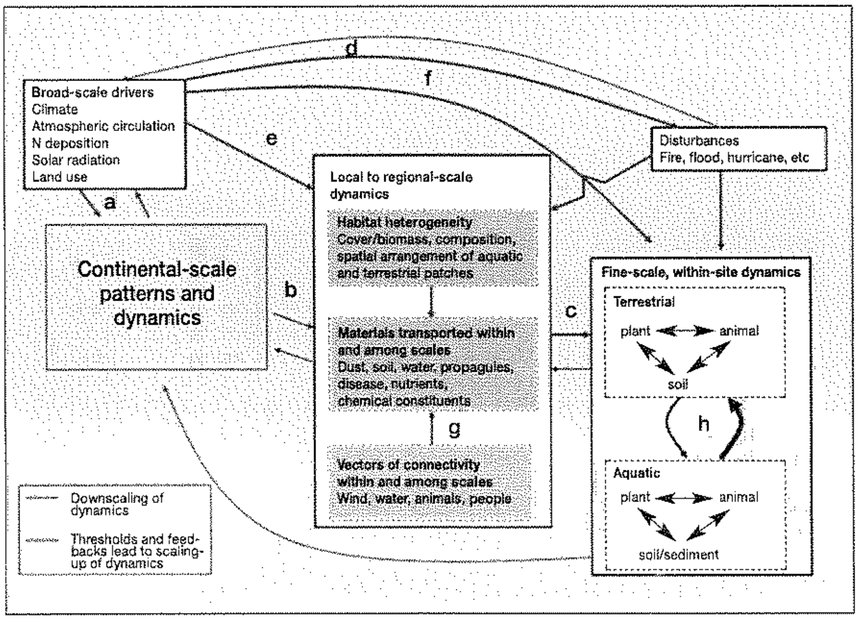

Figure 2. *Continental-scale patterns and dynamics result from climate and people as broad-scale drivers interacting with finer-scale vectors that redistribute materials within and among linked terrestrial and aquatic systems. Climate and land-use change interact with patterns and processes at multiple, finer scales (blue arrows). (a) These drivers can influence broad-scale patterns directly, and these constraints may act to overwhelm heterogeneity and processes at (b) meso-scales and at (c) the finer scale of local sites. Broad-scale drivers can also exert an indirect impact on broad-scale patterns through their interactions with disturbances, including (d) the spread of invasive species, (e) pattern–process relationships at meso-scales, or (f) at finer scales within a site. Connectivity imparted by the transfer of materials occurs both at (g) the meso-scale and at (h) finer scales within sites where terrestrial and aquatic systems are connected. These dynamics at fine scales can propagate to influence larger spatial extents (red arrows). Feedbacks occur throughout the system. The term "drivers" refers to both forcing functions that are part of the system and to external drivers.*

Thus, connectivity across scales results from climate and land use as broad-scale drivers interacting with finer-scale patterns and processes that redistribute materials within and among linked terrestrial and aquatic systems (Figure 2). Thresholds and feedbacks associated with these dynamics often result in non-linear system behavior, as the rates of change vary discontinuously through time and across space (Peters *et al.* 2004a). Connectivity occurs via transport vectors (eg wind, water, animals, people) that move materials and resources (eg dust, soil, water, energy, nutrients, propagules, diseases, and chemical constituents) within and among terrestrial and aquatic systems across a range of spatial and temporal scales (Reiners and Driese 2003; Peters *et al.* 2006). Changes in drivers and pattern–process relationships through time and across space can alter ecosystem dynamics within particular locations, and can change dynamics across locations and large regions (Allen 2007; Peters *et al.* 2007). Although our framework shares some similarities with hierarchical systems theory (Allen and Starr 1982), this approach is designed to understand and predict the conditions when broad-scale drivers will overwhelm fine-scale variability, and when fine-scale processes propagate to influence broad spatial extents. This approach also needs to account for uncertainties in predictions that exist for large-scale systems (Ludwig *et al.* 1993).

■ What can we expect in an increasingly connected world?

Globally, some materials and resources are becoming more concentrated over time (eg nitrogen), while others are becoming more broadly distributed (eg infectious diseases, invasive species). Some resources, such as those in freshwater, are becoming both more concentrated and more widely distributed, depending on the spatial and temporal scales of observation (Baron *et al.* 2002). In certain cases, connectivity in one vector can either increase or decrease connectivity in other vectors, with consequences for resource redistribution and ecosystem dynamics (Breshears *et al.* 2003). For example, human settlement patterns at fine scales can increase connectivity in non-vegetated areas through wind and water erosion (Nates and Moyer 2005), yet can decrease connectivity in wildlife movement and dispersal of infectious diseases by fragmenting landscapes (Haddad *et al.* 2003). Connectivity of a single resource can change in different ways at different scales. For example, at the continental scale, human activities are increasing connectivity between areas through increases in atmospheric nitrogen (N) deposition, yet N levels are increasing and becoming less connected among spatial units as population density and sprawl increase (Figure 4).

Our framework is particularly useful for focusing a suite of ecological questions on the key drivers of contemporary change at multiple scales. These questions were identified by the ecological community as critically important to forecasting future ecosystems at broad scales (eg NRC 2001; AIBS 2004 a,b; MacMahon and Peters 2005). Specific hypotheses can be tested, based on our connectivity framework (see WebPanel 1). These hypotheses are organized around two major issues: ecological effects of connectivity at local versus global scales, and the effects of increasing versus decreasing connectivity, as influenced by different transport vectors.

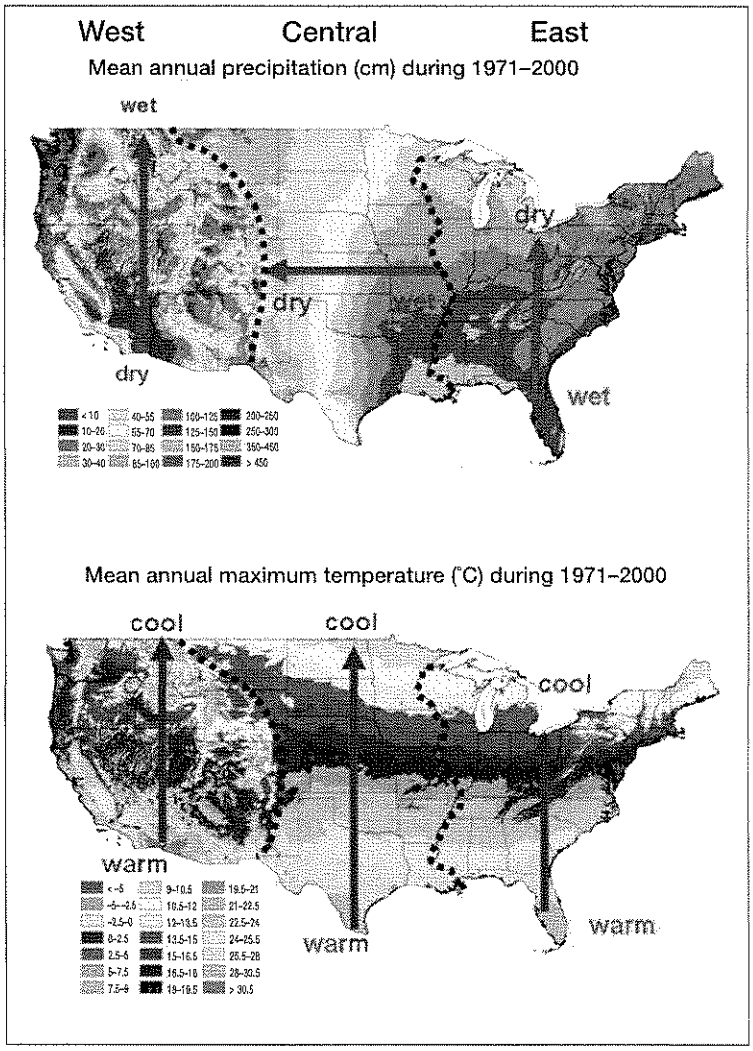

Figure 3. *The US can be divided into three general regions based on a combination of broad-scale patterns in (a) precipitation (annual total) and (b) annual maximum daily temperature. Shown are average annual values (1971–2000) from the PRISM model (http://prismclimate.org). Gradients for each climatic variable are shown in blue (precipitation) or red (temperature).*

■ Approach to conducting continental-scale research

Testing hypotheses and addressing questions from our framework (WebPanel 1) will require a new strategy for experimental design that includes a network of sites distributed across the US (as representative of North America) and the globe, and along the continental margins. Our design strategy consists of five steps, outlined below.

Step 1. Identify continental-scale patterns in broad-scale drivers

Spatial patterns in three broad-scale environmental drivers critical to our framework and relevant to ecosystems (precipitation, temperature, and N deposition) can be discerned using long-term data (> 30 years) collected from standard weather stations (www.nws.noaa.gov/) and sampling collectors of atmospheric chemistry (eg http://nadp.sws.uiuc.edu/) located throughout the US. Average seasonal and annual precipitation, and minimum, average, and maximum seasonal and annual temperatures are some of the most important climatic variables controlling ecosystem dynamics by influencing connectivity of resources across scales (Figure 3).

Step 2. Stratify a continent into regions, based on broad-scale patterns in drivers

The US can be roughly divided into Eastern, Central, and Western regions, based on a combination of broad-scale patterns in key climatic drivers. The Rocky Mountains and the Mississippi River provide general demarcations between regions to illustrate broad-scale patterns. Fine-scale variation exists within these general regions that may not follow the regional-scale pattern. Each region has contrasting patterns and correlations between precipitation and temperature (Figure 3), variable human population settlement and growth dynamics, and contrasting forecasts for climate change (IPCC 2007).

In the Eastern region of the US, the dominant climatic pattern is a positive correlation between temperature and precipitation, with both variables, in general, decreasing from south to north (Figure 3). Spatial variation in N inputs results mainly from nitrogen oxide (NO_x) emissions from agricultural regions, NO_x emissions from industrialized regions, and transport via wind and deposition as rain and snow (Figure 4). This region contains about 60% of the total US population, mostly living in coastal counties, which comprise only 17% of the land area. Most people are concentrated in the Northeast, which includes four large metropolitan areas (New York, Washington/Baltimore, Philadelphia, and Boston), and represents the most densely populated coastal region in the nation (Crossett *et al.* 2004). Most invasions of exotic plants and animals originate here, especially along the coastal flyway and major river systems (eg the Mississippi–Ohio and the St Lawrence), which serve as invasion corridors to the mid-continent. The Eastern region has a long history of intensive land use followed by abandonment (Foster and Aber 2004). Most of the forests are still regrowing and absorbing substantial amounts of carbon, and much of the land is privately owned. Older urban areas along the eastern seaboard are losing population as extensive residential developments continue to spread in suburban and exurban lands.

In the Central region, precipitation and temperature occur as orthogonal, linear gradients that result in natural experimental opportunities with almost completely independent driving variables (Figure 3). This region includes a climate threshold of historical relevance. The 100th meridian, the north–south precipitation isoline of approximately 63.5 cm average rainfall per year, marks the boundary between rain-fed cultivation and grazing-based agriculture. This threshold has shifted back and forth with climatic cycles, with disastrous consequences to humans and the economy. The relatively flat topography eliminates orographic effects (effects related to or caused by physical geography) and allows unimpeded north–south and west–east movement of weather fronts, including some of the most violent storms on the planet. This corridor includes the central migratory flyway for birds, and provides a clear path for invasion by southern plants, animals, and pathogens into the center of the country.

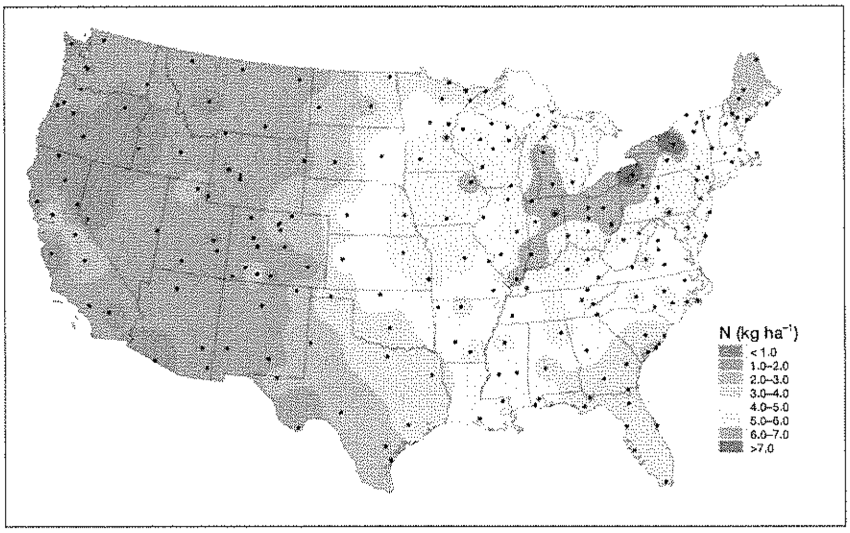

Figure 4. *Continental variation in N deposition (NADP 2007). The map depicts 5-year (2002–2006) annual weighted-average concentrations of ammonium and nitrate at National Trends Network (NTN) sites. To include sites with high proportions of snow, NADP data completeness criteria (http://nadp.sws.uiuc.edu/documentation/completeness.asp) were relaxed from 75% to 60%, except for the criterion requiring precipitation depth measurements at least 90% of the time.*

The Central region encompasses much of the Mississippi River watershed, which eventually drains into the Gulf of Mexico. Large-scale N-deposition gradients are related to human population density (Figure 4). This region also includes a gradient of human population density because the eastern portion has much higher densities than the western portion. The high proportion of private ownership of agricultural land has limited the impact of federal land management agencies, in contrast with the West. In warmer parts of the Central region, urban and suburban areas are experiencing large influxes of population, resulting in an emerging north–south gradient in population.

The Western region differs from both the Eastern and Central regions because of high topographic variability (Figure 3). A relatively uniform heterogeneity of elevation-driven temperature and precipitation gradients is associated with mountain ranges across the western US. Precipitation and temperature have a strong negative correlation at both the local scale (eg elevation gradients) and the sub-continental scale (from the warm, dry south to the cool, wet north). Strong seasonality in rainfall and snowmelt drives runoff characteristics in the region. Runoff can also be altered by water management; in California, reservoirs store spring snowmelt for use in the summer, when water demand for agriculture and power is highest, effectively truncating the normal spring peak in the hydrograph (Kimmerer and Schubel 1994). Dry deposition accounts for most spatial variation in N, and high N inputs are concentrated in, and upslope of, basins with either high human population densities or intensive agriculture (Fenn *et al.* 2003). Overall, portions of the Western region have the lowest precipitation rates and human population density, and greatest public ownership of land compared to the other two regions. Not surprisingly, human population density is strongly correlated with water availability along the continental precipitation gradient, and in areas where water is concentrated by either topography or engineering. Nevertheless, the West is experiencing rapid urbanization, and harbors some of the fastest-growing metropolitan regions in the country (eg Phoenix, El Paso, Las Vegas). California had the fastest growth in coastal population in the US between 1980 and 2003, increasing by 9.9 million people (Crossett *et al.* 2004).

Step 3. Define gradients and identify sites within and among regions

Fine-scale gradients nested within broad-scale drivers can be selected to answer the same questions in different parts of the continent with different environmental conditions. These gradients are often hierarchical and related to meso- and sub-continental-scale patterns in climate, atmospheric chemistry, resource quality and quantity (eg water, nutrients), and land use. River basins, in particular, provide a sub-continental gradient in water availability that connects adjacent and non-adjacent areas via the transfer of materials, organisms, and information (WebFigure 1). Other gradients nested within river basins can be connected by other transport vectors. Understanding the interactions among these vectors and ecological patterns across spatial and temporal scales can provide new insights to continental-scale dynamics.

In the Southwest, for example, a snowmelt gradient associated with the Rio Grande starts in southern Colorado and extends to southern Texas, where the river reaches the Gulf of Mexico (WebFigure 1). Associated with this snowmelt gradient and regional-scale transport by water are gradients in temperature and precipitation that are not necessarily linear along the river, which generally flows north to south. Mosaics of land use, invasive species, infectious diseases, and nitrogen deposition occur within these regional-scale gradients. Fine-scale patterns in land use (eg rural, exurban, suburban, urban) exist, and are similar to those in many parts of the country. Ecological systems now considered wildlands, as well as managed lands, are being encroached upon by growing urban areas (see Grimm *et al.* [2008] in this issue). These urban fringes may consist of suburban and exurban sprawl areas that are expanding and creating either barriers or corridors to connectivity in adjacent or embedded wildlands. Barriers disrupt migratory pathways of animals, while corridors increase rates of spread of exotic species from cities to natural areas. Land-use gradients of wildland–urban fringe–urban areas occur throughout the country, although the characteristics of each land-use type (eg housing density, wildland type), distances between types, and connectivity in terms of the rates of transfer among types differ regionally (Grimm *et al.* [2008] in this issue).

River basins in other regions, such as the Columbia, Colorado, San Joaquin, and Missouri, have similar hydrologic, climatic, and land-use gradients that can be used to evaluate the regional- to continental-scale consequences for ecosystem dynamics of connectivity in multiple transport vectors. In addition, repeated patterns of interacting gradients can be used to investigate continental-scale terrestrial and aquatic responses to drought and other extreme climatic events (Marshall *et al.* [2008] in this issue; Williamson *et al.* [2008] in this issue), spread of invasive species and infectious diseases (Crowl *et al.* [2008] in this issue), transfer of pollutants (Grimm *et al.* [2008] in this issue), coastal instability (Hopkinson *et al.* [2008] in this issue), and disturbances, such as fire and hurricanes (Hopkinson *et al.* [2008] in this issue; Marshall *et al.* [2008] in this issue). The nested gradients selected will depend on the specific questions and responses being addressed.

Site selection should capture key characteristics of the gradients being studied. Sites that are expected to exhibit state changes in the near future (decades) and those that are expected to be comparatively stable (centuries) should be included in the design.

Step 4. Sampling scheme for measuring importance of connectivity across scales

Measuring the importance of connectivity to ecosystem dynamics in adjacent and non-contiguous areas requires coordinated and integrated efforts to sample transport processes and spatial context as well as drivers and local processes at each site. Changing pattern–process relationships across scales need to be studied explicitly (Peters *et al.* 2007). Representative samples with adequate replication are required at each scale, along with standardized indicators of change and sampling techniques (eg Herrick *et al.* 2005). Coordinated sampling among sites is insufficient without integration and an understanding of the key connectors across space and through time. For example, the same set of investigators collected similar measurements at sites located throughout the Dust Bowl region, yet they were unable to predict the continental-scale consequences of locally high plant mortality and movement of dust (Weaver and Albertson 1940).

In general, there are three parts to the sampling scheme. First, patterns and processes need to be characterized at each spatial scale. Key transport vectors (water, wind, animals, people) that move materials among spatial units and processes that occur within spatial units (eg sedimentation, fertilization, denitrification, land-use conversions) should be identified. The sources and sinks of materials need to be determined for each transport vector at each scale. The initial patterns in biota, soils, and climate should be documented along gradients of sites with different broad-scale drivers and transport vectors.

Second, short- and long-term dynamics must be documented using observations, experiments, and simulation models. Changes in pattern need to be monitored through time as the broad-scale drivers vary naturally. Drivers or patterns can also be manipulated experimentally to observe ecosystem responses under altered, yet controlled, conditions (eg Cook *et al.* 2004). Realistic mechanistic models are needed to predict ecosystem dynamics as drivers and transport of materials change along gradients and across the continent. These dynamics must be compared statistically with historical trends, if possible, to determine if changes constitute natural fluctuations, directional dynamics, or heightened variability.

Third, information should be integrated and synthesized, both within and across scales. The relative importance of local and transport processes to ecosystem dynamics needs to be compared statistically as drivers change through time. The results must be synthesized among sites, both within and across gradients and within and across regions, to compare responses and seek generalities.

Finally, this information can be used to determine when and where fine-scale processes propagate to influence large areas (adjacent or not), and the conditions under which broad-scale drivers overwhelm fine-scale processes.

■ Forecasting future dynamics

Addressing continental-scale questions will require development of ecological, hydrological, climatological, and sociological models that are integrated and linked with one another. Some models will address questions at local to regional scales, whereas others will incorporate fine-scale patterns and processes to simulate regional- to continental-scale dynamics. Still other models will forecast a future with conditions that are unprecedented in Earth's history; an empirical extrapolation of responses based on current or past conditions is therefore impossible and a mechanistic modeling approach will be required. In addition, these forecasting models will need to be both spatially explicit and spatially interactive to project experimental results from plots to local, regional, and continental scales (Peters *et al.* 2004b).

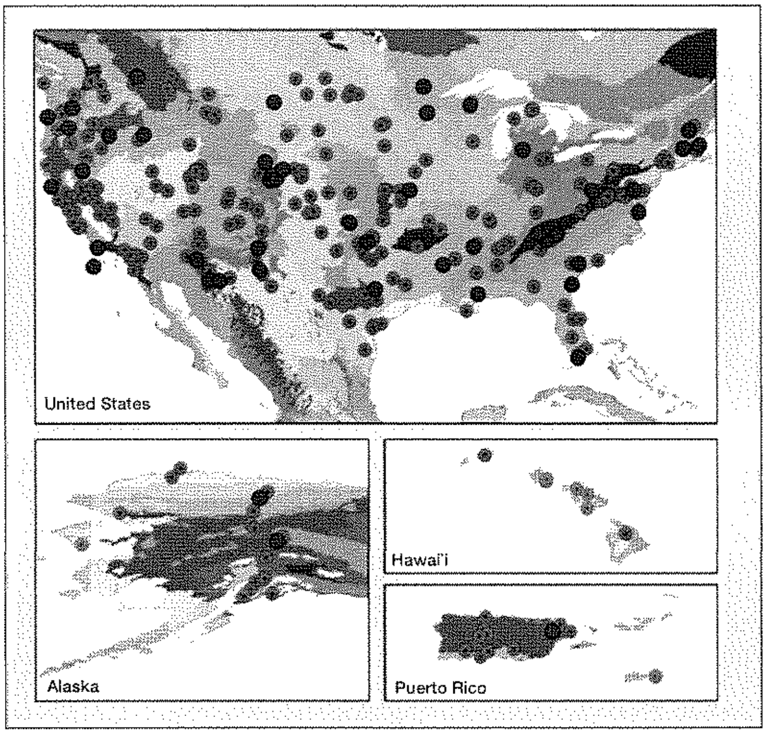

Figure 5. *Location of > 250 existing ecological research sites in the continental US, Alaska, Hawai'i, and Puerto Rico on a map of ecoregions. Red dots indicate sites in the EcoTrends project of long-term data (www.ecotrends.info); blue and red dots indicate sites in the Pole-to-Pole Ecological Lattice of Sites project (www.p2erls.net). See www.worldwildlife.org for ecoregion legend. Underlying ecoregions map downloaded from www.worldwildlife.org/science/data/terreco.cfm.*

Most models thus far have been developed for specific sites with defined spatial and temporal resolutions, are based on existing input parameters, and have been validated under current environmental conditions (eg Schimel *et al.* 1997). A new generation of models is needed to address cross-scale interactions such as those posed here. These new models can build on existing models, but will require advances in programming and cyberinfrastructure to simulate responses that change through time or across space, and to identify and forecast potential thresholds. Simulating coupled socioecological systems will require linking models after resolving differences in spatial and temporal scales (eg Costanza and Voinov 2003). For example, ecohydrologic models couple biogeochemical processes with hydrologic transport to describe connectivity by water for hillslopes and watersheds (eg Tenhunen and Kabat 1999). Coupling advanced fluid-dynamic models, population dispersion models, or human demographic models with ecosystem models would dramatically improve our understanding of connectivity via multiple interacting vectors.

■ Relationship with existing and emerging networks of continental-scale research

Understanding connectivity in the flow of materials, organisms, and information at the continental scale requires a network of ecological research sites that provides spatial breadth (eg comprehensive representation of the full range of climatic, ecological, and socioeconomic conditions) and temporal depth (eg sites with long-term records). The concept of creating an ecological "network of networks" to study global climate change and other broad-scale phenomena dates back to a 1991 workshop (Bledsoe and Barber 1993). The report called for the creation of a network that included the National Science Foundation's Long Term Ecological Research (LTER) Network and Land-Margin Ecosystem Research sites (now folded into the LTER Program), National Oceanographic and Atmospheric Administration Marine Sanctuaries, the Department of Energy Research Park Network, the US National Park Service, and the Man and the Biosphere Reserves. Today, such an ecological network of networks in the US would also include US Geological Service (USGS) and USDA Forest Service and Agricultural Research Service sites, biological field stations and marine laboratories (eg Organization of Biological Field Stations, National Association of Marine Laboratories), the AmeriFlux network, and emerging environmental observatories (eg National Ecological Observatory Network, WATERS, Oceans Observatories Initiative). This network would encompass sites in every major ecoregion (Figure 5) to include the full range of climatic and environmental conditions. The network would also encompass valuable, long-term observations from an array of research sites that are presently being compiled in EcoTrends (www.ecotrends.info), a collaborative effort, designed to make long-term ecological data accessible for science and education.

Achieving a continental-scale understanding of the multiscale connectivity interactions raised here necessitates international collaboration to include Canada's Environmental Monitoring and Assessment Network, Mexico's National Commission for the Knowledge and Use of Biodiversity (CONABIO), and other relevant research sites and networks throughout North America. The availability of data from a North American "network of networks" would substantially augment the knowledge base that is emerging from international research networks like FLUXNET, the International Long Term Ecological Research Network, the OCEAN Sustained Interdisciplinary Timeseries Environment Observation System, the Global Lake Ecological Observatory Network, and the International Geosphere–Biosphere Program. Cyberinfrastructure would provide the data and resources for understanding ecological connectivity at the global scale and would entail closer integration of US (eg USGS NBII, NASA DAACs, Knowledge Network for Biocomplexity) and global (eg Committee on Earth Observation Satellites International Directory Network, the Global Observing Systems Information Center, the International Oceanographic Data and Information Exchange) networks. An initial step toward networking ecological sites globally is being made with the development of a common web interface that allows information about sites to be made easily accessible to users (www.p2erls.net).

■ Conclusions

Given the availability of existing global networks, this is an exciting time for ecological research. Together, these networks provide a platform for continental-scale research with their legacy data, site-based knowledge and expertise, and, in many cases, shared concerns about the consequences of an ever-changing, increasingly connected world. A framework focused on connectivity provides a way to integrate the information being collected in a way that both facilitates and shows the necessity for collaborative research across multiple scales. The integrated understanding of an increasingly connected world derived from a global network of networks is essential for the continental-scale science needed to understand and forecast the causes and consequences of anthropogenic global environmental change.

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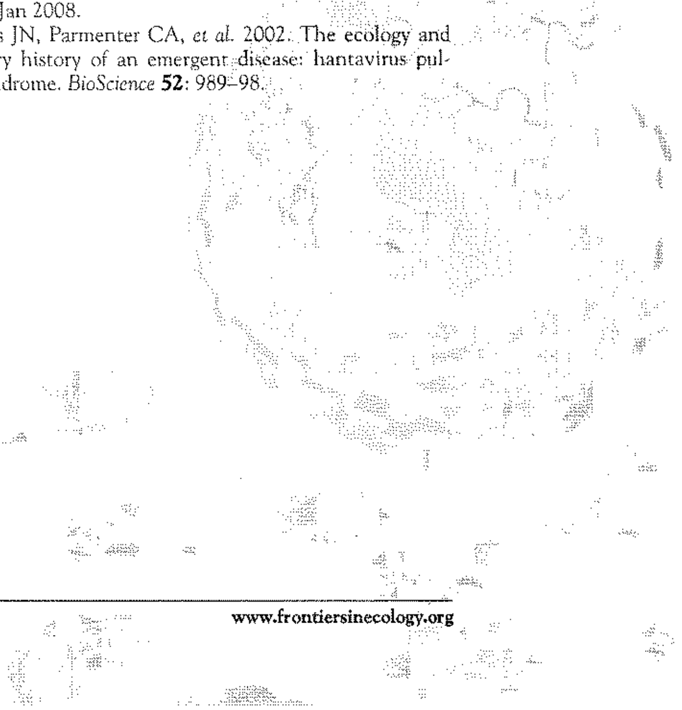

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TELLUS

An overview of regional land-use and land-cover impacts on rainfall

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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, this type of human disturbance of the climate system will continue and become even more significant in the coming decades.

1. Introduction

The role of landscape change in altering convective rainfall has been well documented (e.g. Pielke, 2001; Pitman, 2003). This paper summarizes the subject by landscape conversion type with a particular focus on how regional change results in changes in rainfall, in the same area. The teleconnection effect, where regions remote from the landscape conversion have altered rainfall (e.g. as discussed in Chase et al., 2000 and Avissar and Werth, 2005) is not the focus of this paper, as this is discussed elsewhere (e.g. Pielke et al., 2002; Marland et al., 2003).

Cotton and Pielke (2007; Table 6.2) list papers on the issue as to how regional weather patterns are affected by land-use and land-cover change. Warm season rainfall should be expected to change whenever deep cumulus convection is common in a region, since the surface fluxes of moisture, sensible, and latent heat change. This is the fuel for thunderstorms both in terms of moisture and in altering the convective available potential energy (Stull, 1988). The effect on cold season rain and snowfall, if any, is much less clear, and is not discussed in this paper.

The structure of the paper is to present examples of the role of human land-cover/land-use change for several landscape types. The main goals are to update earlier review papers as well as to further demonstrate the important role of landscape change as a first-order climate forcing. Land-use/land-cover change, while highlighted as a major climate forcing in National Research Council (2005), is still not generally recognized in international climate assessments as having a role on precipitation that is at least as large as caused by the radiative effect of the human addition of added well-mixed greenhouse gases.

We categorize the human landscape conversions with respect to several biome classes. We chose the specific categorization framework in Sections 2 to 9 since the different responses can be more effectively presented. While not inclusive of all landscapes, the examples that we present clearly document the important (and diverse) role of land-use/land-cover changes on climate.

2. Short-grass conversion to dryland agriculture and irrigated agriculture

Prior to agricultural settlement in the mid-19th-Century, grasslands comprised 300 million hectares of central North America, 21% of which (61.5 million ha) was short-grass steppe (Küchler, 1964; Sims and Risser, 2000). Short-grass steppe occupies a region that stretches from Western Nebraska to Western Texas, adjacent to the eastern front of the Rocky Mountains. It is dominated by low stature (5–30 cm), drought-tolerant, warm-season grasses such as *Bouteloua gracilis* and *Buchloë dactyloides* (Archibold, 1995; Sims and Risser, 2000).

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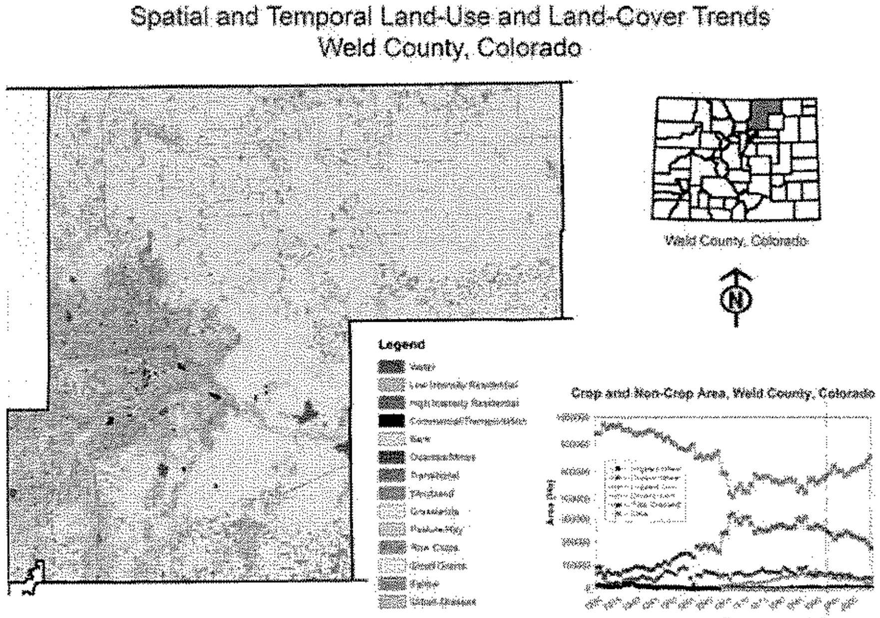


Fig. 1. National Land Cover Data (Vogelmann et al., 2001) illustrate the 1992 distribution of land-cover classes in Weld County, Colorado, a county within the short-grass steppe that has undergone extensive modification since the mid-19th Century. In general, areas closer to rivers are irrigated, while upland areas support dryland farming and short-grass steppe rangelands. The graph illustrates changes in agricultural area in Weld County from 1929 to 2004 due to precipitation changes, economic conditions, and implementation of irrigation (statistics from National Agricultural Statistics Service, http://www.nass.usda.gov/). With the exception of wheat, most crop statistics start in the late 1950s and early 1960s, hence the apparent jump in total cropland during 1963 (corn reported) and 1965 (hay included). The "other" class is cropland area subtracted from the county total, and it includes short-grass steppe, fallow, water, and residential classes.

Over the course of the next 150 years following settlement, somewhat less than half of the short-grass steppe was converted to agricultural land covers, principally dryland and irrigated croplands, to create a mosaic of native vegetation and croplands (Lauenroth and Milchunas, 1991; see Fig. 1 as a county scale example). Overall, vast areas of short-grass steppe were converted to dryland farming, where a wheat-fallow rotation is used for periodic soil moisture recharge. With the development and implementation of irrigation from the 1940s to 1980 (Chase et al., 1999; Parton et al., 2005), dryland farming area declined slightly, yields increased (Burke et al., 1994), and crops with higher water requirements (e.g. *Zea mays*) were planted. Further, ongoing technological advances (e.g. tillage practices, crop rotations, genetic characteristics) and changes in economic conditions and government programs (e.g. Conservation Reserve Program) produce chronic shifts in land cover and occasional conversion back to grasslands.

The conversion from native short-grass grassland to cropland is manifested in biophysical effects that influence energy and water cycling. Seasonality, 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 short-grass steppe (Paruelo et al., 2001). Moreover, surface roughness is higher with the taller agricultural plants (Chase et al., 1999; Bonan, 2002). Lastly, moisture fluxes are higher in the agricultural systems, especially irrigated croplands (Baron et al., 1998; Chase et al., 1999; Stohlgren et al., 1998).

Growing season dynamics are changed with conversion to agriculture. With short-grass 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 short-grass, respectively (Paruelo et al., 2001).

The effect on air temperature and precipitation produced with short-grass conversion varies with the conversion, spatially and temporally. The magnitude of change from short-grass 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 with irrigated croplands (Segal et al., 1989; Chase et al., 1999). At larger scales, given the same brief temporal scale, this difference produces a regional cooling effect and precipitation increase in the immediate lee of adjacent Rocky Mountains (Stohlgren et al., 1998). In a coarse resolution (50 km grid increment) regional modeling comparison of natural and current vegetation change over a much larger area of the Great Plain, Eastman et al. (2001) showed a 0 to 1°C increase in maximum temperatures over unconverted short-grass steppe, while a 2 to 3°C increase occurred in areas converted to dryland crops. Precipitation changes were heterogeneous. Irrigation has recently been shown in a global model to be an important climate forcing (e.g. Lobell et al., 2006).

Future work on the short-grass steppe must address scaling issues, future scenarios and linking altered energy and water dynamics to ecosystem functions. A gap in our knowledge exists with respect to spatially fine-scale resolution over longer time periods (e.g. seasonally) and detailed knowledge of annual precipitation patterns are lacking. Future scenarios of relevant economic and environmental forcings on land cover should also be considered. For example, how does the short-grass steppe change with reductions in available irrigation water? How would changes in tillage practices and crop rotations change weather impacts? Last, how do altered land-cover types and their associated physical changes impact ecosystem functions such as decomposition, nitrogen cycling and soil carbon (Epstein et al., 2002; McCulley et al., 2005)?

3. 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 and Schickendanz, 1984; Alpert and Mandel, 1986; Pielke and Zeng, 1989).

Barnston and Schickendanz (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 planetary boundary layer (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 Galleé (1998) used an European regional numerical model (Modèle Atmosphérique Règional) 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. Lohar and Pal (1995) used the Regional Atmospheric Modeling System (RAMS) to show that irrigation can reduce the intensity of sea-breeze convection during the pre-summer monsoon season in eastern India and lead to the observed reduction in regional rainfall. 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, 2001). 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). Much of the corn area replaced the tall grass prairie. 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, as reported in Adegoke et al. (2006) a modeling study consisting of four land-use scenarios over the 15-day period from 1–15 July 1997 was conducted for this region. 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 data set, and the fourth scenario (natural vegetation run) represented the potential (i.e., pre-European settlement) land cover from the Küchler vegetation data set. 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 universal time coordinate (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 re-analysis data (Kalnay et al., 1996) were used to create identical lateral boundary conditions in the four cases (see Adegoke et al., 2006, for additional details on the experimental design).

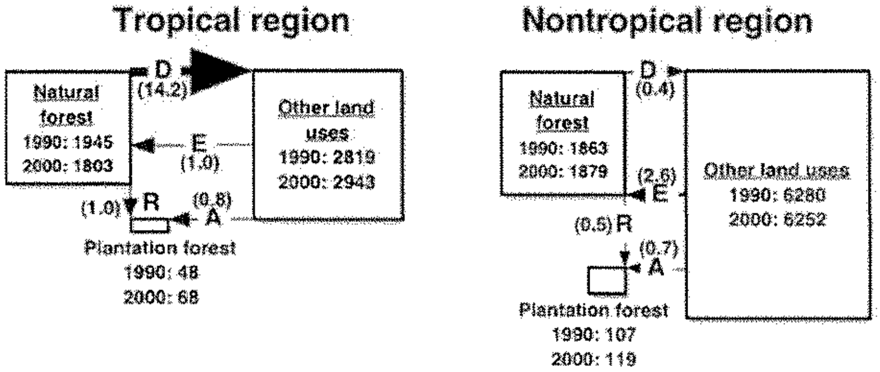
A key finding of this study is that midsummer 2 m temperature over Nebraska might be cooler by as much as 3.4°C under current conditions. The domain-average difference between the control and OGE dry runs computed for the 6–15 July 2000 period was 1.2°C. The cooling effect and the surface energy budget 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 vapour flux (at 500 m) 38% greater in the control run compared to the natural landscape run. Important physical changes between the natural 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, 2001; Holt et al., 2006).

4. Mid-latitude deciduous forest conversion to agriculture

Similar to the grasslands, mid-latitude forests have a discernible impact on the regional weather patterns and climate. However, the forests are a significant terrestrial sink of global carbon. Forest covers have declined through the earlier 20th Century and there has been regrowth of newer forests (Fig. 2). This could be one reason that long-term observational impacts are not well documented for mid-latitude deciduous forests. Lambin et al. (2003) synthesized several cases to present the following pathway for the midlatitudinal landscape conversion as a complex function of: (i) population and resource availability stresses; (ii) opportunities due to market process, production and technology; (iii) policies related to subsidies, taxes, property rights, infrastructure and governance; (iv) vulnerability to external perturbations and coping capacity; and (vi) social organization related to resource access, income distribution, household features and urban-rural interactions which has been further highlighted in Pielke (2004) and Douglas et al. (2006).

Asner et al. (2004) document that agricultural activities associated with grazing operations is another important driver for the deciduous forest to be converted to grasslands and pastures particularly under poor soil conditions. This conversion is summarized to have hydrological impacts through a reduction in the rate of the spring snow melt, a reduction in the cloud condensation level and hence moisture availability, a reduction in the moisture interception due to a reduction in the LAI, and increased runoff and soil evaporation and decreased transpiration. This latter effects leads to higher fluxes of soil moisture and discharge over the landscape, which results in erosion and poor soil conditions over the region. Typically, the change in landscape from forest to grasslands leads to a significant reduction in moisture flux, while the change to cropland can have variable influences on the regional moisture flux (because of crop photosynthetic pathways and transpiration rates, cropping patterns, irrigation, etc.).

Pinty et al. (1989) showed that a nonlinear feedback between soil moisture availability and the forest cover can lead to higher regional precipitation. Anthes (1984), Pielke (2001) and National Research Council (2005) reviewed observational and modeling studies to conclude that landscape changes can modify large-scale atmospheric conditions, and result in increases of convective precipitation. The landscape change impacts are


Tropical region

Nontropical region

Fig. 2. Forest land-use change dynamics for tropical and nontropical regions. All data are averages for 1990–2000, and the units are million (10^6) hectares. Pools (*squares*) and fluxes (*arrows*) are drawn approximately to scale. Abbreviations for fluxes are D, deforestation; E, expansion of natural forests; R, reforestation; and A, afforestation (from Gower, 2003).

manifested through modified moist convection and low-level moisture and heat, changes in albedo, net radiation, and evaporation/transpiration leading to altered circulation and convection, and thus a modification of the regional water recycling. Otterman et al. (1990) provide observational evidence that suggests landscape changes have caused significant precipitation variability in southern Israel. The increase in precipitation is specifically attributable to an intensification of the convection and advection processes due to afforestation and increased cultivation-induced enhancement of the daytime sensible heat flux from the generally dry surface; the enhancement is from both the reduced surface albedo and the reduced soil heat flux, when insolation is strong. Greater daytime convection can lead to penetration of inversions capping the planetary boundary layer, while strengthened advection can furnish moist air leading to circulation changes, and higher precipitation.

Hogg et al. (2000) used field measurements over deciduous forest to show 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 increased moisture availability and precipitation. A number of studies such as Pielke et al. (1991), Xue (1996), Chase et al. (1999), Bounoua et al. (2000), Zhao et al. (2001), Feddema et al. (2005), Niyogi and Xue (2006) have each asserted with different models and independent experiments (and ranging from global to landscape levels) that landscape changes impact surface radiative and biogeochemical fluxes, which in turn affect regional surface temperatures and precipitation either directly or as a feedback to changes in the regional circulation pattern.

For instance, results from 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. Bounua et al. (2000) concluded that for the midlatitudinal forest region, the resulting impact of LAI changes was a decreased albedo; cooling of about 1.8 K during the growing season and slight warming during winter due to snow albedo masking; and 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 U.S. land use/land cover using the Ecosystem Dynamics (ED) model constrained by available data. The RAMS model was used to simulate 3 case scenarios with 3 different surface vegetation distributions – 1700 (pristine), 1910 (maximum deforestation) and 1990 (current conditions). They found that changing the land-use/land-cover pattern can lead to several degrees of warming/cooling at the surface accompanied by significant changes in precipitation patterns.

Unlike the tropics, the impact of deforestation and midlatitudinal precipitation changes are difficult to estimate because of frontal systems and the variety of air mass source regions. Therefore, surrogate hydrological data fields need to be further considered to assess the precipitation changes. Swank and Vose (1994) reviewed four decades of research on changes in water yield and timing of streamflow, following landscape changes from two mixed deciduous hardwood forests to plantations of eastern white pine. Within 10 years after the change, annual streamflow in watersheds was less than expected from mixed hardwoods due to greater transpiration from pines as a result of a higher LAI and corresponding higher interception loss in the dormant season and more transpiration loss in early spring and late fall. Flow duration analysis showed that the conversion to pine reduced the frequency of both high and low flows by 33 to 60 percent both due to precipitation changes and ensuing water loss due to transpiration/interception.

This summary is not exhaustive but yet provides significant clues that the midlatitudinal deciduous land-use changes have also resulted in regional precipitation changes. The complexity of detecting the signature within a naturally high frequency meteorological system and associated changes in the rainfall patterns, and the nonlinear changes in the forest covers (initial decline followed by a asynchronous regrowth in several regions), and the variable changes in the urbanization, pollution loadings and regional circulation patterns makes the quantitative assessment of this effect quite difficult. Therefore, detailed multi-scale modeling studies will continue to be the principal tools to develop attribution and detections associated with land-use and precipitation changes. It remains to be seen if satellite products can detect this change following techniques similar to those discussed in Shepherd (2005) and Cai and Kalnay (2005) using blended re.-analysis data sets.

5. Tropical evergreen forest conversion to agriculture

Tropical forests, occupying approximately 800 million hectares, are being cleared at the rate of approximately 14 million hectare per year. Observational studies, spanning several decades, and numerical modeling studies both show that tropical deforestation influence cloud formation and rainfall (Sud and Smith, 1985; Meher-Homji, 1991; McGuffie et al., 1995; Costa and Foley, 2000; Cutrim et al., 1995; Pielke, 2001; Silva Dias et al., 2002; Lawton et al., 2001 Durieux et al., 2003; Sen et al., 2004; Fisch et al., 2004; Ray et al., 2006). While prior studies agree that deforestation alters cloudiness and rainfall, there is considerable disagreement on the magnitude and nature of the changes. These studies also show that the processes through which deforestation impacts rainfall, result from changes in the following characteristics: physical evaporation, transpiration, surface albedo, and aerodynamic roughness.

Observational studies (Meher-Homji, 1991; Pielke, 2001; Duriex et al., 2003; Ray et al., 2006) generally fall into two classes: 1. Comparisons of rainfall, cloudiness or satellite observed proxies to rainfall between adjacent forested and deforested sites; 2. Time series analyses of similar data over one site that samples conditions before and after the site was deforested.

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. Difficulties encountered by the first type of studies are in accounting for topographic effects and natural spatial variability of rainfall. When using rain gauge data, both of these techniques have to account for differences related to the use of instrumentation in different settings, namely forested versus deforested, which could be significant (Meher-Homji, 1991). A potential strategy for developing reliable data sets for future studies would be to establish long-term rainfall monitoring sites that take into account the above discussed issues, especially in forest areas that face clearing in the near future.

The majority of the General Circulation Model (GCM) experiments that examine the effect of tropical deforestation on climate assume conversion of forests into pastures with higher albedos and lower surface roughnesses. Most of these studies find that deforestation leads to significant reduction in rainfall over the Amazon, while a few report an increase in rainfall (McGuffie et al., 1995; Costa and Foley, 2000). The impact of deforestation in southeast Asia has a seasonal dependency, with rainfall increasing during the wet season but decreasing in the dry season, while over Africa deforestation has minimal impact on rainfall according to one study (McGuffie et al., 1995). GCM simulations also indicate that deforestation has the potential to significantly modify monsoon rainfall over India (Sud and Smith, 1985), while regional-scale modeling results show that the east Asian summer monsoon is sensitive to deforestation in the Indo-China region (Sen et al., 2004).

One of the drawbacks of the GCM and coarse resolution regional models is the inability to resolve mesoscale circulation features induced by landscape heterogeneity. While heterogeneity-induced mesoscale circulations have the potential to modify cloudiness (Souza et al., 2000; Pielke, 2001; Silva Dias et al., 2002; Baidya Roy and Avissar, 2002; Werth and Avissar, 2002), an assessment of its impact on rainfall is lacking and requires well-designed, longer-term regional-scale modeling efforts.

The conversion of forest to pasture that is commonly assumed in several deforestation experiments is also unrealistic. Satellite imagery shows that the secondary growth in the deforested areas often restores the surface albedo to values close to those observed prior to deforestation in a relatively short period of time. Also, deforested areas often are replaced by a composite patchwork of varied land-use categories that include urban, agricultural crops, plantations, pasture, bare soil, and secondary growth and the aggregate effect of such patch work is not very well understood. Seasonal and diurnal observations of the surface energy budget over some the dominant categories of land-use that replace tropical forests are required for this purpose. Prior studies suggest significant water extraction by deep roots in tropical forest. Nepstad et al. (1994) found that 75% of the water extracted by eastern Amazonian forests during the dry season originates from soil layer below the depth of 2 m. However, the rooting depths specified in regional and global atmospheric models specify rooting depths of approximately 2 m for tropical forests. Proper specification of root structures are needed to realistically simulate important hydrological processes such as precipitation recycling that can account for approximately 25% –30% of the rainfall in the Amazon region (Eltahir and Bras 1996).

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 modeling experiments. Mesoscale numerical modeling experiments also show that lowland deforestation and associated increases (decreases) in the Bowen ratio leads to elevation (lowering) of the orographic clouds (Fig. 3) 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. Since this "horizontal" precipitation can be a significant input to the local water budget, assessments of changes in horizontal precipitation resulting from deforestation are needed.

6. Boreal forest conversion due to fire

Fire in the boreal forest is an integral part of this ecosystem (Stocks, 1991). Fig. 4 from Vidale et al. (1997) illustrates the complex patchwork of different aged forest that occur due to the fire history in the area, as well as other disturbance such as disease, insect infestations and land management (Atlas of Canada, 2006). According to this Atlas, there are about 9000 forest fires recorded annually in Canada. An average of 2.1 million hectares are burned every year; virtually all of it is boreal forest. Lightning accounts for about 85% of all hectares burned annually, and people are responsible for the rest. The fires caused by people are more numerous, but burn a smaller area than those ignited by lightning. This fire frequency should be similar in other boreal forest areas.

As shown in Vidale et al., 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 includes the ubiquitous lakes that exist in the boreal forests. Knowles (1993) reported that cumulus cloud 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 cloud will more likely initiate fires immediately downstream of a recent burn scar, rather than elsewhere in the forest. After a period of time, as the forest regenerates, the burned area may be lighter than

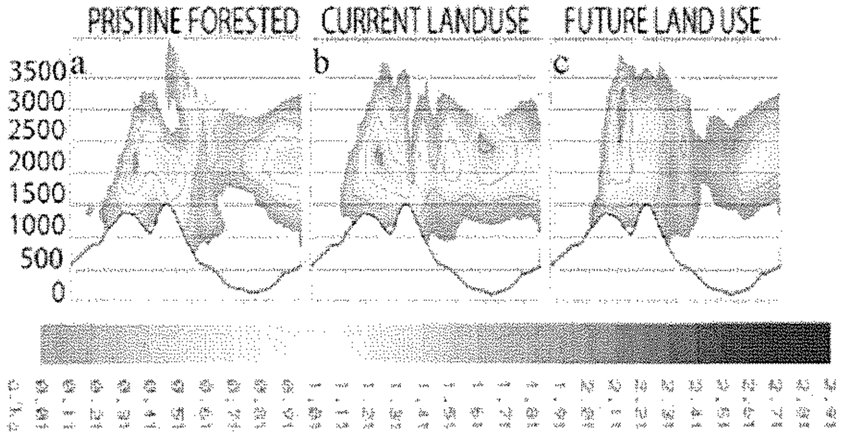


Fig. 3. Numerical simulation of orographic cloud formation for three lowland deforestation scenarios in Northern Costa Rica: a) pristine forests; b) current land-use; c) complete deforestation of the lowlands. East-West cross sections of cloud water mixing ratio, simulated by the Regional Atmospheric Modeling System, show orographic cloud bank form at lower elevation when there is forest cover in the lowland areas (Nair et al., 2006).

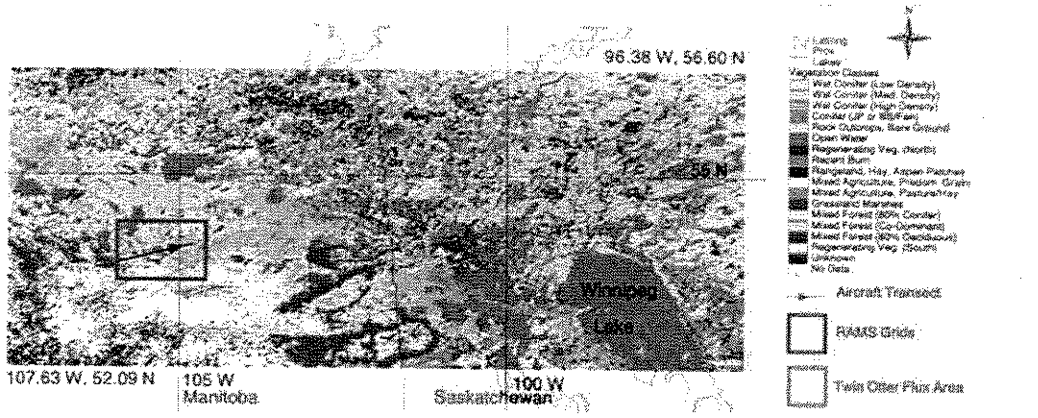


Fig. 4. AVHRR 1 km BOREAS regional land-cover classification. Dark lines and letters indicate latitudes and longitudes with an interval of 5 degrees. The map corresponds to RAMS grid 52.09° to 56.60°N and 107.63° to 96.38°W. From Vidale et al. (1997).

the surrounding unburnt landscape, as aspen and other second 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 the 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 and 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.

7. Urbanization

While the fraction of the Earth' s surface currently classified as urban accounts for less than 2% of 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 (Oke, 1988; Arnfield, 2003; Shepherd, 2005). 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 back over three decades (e.g. Huff and Changnon, 1973). Studies in the U.S. have been especially concentrated in three urban areas, St. Louis, Atlanta, and Houston. These studies have generally demonstrated increases in rainfall over and downwind of urban areas (Shepherd and Burian, 2003; Dixon and Mote, 2003; Bornstein and Lin, 2000; Huff, 1986; Huff and Changnon, 1973) attributed largely to the Urban Heat Island (UHI) initiated convergence zone and to a lesser extent, to the increased surface roughness. 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 and Lin (2000) also found urban influence on established thunderstorms approaching an urban area.

Laboratory and mesoscale modeling studies have demonstrated that the UHI impacts local mesoscale circulation patterns. These changes to the circulation should be expected to have an effect on precipitation as these circulation features are often accompanied by or provide the forcing mechanism for precipitation. Studies have demonstrated significant changes to the convective boundary layer structure (e.g. Hildebrand and Ackerman, 1984; Baik et al., 2001) and even influence the behavior of cold fronts (Gaffen and Bornstein, 1988). But the most completely studied influence is that of a UHI with a coastal sea breeze (Yoshikado, 1992; Kusaka, 2002; Ohashi and Kida, 2002, 2004; Cenedese and Monti, 2003; Martilli, 2003) where nearly all found a significant influence of the urban area on the development (timing and intensity) of the sea breeze front.

Most recently, urban parameterizations schemes (e.g. the Town Energy Balance (TEB) model; Masson, 2000; Lemonsu and Masson, 2002) have allowed mesoscale models to simulate the impacts of urban areas on mesoscale flow. This has permitted detailed sensitivity experiments (van den Heever 2005; Molders and Olson, 2004; Nobis, 2006) plus more sophisticated studies of actual events (Craig, 2002; Rozoff et al., 2003; Gero et al. 2006; Nobis 2005; Niyogi et al., 2006). Results from these studies have further confirmed the role of urban areas in precipitation modification and could be utilized in land-use planning and operational forecasting.

The biggest single unknown to the urban induced precipitation problem is the role of urban aerosols. Studies like van den Heever and Cotton (2005) have begun to examine the relative sensitivities involved, but as Shepherd (2005) points out, while evidence points strongly to a role for aerosols in urban precipitation modification, the details of that role remain highly uncertain.

8. Tropical forest fires and resultant biomass burning effect on rainfall

The role of tropical evergreen forest conversion to agriculture was discussed in Section 5. In this section, the specific focus is on the role of fires in the tropics, often ignited by direct human intervention, on rainfall. Deforestation in the tropics has been accelerating over the past several decades (Skole and Tucker, 1993) and is often accomplished by biomass burning (Setzer et al., 1994) as a means for land clearing (Crutzen and Andreae, 1990). Biomass burning produces smoke plumes with large quantities of aerosols (tiny particles) which can potentially affect the regional, even global hydrological cycle (Ramanathan et al., 2001).

Aerosols serve as cloud condensation nuclei which affect the formation of cloud droplets (Cotton and Anthes, 1992); thus the extensive input of aerosols from fires could significantly affect cloud properties and rainfall. The first study to suggest this connection was based on significantly elevated concentrations of cloud droplets observed downwind of sugarcane fires (Warner and Twomey, 1967). Later, aerosols were hypothesized to reduce precipitation by increasing the number of small cloud droplets but suppressing their coalescence into larger, precipitation-sized drops (Albrecht, 1989).

In addition to affecting cloud microphysics, aerosols absorb and scatter radiation. Increased aerosols in the atmosphere from forest fires thus 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 and Feichter, 2005).

The arrival of satellite-based observations of aerosols and rainfall in the 1990s first enabled monitoring over large spatial scales. Kaufman and Fraser (1997)—based upon satellite observations from the AVHRR sensor—have shown a reduction in the cloud droplet radius with aerosol loading from biomass burning in the Amazon, but did not quantify the effect on precipitation. Rosenfeld (1999), using satellite-based precipitation observations from the Tropical Rainfall Measuring Mission (TRMM), illustrated for a single day that aerosols from a biomass burning event in Indonesia shut down warm-rain processes.

While research concerning the impact of biomass burning on rainfall—such as Rosenfeld (1999)—have generally been limited to short time periods and have been focused on warm-rain processes, recent studies have revealed the crucial role of ice processes and dynamical feedbacks that go beyond the previous simple microphysical and radiative considerations. For instance, Andreae et al. (2004) analyzed Amazonian aircraft observations, and found delays in the onset of precipitation within smoky clouds. However, the lack of early warm-rain processes enabled updrafts to accelerate and reach higher altitudes and produce stronger storms. Thus the authors concluded that the net effect of aerosols on total precipitation "remains unknown." A recent modeling study incorporating state-of-the-art spectral microphysics (Khain et al., 2005) has shown 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 (Khain et al., 2005).

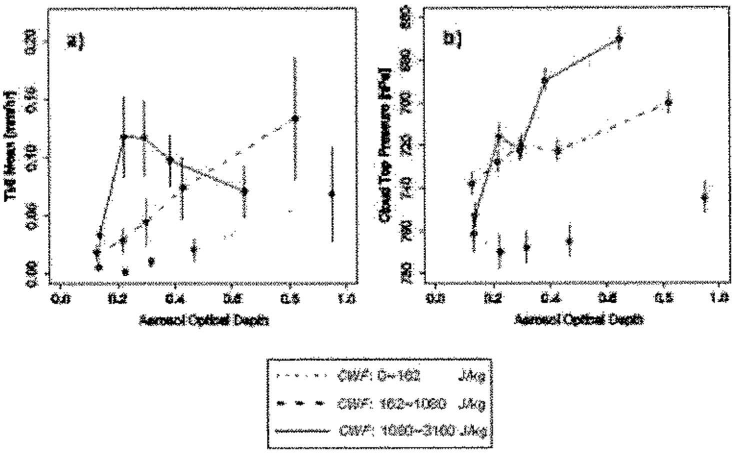


Fig. 5. (*a*) Relationships of rainfall measured by the TRMM-TMI sensor with MODIS aerosol optical depth (τ_a), for the year 2003. The data are binned by τ_a, with each bin spanning 20%tile of the τ_a values and further stratified into different *CWF* regimes. The dotted, dashed, and solid lines range from the lowest third to the top third values of *CWF*, respectively. The error bars denote the standard errors ($\sigma/\sqrt{N}$) of the bin-average. (*b*) The relationship between MODIS cloud top pressure and τ_a. Note the y-axis has been inverted to indicate the fact that higher cloud is associated with lower cloud top pressure.

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 (Fig. 5a), even after accounting for the atmospheric stability environment through the cloud work function (*CWF*). Changes in cloud properties were also correlated with aerosol loading; i.e. higher cloud tops (Fig. 5b), increased presence of ice, and enhanced cloud cover.

Thus aerosols from biomass burning have been demonstrated to have complicated effects on rainfall. This topic will likely continue to attract significant scientific interest in the coming years (National Research Council, 2005), especially as tropical precipitation provides three-fourths of the energy that drives the atmospheric wind circulation through latent heat release (Kummerow et al., 2000); thus perturbations to tropical rainfall from biomass burning can have potentially critical climate consequences. Such alterations to the hydrological cycle can also have major effects for the biogeochemical cycles (Niyogi et al., 2004), and the fresh water supply (Ramanathan et al., 2001; Lohmann and Feichter, 2005).

9. 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). Afforestation refers to locations that did not have natural forest cover, while reforestation replaces a forest that was removed. In southern South America, A&R plans started 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; Jackson et al., 1996; Pitman, 2003). Changes in these parameters can modify the near-surface energy fluxes, which can influence temperature and humidity (Pielke, 2001). In general, observations and modeling studies agree that A&R would decrease near-surface temperature and increase latent heat (e.g. Fahey and Jackson, 1997; Xue and Shukla, 1996; Nosetto et al., 2005). Simulated impacts on precipitation are not so clear, and they depend on geographical location, regional atmospheric characteristics, extent of the afforested-reforested area (Xue and Shukla, 1996; Pitman and Narisma, 2005) and biophysical parameters involved in the land-use/land-cover change (Xue et al., 1996).

Regional and global modeling studies have usually addressed deforestation effects on precipitation (e.g. Xue and Shukla, 1993; Chase et al., 1996; Kanae et al., 2001; Baidya Roy and Avissar, 2002; Narisma and Pitman, 2003; Oyama and Nobre, 2004; Avissar and Werth, 2005, and other references in this paper). Therefore, the effects of A&R could be inferred from those studies. For instance, land-cover changes, from trees to grass or crops over southwestern Australia, from the mid 1700's to present, could partially explain the observed decreases in winter precipitation (Pitman et al., 2004). Thus, large-scale reforestation could increase rainfall in the long-term. However, Xue and Shukla (1996) found that the effects of afforestation-deforestation over the Sahel on precipitation were not linear, but depended on the location of the perturbed area with respect to the position of large-scale circulation features (i.e., subsidence branch of the Hadley circulation).

In general, modeling exercises show rainfall increases in an A&R scenario with respect to a current land cover. Those changes can be attributed to changes in moisture convergence (due to changes in roughness length and displacement height) and latent heat (Xue and Shukla, 1996; Pitman et al., 2004; Beltrán, 2005). Using a global circulation model (COLA-GCM), Xue and Shukla (1996) found increases of 0.8 mm day^{-1} (or 27%) on the Sahel precipitation over the afforested area, and decreases south of it. Using a regional coupled atmospheric-biospheric model, GEMRAMS, over the central Pampas in southern South America, Beltrán (2005) found that afforestation led to increases of 1 mm day^{-1} on average in simulated summer precipitation (i.e. December–January). In both studies, the impact of afforestation on precipitation was relatively high for a "dry year". In a recent study, Jackson et al., (2005), using a U.S. projected afforestation scenario based on the response to payments for carbon sequestration and a regional climate model (RAMS), found that changes in summer precipitation were not noticeable, and depended on site location. A general decrease in rainfall was found in afforested areas located in the northern states. Precipitation increased in a few areas such as in Florida and southern Georgia and in other grid cells not directly affected by the land-cover change. In this case, the shift of available energy from sensible to latent heat in the afforestation experiment reduced the convective precipitation in the temperate regions.

Observational (Jackson et al., 2005) and several modeling studies (i.e. Xue et al., 1996) have shown 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 represent an important tool to study the impacts of realistic patterns of A&R on precipitation.

10. Conclusions

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., 2006), 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 National Research Council (2005); a conclusion which is bolstered by studies such as that of Chase et al. (2000) and Fedemma et al. (2005).

The National Research Council (NRC) had the following conclusion and recommendations in recognition of the important role of land-use/land-cover change on the global climate, including the alteration of precipitation processes:

> 'Regional variations in radiative forcing may have important regional and global climatic implications that are not resolved by the concept of global mean radiative forcing. Tropospheric aerosols and landscape changes have particularly heterogeneous forcings. To date, there have been only limited studies of regional radiative forcing and response. Indeed, it is not clear how best to diagnose a regional forcing and response in the observational record; regional forcings can lead to global climate responses, while global forcings can be associated with regional climate responses. Regional diabatic heating can also cause atmospheric teleconnections that influence regional climate thousands of kilometers away from the point of forcing. Improving societally relevant projections of regional climate impacts will require a better understanding of the magnitudes of regional forcings and the associated climate responses.

The NRC Report recommended that we should

> Use climate records to investigate relationships between regional radiative forcing (e.g. land-use or aerosol changes) and climate response in the same region, other regions and globally.
>
> Quantify and compare climate responses from regional radiative forcings in different climate models and on different timescales (e.g. seasonal, interannual), and report results in climate change assessments.'

The report also concluded

> "Several types of forcings—most notably aerosols, land-use and land-cover change, and modifications to biogeochemistry—impact the climate system in nonradiative ways, in particular by modifying the hydrological cycle and vegetation dynamics. Aerosols exert a forcing on the hydrological cycle by modifying cloud condensation nuclei, ice nuclei, precipitation efficiency, and the ratio between solar direct and diffuse radiation received. Other nonradiative forcings modify the biological components of the climate system by changing the fluxes of trace gases and heat between vegetation, soils, and the atmosphere and by modifying the amount and types of vegetation. No metrics for quantifying such nonradiative forcings have been accepted. Nonradiative forcings have eventual radiative impacts, so one option would be to quantify these radiative impacts. However, this approach may not convey appropriately the impacts of nonradiative forcings on societally relevant climate variables such as precipitation or ecosystem function. Any new metrics must also be able to characterize the regional structure in nonradiative forcing and climate response.
>
> Improve understanding and parameterizations of aerosol-cloud thermodynamic interactions and land-atmosphere interactions in climate models in order to quantify the impacts of these nonradiative forcings on both regional and global scales.
>
> Develop improved land-use and land-cover classifications at high resolution for the past and present, as well as scenarios for the future.

Our summary of research on land-cover/land-use change on rainfall also results in the following recommendations:

- Future work for each biome must address scaling issues (from local to regional to global), future land use and land cover scenarios, and the resultant altered energy and water dynamics as they effect ecosystem function;
- Tropical and higher latitude deforestation appears to result in different responses to precipitation. This could be due to the role of cold and warm frontal (i.e. baroclinic) dynamics in the higher latitudes in precipitation processes even in the summer; . . .
- More research is needed to better understand the role of landscape patterning on precipitation. Such studies need to discriminate topographic effects and natural spatial variability of rainfall, from changes due to human land-use/land-cover change.
- Long-term rainfall monitoring sites in forest and grassland areas that face future land-cover/land-use change (e.g. such as deforestation or expansion of irrigation in grasslands) should be a priority. This will provide an observational basis to document the actual role of the landscape conversion on precipitation.
- A major under-monitored climate variable is rooting depth of the vegetation. We need accurate rooting depth specification in the models.

- All of the vegetation and soil information needs to be monitored and made available using the same parameters as required in the models. For example, rather than specifying that a soil is sandy loam, we need the soil density, conductivity, heat capacity, etc, expressed in quantitative units.
- Since model domain size, grid spacing and parameterizations (e.g. convective schemes) significantly influence simulated precipitation (e.g. Castro et al., 2005), more comprehensive regional modeling sensitivity studies are needed to assess those impacts.

Since it is now recognized that land-use change influences precipitation on the regional and the global scale, this important climate forcing should be elevated as a research priority within the climate community.

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