Towards a Policy Framework for Addressing Biophysical Changes due to Land Use

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As the international community gets serious about curbing anthropogenic climate change, several efforts have developed to address – either directly or indirectly – the role that land use change plays in climate. However, by focusing entirely on greenhouse gas (GHG) emissions, often just carbon dioxide, these policies and initiatives are missing an important aspect of the climatic signal resulting from land use change.

In addition to playing a major role in the global carbon cycle, terrestrial ecosystems also shape physical properties of the earth's surface in important ways that help to maintain patterns of climate. The vegetation in these ecosystems reflects and absorbs heat, transpires water, shades soil and snow, and acts as a sink for atmospheric momentum – biophysical processes that in turn help to determine important aspects of climate such as temperature, precipitation, boundary layer height, cloud cover, and air circulation.

As opposed to greenhouse gasses, which exert undoubtedly global influence on the climate due to their well-mixed nature, these biophysical aspects of land use change operate at local and regional spatial scales, which may or may not in turn influence larger scale atmospheric circulations(16). At those local and regional spatial scales, however, the effect of biophysical land use changes on climatic variables of interest to humans and ecosystems (e.g. temperature, precipitation) can be orders of magnitude greater than the effect of GHG emissions resulting from those same land use changes(18). Further research is needed to elucidate which biophysical changes are most influential for which climatic outcomes at what spatial scales.

Terrestrial ecosystems are well recognized as important vehicles of climatic feedback – anthropogenic climate change alters the structure of ecosystems, which in turn leads to additional climate change through both carbon cycle and biophysical mechanisms(5, 24). However, the biophysical aspects of direct human interference with the land surface – which we refer to as "biophysical changes" - are a first order climate perturbation unto themselves.

In the context of large-scale climate change resulting from fossil carbon emissions, biophysical changes also offer the possibility of local or regional adaptation strategies. For instance, Ridgwell et al. suggest that simply switching to higher albedo crop varieties could induce a 1 degree Celsius cooling effect across temperate agricultural zones and surrounding areas(20). Well-informed landscape design and land management practices might enhance regional water cycling, temper heat islands, reduce wind speed, or even influence storm dynamics. On the other hand, naïve practices could unwittingly reinforce the most damaging climate change effects.

While the overall importance of biophysical land surface processes in shaping patterns of climate is well-recognized (13), more research is needed linking specific land use practices to specific climate outcomes in order to inform policies aimed at mitigating or adapting to climate change by influencing land use.

The Treatment of Land Use Change in Existing Climate Policies and Initiatives

Several policy mechanisms exist or are under development to encourage or discourage specific land uses based on their effect on atmospheric GHG concentrations. The Clean Development Mechanism (CDM) of the Kyoto Protocol permits the generation of carbon credits for afforestation and reforestation projects. In addition, several proposals are being debated within the UN Framework Convention on Climate Change (UNFCC) to provide incentives for reduced deforestation and degradation (REDD), most of which involve the transfer of funds to participating countries in proportion to some calculated value of reduced carbon emissions from forestry activities. Private forestry carbon offset projects exist as well. For the agricultural sector, incentives are being developed to compensate farmers for specific land management practices that promote carbon sequestration or reduce carbon emissions. For example, drafts of the US cap-and-trade policy under consideration in the US Congress offer carbon offset payments for practicing conservation tillage.

Furthermore, the recognition that conventional biofuels have significant land use change impacts has sparked a debate about how to account for and reduce emissions from those land use changes in policies primarily intended to address the energy sector(8, 23). Both California's Low Carbon Fuel Standard(9) and the US Renewable Fuels Standard contain provisions that require a calculation of the life-cycle GHG emissions due to biofuel production – provisions that have generated a great deal of controversy stemming from the deep uncertainties, yet high stakes for biofuel producers of estimating emissions from land use change, especially land use change mediated by market interactions.

All of this concern regarding carbon emissions from land use change is certainly justified. Terrestrial ecosystems contain approximately three times as much carbon as does the atmosphere, mostly in the form of living plants and their remains in soil. Alteration of those ecosystems – through whole scale conversion of landcover (from forests, savannahs, and grasslands to croplands, pastures and cities) as well as through ongoing management of agricultural and forestry systems – represents a perturbation to the global carbon cycle on the same order of magnitude as the release of fossil carbon by energy use. The Intergovernmental Panel on Climate Change (IPCC) estimates that deforestation and forest degradation contribute roughly 20% to global anthropogenic carbon dioxide emissions. However, a more recent analysis revises this number to approximately 12% with an additional 3% owing to degradation of tropical peat soils(26).

Meanwhile, terrestrial ecosystems are thought to absorb approximately 30% of all anthropogenic carbon dioxide emissions(4), which demonstrates the huge potential for carbon sequestration that is possible through terrestrial systems, but also points to the dangers of interfering with those systems. The degradation of this carbon sink would act to accelerate climate change resulting from GHG emissions.

Land use change associated with the production of conventional biofuels such as those made form corn, soybean, or sugarcane can lead to significant GHG impacts (8, 21, 23). According to some estimates, land use change emissions constitute more than 50% of all life-cycle emissions(23).

Understanding Biophysical Change for Policy Making

From a policy perspective, the biophysical aspects of land use change raise several important questions:

- How significant are biophysical changes relative to carbon cycle effects of land use change?
- Which biophysical changes are the most significant?
- At what spatial scales are biophysical changes significant?
- To what degree do various biophysical changes interact with one another?
- How can biophysical changes be accounted for in policies intended to encourage or discourage specific land uses based on their climatic signature?
- Should the various climatic aspects of land use change be addressed together through comprehensive policies, or separately, perhaps by different agencies with different priorities?

Much of our knowledge about the climatic consequences of land use change comes from coupled land surface and atmospheric models, although some empirical work has also examined the effects of land use change on climatic conditions. These studies have begun to address some of the above policy questions, but the questions are by no means resolved.

For instance, several modeling studies have examined the effect of historical land use change on climate, either at global(6, 17, 29) or continental(2) scales. Others have explored the role that future land use changes play in shaping predictions of future climate(10). Still others have explored broad scale conversion to specific ecosystem types such as global forestation(11) or broad scale adoption of land management practices(14). Some modeling studies have also isolated regional impacts of specific types of land use change, such as Amazonian deforestation(7), boreal deforestation(3), and the adoption of irrigation(22).

These latter studies that isolate specific land use changes in specific regions are potentially the most useful to policy makers seeking to regulate the climatic consequences of land use change because they provide insight into the repercussions of individual actions.

Interestingly, empirical studies of biophysical change tend to isolate specific land use actions as well.(15, 25, 27) Empirical approaches to estimating the climate signature of biophysical change offer the possibility of sidestepping model-related uncertainties, which are substantial, as demonstrated by a recent review of model representations of historical land use change. On the other hand, empirical methods require the existence of "natural experiments" in the climate and land use record, which may or may not exist for all land use changes of interest and may not apply for land use changes in the future. Still, the increased availability of remote sensing data presents the possibility of detecting more climatic signatures attributable to specific land use changes.

In order to move forward with a policy framework for addressing biophysical change, research on the climatic signatures of specific kinds of biophysical change must be synthesized and coordinated in order to address questions like the ones raised above. In the next section of this paper, I explore in more detail what a policy framework for addressing biophysical change might look like, identifying more clearly the constraints on a metric that could equate biophysical changes with GHG emissions. In the following section, I outline a modeling proposal to examine biophysical effects of land use change resulting from corn ethanol production - changes that occur in many regions of the world and involve many kinds of ecosystems due to the diffuse nature of market-mediated effects. The model experiments are designed to address fundamental questions about biophysical change that can inform the development of a policy framework for addressing them as well as informing more specific policy debates about the social costs and benefits of biofuels.

Measuring Biophysical Change

Although the need for a metric to account for biophysical changes due to land use is acknowledged in the academic literature(16, 18), none of the major climate policies and initiatives that address land use change employs such a metric. As Marland et al note, the definition of anthropogenic climate change used by the UNFCC refers only to changes in atmospheric constituents whereas the IPCC defines climate change more and explicitly references land use as a direct driver of climate change(16). By focusing on GHG emissions, the current policy paradigm effectively equates the climatic signature of particular land uses with those aspects that can be measured in terms of carbon dioxide equivalents through the global warming potential (GWP) framework. However, due to the varying spatial scales and multiple mechanisms of biophysical climate perturbation, these effects are difficult to characterize within the GWP framework.

Valuing terrestrial carbon through policy mechanisms without valuing or constraining the other climate services provided by ecosystems could produce unintended climate outcomes, just as Wise et al demonstrate through integrative assessment modeling that valuing terrestrial carbon can produce unintended consequences on food prices(28). Continuing this analogy, however, guaranteeing food security in a carbon constrained world does not necessarily require that food security be measured and equated with terrestrial carbon – it could be addressed through a variety of regionally-specific policies such as those that promote technology adoption, preserve farmland, subsidize consumption for the poor etc. Likewise, biophysical climate effects of land use change need not necessarily be equated with carbon through a common global metric. These effects may be more appropriately addressed at the regional scales where they are most pronounced.

The options for addressing biophysical change in the context of GHG change due to land use can be thought of as lying within a two-dimensional matrix (fig 1). The vertical dimension of the matrix represents the degree to which terrestrial GHG regulation is integrated with fossil and industrial GHG regulation through trading mechanisms, whereas the horizontal dimension represents the degree to which biophysical effects of land use are integrated with GHG effects through a common metric. Current policy is moving from the upper left toward the lower left potion of this matrix through various mechanisms that value terrestrial carbon – offset programs, REDD proposals, life-cycle accounting frameworks etc. However, other cells of the matrix may offer advantageous strategies. For instance, while integration of fossil, industrial, and land use carbon emissions under a unified trading scheme is theoretically more economically efficient than separating them, the types of behaviors related to land use carbon emissions are qualitatively different from those related to fossil and industrial emissions. Within the realm of land use, it may make sense to separate the climatic effects due to one-time land conversion activities from on-going management activities, although both of these types of activities have GHG and biophysical components. In order to understand the right-hand side of column of the matrix better, we turn now to a discussion of the GWP metric and its alternatives.

	Biophysical and GHG effects *not* expressed through common metric	Biophysical and GHG effects expressed through common metric
Terrestrial GHG *not* traded with fossil and industrial GHG		
Terrestrial GHG traded with fossil and industrial GHG		

Figure 1 – A schematic representation of policy options for addressing biophysical effects of land use change on climate within the context of greenhouse gas (GHG) effects of land use change. Current policy is moving from the upper left to the lower left portion of the matrix.

Climate Metrics

Figure 2 presents a simple schematic of the relationship between human and climatic systems. Human activity perturbs some aspect of the climate system, known as climate forcing. This forcing in turn produces climate impacts, which are changes in the actual patterns of climate resulting from both the initial forcing and feedback processes. Finally, the result of these climate impacts for human and natural systems can be conceptualized in terms of “damages”.

In seeking to measure and regulate climate-perturbing activities, policy makers are ultimately concerned about addressing damages to society. Thus, an ideal metric for comparing the climatic consequences of various activities should correspond as closely as possible with the actual damages. That is, activities or combinations of activities ranked by the metric should also rank damages.

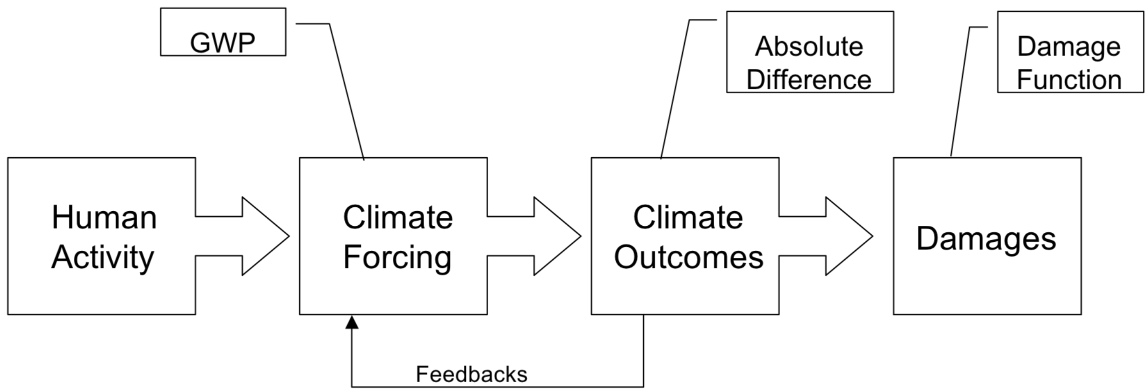

Figure 2 – Schematic representation of human influence on the climate system showing the components of the system measured by various climate change metrics.

Global Warming Potential (GWP)

Global warming potential calculates the cumulative globally-averaged radiative forcing (RF) due to emission of a particular atmospheric constituent over some set time frame and normalizes it by the cumulative radiative forcing of a reference constituent, carbon dioxide, over the same time frame(13). This allows different gases to be expressed in terms of carbon dioxide equivalents.

As a metric for comparing different well-mixed greenhouse gases, global warming potential has some very nice properties. By focusing on the forcing stage of climate perturbation, it avoids the need to calculate, through some sort of modeling, the actual climate impact or damages due to forcing itself. Since well-mixed greenhouse gases exert their radiative influence on the climate in essentially the same fashion over the same spatial areas, it is guaranteed that a unit of radiative forcing due to one or another well-mixed GHG produces the same effect on climate and social damages. Note that although GWP is based on radiative forcing, the climate outcomes and damages that result from this forcing are also hydrological and ecological in nature because the various components of the earth system are coupled.

Even though the relationship between RF and damages may not be linear over different total magnitudes of RF, the relationship can reasonably be expected to be monotonic, so at least RF ranks emissions in the correct order in terms of their damages. The use of GWP does raise concerns about the temporal aspect of RF, though. Some damages may be related to instantaneous RF (e.g. heat waves) whereas other may be related to cumulative RF (e.g. ice melt).

Biophysical effects do not fit into the GWP paradigm for two reasons: 1) The radiative aspect of biophysical change is not distributed over the earth in the same "well-mixed" manner as the principle GHG's, and 2) biophysical change forces the climate system through non-radiative mechansisms in addition to radiative ones.

For example, the albedo increase associated with Amazonian deforestation may induce a local cooling effect. Averaging this effect globally and equating it with the forcing due to carbon dioxide emissions would suggest that albedo changes from Amazonian deforestation might mitigate polar ice melt, which is unlikely. Ultimate climate impacts and damages are very different when radiative forcing is spatially constrained. Furthermore, the change in evapotranspiration associated with this same deforestation exerts both a radiative and hydrological forcing on climate and the hydrological part does not fit into the RF framework at all. This change in water flux to the atmosphere has important implications for regional precipitation, groundwater levels, and surface flows - important climate impacts with the potential to cause social damages that would be unaccounted for by a metric based solely on RF.

Still, globally averaging the radiative effects of biophysical change can give insight into the overall magnitude of these changes, even if doing so represents a departure from approximating the true damages. Some biophysical effects are significant at the globally averaged level (e.g. albedo effects from boreal forest clearing(19)) indicating that they are even more significant at the smaller spatial scales where these effects tend to be concentrated.

Regional Warming Potential

In order to approximate the order of magnitude of radiative climate forcing at different spatial scales, one could imagine a modification of the GWP framework that restricts the consideration of RF to a particular region of interest - a regional warming potential (RWP). However, this metric still would not account for non-radiative forcing mechanisms as discussed above.

To illustrate the insight that could be gained from such a metric, table 1 presents a back-of-the-envelope calculation of the 100 year RWP at three different spatial scales associated with the albedo and carbon stock change from converting 1 hectare of forest to cropland in North America. The change in carbon stock is globally well-mixed and so exerts the same RWP at each scale. However, the spatial extent of the RF due to albedo change is unknown. If it were totally unmixed, affecting only the 1 hectare of land converted, it would represent -9 billion tons of carbon dioxide equivalents on that 1 hectare of land. At the other extreme, if the effect truly were globally averaged, it would still be on the same order of magnitude as the carbon stock change, At the continental scale, it represents -13,000 carbon dioxide equivalents, which is two orders of magnitude greater than the GHG forcing. If this were the case, deforestation would produce a cooling affect at the continental scale due to albedo change, but a mild warming effect outside that region due to GHG emissions. Given the wide range of radiative forcing possible at different spatial areas impacted by biophysical changes such as albedo change, characterizing the spatial scale of various biophysical changes is essential to understanding their role in climate.

Spatial Extent of Albedo Forcing	Albedo Change	Carbon Stocks
	Mg CO2e	Mg CO2e
1 ha	-9.E+12	500
Continental US	-13,000	500
All of Earth	-175	500

Table 1 – A back-of-the-envelope calculation of the 100 year Regional Warming Potential for albedo and carbon stock changes resulting from conversion of 1 ha from forest to cropland in North America. The spatial scale is varied to demonstrate the dramatic differences in the strength of the albedo effect when its radiative forcing effect is distributed over different areas.

Absolute Climate Difference Metric

One approach to accounting for multiple forcing mechanisms within a single metric is to focus on climatic indicators rather than the forcings themselves. For climate indicators such as precipitation and even temperature, both increases and decreases represent a departure from baseline climate and so should be counted as such. Furthermore, since some climate indicators are naturally more variable, departures from their average value in an altered climate may not be as drastic as for more stable indicators.

An absolute climate difference metric would sum the absolute deviations from baseline climate conditions for a number of variables of interest, normalizing by the standard deviation of each variable in the baseline climate in order to weight deviations from less variable indicators more strongly.

Note that this approach requires an understanding of climate feedback processes and interactions among the various components of the earth system in order to generate estimates of the various outcome indicators of interest to humans. Furthermore, this approach might not be monotonic with respect to true damages if one dimension of climate deviation produces very little actual damage and another dimension does. To avoid this, the variables monitored in such a metric would have to be chosen appropriately.

Damage Function

Whereas a metric such as absolute climate difference values climate stabilization by measuring deviations from baseline climate in any direction, not all climate deviations are equally destructive for society or ecosystems. A metric focused on the true damages of climate change would promote climate optimization rather than climate stabilization.

While this approach may not be practical, it provides a useful theoretical extreme against which to contrast other metrics. It also raises the fact that climate change and land use change are related to many different kinds of values for many different actors and these actors may not agree about which aspects of climate and land use are most important.

One practical approach to implementing a damage function would be to weight the various indicators in the absolute difference metric by regional priority factors.

Discussion

As the discussion of appropriate frameworks and metrics for regulating biophysical aspects of land use change evolves, it is important to keep in mind the differing priorities of different agents and policy makers at different scales. More modeling and empirical work that explores the spatial extent, dominant mechanisms of perturbation, and interactions among all the climatic effects of land use change are needed to better characterize the climate signature resulting from specific land use actions and guide the development of appropriate regulatory frameworks. In the next section, I discuss a modeling proposal to address some of these issues for the case of land use change resulting form corn ethanol production in the US.

Modeling Project Phase I –
Analysis of the full climatic land use consequences of US maize ethanol

This study aims to quantify both the GHG and biophysical aspects of global cropland expansion that results from US corn ethanol production. In doing so, we examine cropland conversion in many regions of the world, from many kinds of ecosystems, contrasting diverse regional scale effects of land use change with the globally averaged signal expressed through a variety of potential metrics. This study will inform debates about the social costs and benefits of biofuel production while supporting the development of a framework for comparing climatic perturbations due to biophysical land use changes with those due to GHG emissions.

There are now three prominent economic modeling studies that estimate GHG emissions from the global changes in crop area due to expanded US ethanol production(1, 12, 23). We take one of these(12) as a starting point to model the full climate effects of those land use changes in the Community Climate System Model (CCSM) earth system modeling framework developed by the National Center for Atmospheric Research (NCAR).

Methods

Modeling Tools

Model experiments will take place in a land surface model known as the Community Land Model (CLM) coupled to a global atmospheric model known as the Community Atmosphere Model (CAM). CLM represents energetic, hydrological, biogeochemical, and phenological land surface processes, whereas CAM represents thermodynamic, kinetic, radiative, and chemical processes in the atmosphere.

The land surface in CLM is represented as a grid of cells, each composed of fractional areas of 5 primary landcover types (glacier, lake, wetland, urban, vegetation) and vegetated areas are further subdivided into fractional areas of up to 4 out of 16 potential plant functional types (PFT's). It is the alteration of these plant functional types – from natural vegetation types to cropland – that concerns us. The current version of CLM only features one PFT for all types of cropland. However, for our present purposes, this will suffice because the biophysical change between forests and grasslands to crops captures much of the signal we are concerned with. Future studies (in particular phase II of this project) can explore more subtle biophysical changes associated with different kinds of managed ecosystems, which is relevant for novel bioenergy feedstock systems that may resemble native perennial systems more closely than do annual croplands.

Land Use Change Scenarios

Land use change scenarios associated with corn ethanol production will be generated by modifying the default CLM global land surface dataset, which is based on satellite imagery from 1992-1993 at 1 km resolution. Cropland expansion values will be taken from Hertel et al(12), who performed a market analysis of expanding corn ethanol production to meet the provision of the US Renewable Fuels Standard that calls for 15 billion gallons of renewable fuel utilization by 2015. Hertel et al estimate the area of cropland expansion in each of 18 regions, further subdivided into as many as 18 agroecological zones, which are delineated based on climatic conditions such as length of growing season and precipitation. In addition, Hertel et al estimate the fraction of new cropland in each zone that comes from forest versus grassland ecosystems.

A downscaling algorithm is required to translate the area changes estimated by Hertel et al into 1 km grid level changes for use in CLM. This algorithm will follow the methodology of Hurtt et al, and will take into consideration proximity to existing cropland in order to choose grid cells for cropland conversion that are consistent with the lower resolution estimates of Hertel et al. In addition to proximity to existing cropland, this algorithm might also be augmented to consider existing road networks and topography to further constrain the placement of newly converted cropland onto the land surface grid.

A global land use change scenario incorporating all of the changes estimated by Hertel et al. will be contrasted with a baseline scenario with no anthropogenic influence on climate. In order to isolate the biophysical aspects of land surface changes from GHG emissions from those same land use changes, the global land use change scenario will be run twice – once with GHG emissions from land use change and once without.

In addition a handful of single-region, single-ecosystem scenarios will be generated in which land use is held constant except in one region for one type of ecosystem conversion (e.g. forest conversion to cropland in Brazil). These single-region single-ecosystem scenarios will isolate the contribution of that particular type of land conversion to the global pattern of climate change observed in the global scenario. These additional scenarios will most likely focus on those regions estimated to experience the most land use change by Hertel et al – North America, Europe, South Asia, and Brazil. However, the choice of these isolated scenarios will also be informed by the results of the global land use change scenario, which may reveal interesting climatic phenomena in particular regions worthy of additional investigation. Finally, in order to facilitate the linearity analysis described below, an inverse scenario in which all the land conversions considered in the global scenario not considered by one of the single-region single-ecosystem scenarios will also be evaluated. In summary, the scenarios to be evaluated include:

- A baseline scenario with no anthropogenic climate change
- A global biofuels land use change scenario with land use GHG emissions
- A global biofuels land use change scenario without land use GHG emissions
- Several single-region, single-ecosystem scenarios
- An inverse scenario

Each scenario will be evaluated in the CLM-CAM coupled model system in a transient mode for 50 model years subject to the same set of climatic forcing data and same parameter settings so that the only difference among scenarios are those described above.

Diagnostic Variables

In order to evaluate the climatic change associated with the land use change scenarios, several variables of interest will be monitored at monthly temporal resolution and 1 km spatial resolution. Their monthly mean and standard deviation values will be tracked. These include variables related to climatic forcing, climatic mechanisms, and climatic outcome variables of consequence to humans and ecosystems:

- Radiative forcing
- Evapotranspiration
- Boundary layer height
- Cloud cover
- Mean temperature
- Maximum daytime temperature
- Minimum nighttime temperature
- Growing degree-days
- Precipitation
- Solar insolation

In addition, because CLM models biogeochemical processes, it can provide an estimate of changes in biomass and soil carbon stocks. That result from land use change. These values can provide an additional data point to existing studies that have estimated the carbon dioxide emissions due to land use change induced by corn ethanol production and also provide insight into the time course of such emissions following land use change.

Global Analysis

The global mean value of each diagnostic variable will be compared among the baseline and two global land use change scenarios. In addition, global metrics derived from those values, such as GWP will also be calculated.

Spatial Scale Analysis

The single-region single-ecosystem scenarios will be used to support a spatial scale analysis that attempts to determine the spatial extent of climatic changes due to the specific types of conversion modeled in those scenarios. This will be done by identifying grid cells in which the mean monthly value in the perturbed scenario differs by more than some fraction (alpha) of a standard deviation from the mean value of the same variable in the baseline model. Thus if are concerned with the spatial scale of precipitation changes and alpha is .5, then we would identify months and grid cells for which the perturbed precipitation differs by more than .5 standard deviations from the baseline precipitation level. The spatial scale of the change will then be identified as the maximum distance between grid cells that meet this threshold requirement and grid cells where land use change actually occurred.

Linearity Analysis

To explore the linearity of the climate changes associated with specific types of land conversion, the sum of changes identified by the single-region single-ecosystem scenarios and the inverse scenario in which all other land use changes are modeled will be compared to the full global land use change scenario. Notable deviations between these two climates will offer insight into any non-linear interactions among climatic processes induced by different types of land conversion.

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