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Land Use Change is a Critical Influence on the Climate Effects of Climate Policies

By

Andrew D. Jones

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy
in
Energy and Resources
in the
Graduate Division
of the
University of California, Berkeley

Committee in charge:
Professor Margaret S. Torn, Chair
Professor Michael O'Hare
Professor William D. Collins

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Abstract

Land Use Change is a Critical Influence on the Climate Effects of Climate Policies

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Andrew D. Jones

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Professor Margaret S. Torn, Chair

Proposed strategies for managing terrestrial carbon in order to mitigate anthropogenic climate change largely ignore the direct effects of land use change on climate via biophysical processes that alter surface energy and water budgets. Subsequent influences on temperature, hydrology, and atmospheric circulation at regional and global scales could potentially help or hinder climate stabilization efforts. However, due to geographic variability, incomplete understanding of the relevant physical processes, and differences in the spatial scale of biophysical influences compared to greenhouse gases, the best strategies for addressing biophysical aspects of land use change are not clear. To provide insight into this problem, I explore the theoretical implications of various metrics for characterizing the full climate effects of land use change. Furthermore, using a state-of-the-art earth system model coupled to an integrated assessment model that generates scenarios of future anthropogenic climate forcing, I address policy-relevant questions regarding the physical climate system response to land use change.

I demonstrate that the biophysical effects of land use change can be large and vary significantly among policies. Thus ignoring these effects in greenhouse gas policies can lead to unintended consequences. Different hypothetical strategies for meeting an identical global greenhouse gas concentration target – either one with modest afforestation or one with large-scale deforestation for biofuel production – yield different global and regional patterns of climate change, particularly when Boreal forests are converted to agriculture. Additional simulations illuminate the forcing and feedbacks processes that drive regional differences between these scenarios.

Many policies and programs rely on a measure of net CO_2 emissions to rank the climate damages of different activities or to generate credits within a trading scheme designed to minimize negative climate outcomes. While it is relatively straightforward to include well-mixed non-CO_2 greenhouse gases in such schema using metrics based on radiative forcing, the climate system response to biophysical forcing differs from that of greenhouse gases. I examine the size and nature of this theoretical difference by modeling the equilibrium climate response to equivalent levels of radiative forcing from both land use change and elevated atmospheric CO_2 concentrations, drawing conclusions about the climate consequences of including biophysical forcing in carbon markets using this metric.

This document is dedicated to
Alex Farrell
without whose inspiration I would not have pursued these questions
and to
Ryan Jones
for showing me what is really important in life

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1 Towards a Policy Framework for Addressing the Full Climate Consequences of Land Use Change

1.1 Introduction

As part of a growing effort at multiple levels of governance to mitigate anthropogenic climate change, nascent 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 long-lived greenhouse gases, which influence climates globally owing to their well-mixed nature, biophysical aspects of land use change operate at local and regional spatial scales, and may or may not in turn influence larger scale atmospheric circulations (Marland et al. 2003). 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 (Pielke et al. 2002). 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 is likely to alter the structure of ecosystems, leading to additional climate change through both carbon cycle and biophysical mechanisms (Chapin et al. 2008; Shaver et al. 2000). 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°C cooling effect across temperate agricultural zones and surrounding areas (2009). 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 (IPCC 2001), 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. In addition, decision-makers are faced with the challenge of selecting appropriate metrics for characterizing the positive and negative consequences of land use change in a manner that reflects social costs as accurately as possible.

This thesis seeks to demonstrate the relevance of biophysical change in shaping future climate and to evaluate potential strategies for addressing the full climate consequences of land use change within mitigation efforts. In this chapter, I provide a typology of the relevant policies and programs currently under discussion and identify a set of policy-oriented questions regarding the nature of the physical climate system response to land use change. In addition, I discuss several candidate metrics that could be used to rank the impact of various land use changes, characterizing the metrics based on which features of the coupled human-climate system they measure. Subsequent chapters probe the physical system response to land use change using a state-of-the-art earth system model.

1.2 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 cap-and-trade policies that have been considered in the U.S. Congress offer carbon offset payments for practicing conservation tillage.

Furthermore, the recognition that conventional biofuels have significant land use change effects 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 (Fargione et al. 2008; Searchinger et al. 2008). Both California's Low Carbon Fuel Standard (LCFS) (Farrell et al. 2007) and the U.S. Renewable Fuels Standard (RFS) 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.

This concern regarding carbon emissions from land use change is certainly justified by the magnitude of potential emissions. 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 wholesale 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% resulting from degradation of tropical peat soils (van der Werf et al. 2009).

Meanwhile, terrestrial ecosystems are thought to absorb approximately 30% of all anthropogenic carbon dioxide emissions (Canadell; Raupach 2008), 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.

1.3 Understanding Biophysical Change for Policy Making

The types of policies for which the biophysical aspects of land use change are relevant can be divided into three categories, each with its own objectives and constraints.

1.3.1 Carbon offset and trading schemes

Under carbon offset programs and trading schemes, land managers are paid to maintain or enhance carbon stocks. This category of mitigation strategies includes REDD in so far as it is financed by international carbon markets as some have suggested. By linking payments to carbon markets that eventually will operate under global or regional caps, such policies create the conditions for energy and industrial actors to purchase credits for biologically sequestered carbon and emit more fossil carbon emissions than otherwise would be allowed under the cap, or vice versa. Accounting for biophysical change in this context means that offset projects that negatively impact climate through albedo change, for instance, would generate fewer credits than otherwise. On the other hand, projects that reduce climate change through biophysical processes would generate additional credits, allowing additional fossil carbon to be emitted. A critical consideration for these policies, then, is to measure the biophysical climate forcing from land use change relative to that of GHG emissions. A challenge is that this needs to be done in units that are as faithful as possible to the actual social costs of perturbing the climate through each of these mechanisms, a problem discussed extensively in section 1.4.

1.3.2 Policies based on life-cycle assessment

Policies, such as the California LCFS and U.S. RFS use a life-cycle metric of embodied carbon emissions to evaluate the suitability of different fuels for achieving climate mitigation goals within the transportation fuels sector. Similar policies or labeling programs could be developed for land intensive sectors such as consumer food products, suburban housing development, and highway construction. Accounting for biophysical change in this context would mean giving more weight to land use changes that stabilize climate through biophysical mechanisms and less weight to those that do not. Because these life cycle based policies and programs use a metric of embodied carbon emissions, they encounter the same challenge as carbon offset programs – the need for a metric that reflects the true social cost of perturbing the climate via carbon emissions or biophysical change. In addition, because life-cycle carbon emissions involve many land use conversions in many areas of the world resulting from market-mediated effects, life-cycle accounting would require characterizing biophysical change across a wide range of geographic and management factors and integrating those into a single value for the product of interest.

1.3.3 Regional land-use planning

While the previous two categories describe policies that are primarily concerned with reducing human disruption of climate at global scales, other policies address regional scale environmental, economic, and social aspects of land use, such as zoning regulations, technology transfer programs, permitting on public lands, and the designation of parks and ecological reserves. These policies must consider many different competing values and interests from a variety of stakeholders. In this context, the biophysical climate effect of land use change may be more significant than the carbon emissions from those same activities because the biophysical effects are concentrated at regional scales. Opportunities exist to direct conservation efforts to climatically valuable ecosystems, for example, or to encourage management that offsets unwanted climate changes. Some of these outcomes would be best handled on a case-by-case basis based on expert knowledge. A metric for biophysical change in this context would focus on the regional scale climate outcomes and would need to be weighed against competing social and environmental objectives.

1.3.4 Relevant properties of the physical system

In general, policy-makers must weigh the costs and benefits of taking or imposing a particular action versus the costs and benefits of alternative actions, which includes the possibility of taking no action at all. The biophysical aspects of land use change raise several important questions, the answers to which would help to clarify their relative costs and benefits in various contexts and in relation to other aspects of land use change, a necessary first step toward considering these effects in the types of policies outlined above:

- At what spatial scales are various biophysical changes significant?
- How do biophysical changes for the same activity vary as a function of geography?
- How significant are biophysical changes relative to carbon cycle effects of land use change?
- How important are management factors versus vegetation cover?
- To what degree do various biophysical changes interact with one another?
- Are biophysical effects linear and/or monotonic? That is, does additional land use change of the same kind lead to additional climate change of the same kind (monotonic) in the same proportion (linear)?

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 have by no means resolved them.

For instance, several modeling studies have examined the effect of historical land use change on climate, either at global (Chase et al. 2000; Matthews et al. 2004; Zhao et al. 2001) or continental (Bonan 1997) scales. Others have explored the role that future land use changes play in shaping predictions of future climate (Feddema et al. 2005). Still others have explored broad scale conversion to specific ecosystem types such as global forestation (Gibbard et al. 2005) or broad scale adoption of land management practices (Lobell et al. 2006). Some modeling studies have also isolated regional impacts of specific types of land use change, such as Amazonian deforestation (Costa; Foley 2000), boreal deforestation (Bonan et al. 1992), and the adoption of irrigation (Roy et al. 2007).

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 direct repercussions of individual actions. However, as mentioned in the case of fuel life-cycle assessment, land use in one location can influence land use in other locations via market mechanisms. In such cases, the climate effect of indirect land use changes would need to be considered as well.

Empirical approaches to estimating the climate signature of biophysical change (Lobell; Bonfils 2008; Stohlgren et al. 1998; Webb et al. 2005) 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 (Pitman et al. 2009). 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, 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.

1.4 Measuring Biophysical Change

As the discussion in the previous section indicates, identifying a appropriate metrics to account for biophysical change relative to GHG emissions is a critical aspect of developing policies to address this aspect of land use change. Although the need for such a metric is acknowledged in the academic literature (Marland et al. 2003; Pielke et al. 2002), none of the major climate policies and initiatives that currently address land use change employs such a metric. As Maryland 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 broadly and explicitly references land use as a direct driver of climate change (Marland et al.

2003). 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, the varying spatial scales and multiple mechanisms of biophysical climate perturbation make these effects 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 integrated assessment modeling that valuing terrestrial carbon can produce unintended consequences on food prices (Wise et al. 2009). 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, or subsidize consumption for the poor. However, there could still be a food-climate tradeoff present whether or not these two outcomes are measured in the same units and regulated within the same policy framework. 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 conceptualized 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 – e.g., offset programs, REDD proposals, and life-cycle accounting frameworks. Attempting to account for biophysical change within these programs would further move policy to the lower right cell. However, while integration of fossil, industrial, and land use carbon emissions under a unified trading scheme is theoretically more economically efficient than separating them, behaviors related to land use carbon emissions are qualitatively different from those related to fossil and industrial emissions, potentially arguing for policies that remain in the upper half of the matrix. Keeping REDD funding independent of global C markets while integrating biophysical effects would occupy the upper right quadrant, as would regional land use policies that account for a wide range of climate effects. In order to understand the right-hand column of the matrix better, we turn now to a discussion of the GWP metric and its alternatives.

	Biophysical and GHG *not* effects expressed through common metric	Biophysical and GHG effects expressed through common metric
Terrestrial GHG *not* traded with fossil and industrial GHG	Industrial cap-and-trade Industrial carbon tax REDD not part of C markets	Regional land-use climate policies Modified REDD not in C markets
Terrestrial GHG traded with fossil and industrial GHG	REDD in C markets Terrestrial offsets CDM forestry projects	Modified versions of: REDD in C markets Terrestrial offsets CDM forestry projects

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. Attempts to incorporate biophysical effects into carbon accounting would move policy to the right hand column.

1.4.1 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. This initial perturbation is known as climate forcing, which in turn produces climate impacts – 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.

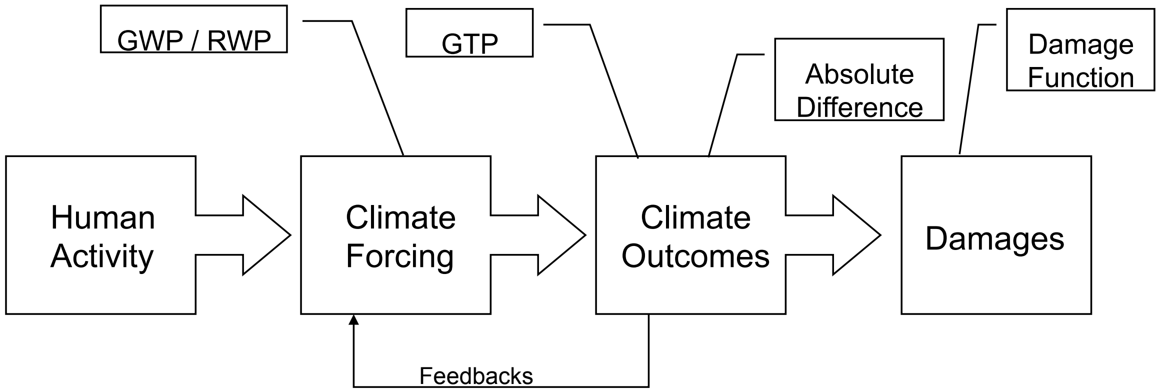

Figure 2 – Schematic representation of human influence on the climate system showing the components of the system (larger boxes) measured by various climate change metrics (smaller boxes above).

1.4.2 Global Warming Potential (GWP)

Global warming potential calculates the cumulative globally-averaged radiative forcing over some set time frame (RF) due to emission of a particular atmospheric constituent and normalizes it by the cumulative radiative forcing of a reference constituent, carbon dioxide, over the same time frame (IPCC 2001). 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 (Hansen et al. 2005), an instantaneous unit of radiative forcing due to one or another well-mixed GHG produces an equivalent effect on climate and social damages. GWP also takes into account the residence times of different GHGs, and so is defined over a given timescale, e.g., 100 years or 30 years. 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, as they are for any climate forcing, 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 principal GHG's, and 2) biophysical change forces the climate system through non-radiative mechanisms in addition to radiative ones.

For example, the albedo increase associated with Amazonian deforestation may induce local cooling. 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.

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 (Randerson 2006)) indicating that they are even more significant at the smaller spatial scales where these effects tend to be concentrated.

1.4.3 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). For instance, policy makers in Brazil may want to understand the net forcing of different types of land conversion within the Amazon on the Amazon region itself in order determine acceptable limits on land conversion or to encourage land conversion in areas where climate disturbance is minimized. The RWP metric would include the regionally significant portion of well-mixed GHG change as well as the effect of albedo change on the regional energy budget. However, as with GWP, this metric still would not account for non-radiative forcing mechanisms.

RWP calculations are highly sensitive to the spatial scale over which albedo effects are averaged. To illustrate this point, table 1 shows the approximate 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 calculation assumes an albedo change of 2.5, a mean top-of-atmosphere insolation at 40 °N of 1020 W/m^2, and an adjustment factor of 0.3 to account for interception of both incoming and outgoing shortwave radiation, resulting in an instantaneous forcing of -2.4 W/m^2 from albedo change. The cumulative forcing over 100 years from 1 kg of CO_2 is assumed to be 8.58E-14 (W years)/(m^2 kg). This value should decline with increasing CO_2 concentrations. However, I assume an approximately linear relationship between CO_2 and forcing, a simplification that breaks down for the very high levels of equivalent CO_2 found when albedo forcing is hypothetically concentrated at very small spatial scales (~ 1 ha). Finally, while the instantaneous forcing from CO_2 declines over time due to removal by terrestrial and ocean sinks, I assume the change in albedo to be permanent – that is, the land is maintained as cropland for the entire 100 years. Thus, the equivalent CO_2 from albedo change increases as one considers longer timescales.

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 -2.8 trillion tons of carbon dioxide equivalents on that 1 hectare of land, a value that exceeds the actual CO_2 content of the atmosphere. Note that because the calculation ignores saturation of the greenhouse effect at higher CO_2 levels, this value is actually an underestimate. At the other extreme, if the effect truly were globally averaged, it would be an order of magnitude smaller than the carbon stock change. At the continental scale, it represents -3,500 tons of carbon dioxide equivalents, which is an order of magnitude greater than the GHG forcing. If this were the case, deforestation would produce a cooling effect at the continental scale due to albedo change, but a mild warming effect outside that region due to GHG emissions.

Given the sensitivity of RWP to the spatial scale over which regional forcing is averaged, characterizing the inherent scale of climate effects due to various biophysical changes is a necessary pre-condition for using such a metric. However, when the appropriate scale is determined, this metric could provide a meaningful estimate of the influence of land use practices within a given region on the region itself.

Spatial Extent of Albedo Forcing	**Albedo Change**	**Carbon Stocks**
	Mg CO_2e	Mg CO_2e
1 ha	-2.8.E+12	500
Continental US	-3,500	500
All of Earth	-56	500

Table 1 – An approximate 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.

1.4.4 Metrics based on climate outcomes

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 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 harmful to society or ecosystems as for more stable indicators. That is, human and biological systems are already adapted to deal with certain kinds of variability.

Global temperature change potential (GTP) has been suggested as an alternative to GWP. This metric describes the expected global mean temperature change from a given activity at a specified time horizon. While this metric does not account for the regionally specific nature of biophysical forcing, it does allow for the integration of multiple sources of climate perturbation even if some are not principally radiative in nature, such as changes in transpiration that cool the surface but do not directly influence the top-of-atmosphere radiation budget. However, by focusing just on temperature change, GTP ignores the potentially significant influence of transpiration effects on rainfall and surface water flows. GTP would only be an accurate representation of climate damages if all other climate effects scaled with temperature change.

An *absolute climate difference metric* would sum the absolute deviations from baseline climate conditions for a number of variables of interest, optionally normalizing by the variance of each variable in the baseline climate in order to weight deviations from less variable indicators more strongly. This metric has the advantage of being regionally specific and accounting for multiple climate outcomes. In addition to mean responses, changes in the frequency of extreme events could theoretically be considered within this metric. However, by introducing multiple indicators, this metric requires consideration of how to weight those indicators against one another. The simplest approach is to weight all normalized deviations from mean baseline conditions equally. However, equal weights are not likely to reflect true social costs.

Furthermore, it should be noted that these approaches require 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. More complex arrays of indicators require more complex modeling and computational capabilities.

1.4.5 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.

In addition to requiring sophisticated understanding of the climate system and the resources necessary to carry out complex model integrations, this approach demands a method to estimate and weigh the consequences of various outcomes for society. While potentially impractical, the notion of a damage function 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.

1.5 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 spatial scales of governance. 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 following sections, I address some of these concerns using earth system models to demonstrate important features of the climate system response to land use change. Chapter 2 examines the global and regional climate consequences of alternative scenarios of future land use change that could result from different policy prescriptions aimed at achieving the same global greenhouse has concentration target. Chapter 3 explores the equilibrium climate implications of including the albedo effect of land use change in an idealized carbon cap-and-trade scheme. This thesis demonstrates the importance of biophysical change within the context of existing and proposed climate mitigation efforts, but also the inadequacy of the current radiative forcing-based approach for quantifying the full climate impacts and consequent social costs and benefits of land use change.

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2 Greenhouse gas policy influences climate via direct effects of land use change[1]

2.1 Abstract

Proposed climate mitigation policies and programs do not account for direct biophysical climate impacts of land use change (LUC). To examine the significance of such effects on global temperature and the spatial pattern of climate change, we simulate a baseline and alternative scenario of future anthropogenic activity within the Integrated Earth System Model, which couples the Global Change Assessment Model and Community Earth System Model. The alternative scenario has high biofuel utilization and approximately 50% less global forest cover compared to the baseline, standard CMIP5 RCP4.5 scenario. By design, both scenarios stabilize radiative forcing from atmospheric constituents at the identical level of 4.5 W/m^2 by 2100. Thus, differences between their climate predictions quantify the biophysical effects of LUC. We also utilize offline radiative transfer and land model simulations to identify forcing and feedback mechanisms driving the coupled response. We find that boreal deforestation strongly influences climate due to increased albedo coupled with a regional-scale water vapor feedback. Globally, the high deforestation scenario yields a warming trend over the 21st century that is 0.5 °C cooler than baseline, driven by a 1 W/m^2 global decrease in radiative forcing. This pattern of relative cooling is distributed very unevenly around the globe. Some regions are warmer in the deforestation scenario and some are actually cooler than in 2005. Thus, biophysical effects of future LUC could have significant global and regional climate impacts and should be considered in the context of climate policies that affect or account for LUC, particularly in Boreal regions.

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[1] This chapter is being prepared for publication with the following co-authors as an article with

2.2 Introduction

Land use changes (LUC) exert multiple influences on climate through direct biophysical effects on surface energy and water budgets as well as through changes in net greenhouse gas fluxes (Bonan, 2008; Foley, DeFries, Asner, & Barford, 2005). Climate change mitigation activities to date, however, have focused almost exclusively on the greenhouse gas consequences of LUC. None of the proposed regulations or programs, including UN Reduced Emissions from Deforestation and Degradation (REDD) program, emerging private forest carbon offset programs, agricultural offsets in proposed US climate regulations, or inventories of biofuel-induced land use change in renewable and low-carbon fuel policies, attempt to account for non-greenhouse gas climate effects of land use change.

This differentiation in how climate effects of LUC are treated is also evident in the largest global effort to simulate potential changes in future climate, the Climate Model Intercomparison Project, now in its 5th incarnation (CMIP5). CMIP5 is based upon a set of scenarios, or Representative Concentration Pathways (RCPs), generated by integrated assessment models (IAMs). The RCPs were designed to span the full range of possible radiative forcing in the 21st century with a series of hypothetical global strategies for climate-change mitigation that constrain the future combined radiative forcing from greenhouse gases (GHGs) and aerosols (Vuuren et al., 2011). While the RCP targets include greenhouse gas emissions from land use activities, they do not incorporate the direct radiative forcings, e.g., changes in albedo, or non-radiative climatic effects, e.g., changes in latent heat flux, that result from those same activities.

Nevertheless, these scenarios can be used to investigate the magnitude of the non-GHG forcing, because detailed information on land use change is passed from the IAMs to the earth system models and influences their simulations of climate change (Taylor, Stouffer, & Meehl, 2011), much as would be the case if real policies were implemented that did not account for biophysical forcing due to land use change.

Each of the RCPs was generated with a different IAM, each with its own model-specific assumptions about the technologies, policies, and demographics of the future. Due to this diversity in the underlying IAMs, the global patterns of deforestation and afforestation present in the various RCP scenarios are essentially uncorrelated with the atmospheric forcing target levels (Vuuren et al., 2011). That is, RCP2.6 (a scenario that reaches a global radiative forcing target of 2.6 W/m^2) shows widespread deforestation over the 21st century, whereas RCP4.5 shows widespread afforestation and RCP6.0 and RCP8.5 each show a mix of deforestation and afforestation in different regions (Lawrence et al., 2012).

The decoupling of greenhouse gas targets and land use change within integrated assessment models is highlighted by Wise et al. (2009), who find that equivalent greenhouse gas targets can be reached with dramatically different patterns of land use, depending on what kind of tax is used to achieve the GHG target. The present study examines a similar set of scenarios within a newly coupled integrated assessment and earth system model known as the Integrated Earth System Model (iESM). We compare the standard CMIP5 RCP4.5 scenario and an alternative

RCP4.5, in which the forcing target is achieved through a tax on fossil fuel and industrial carbon only, leading to large-scale expansion of crops and loss of forest cover.

Many modeling studies have examined biophysical and/or biogeochemical climate effects of hypothetically removing or replacing whole ecosystems – e.g., complete deforestation or afforestation of a given region (Bala et al., 2007; Betts, 2000; Gedney & Valdes, 2000; McGuffie, Henderson-Sellers, Zhang, Durbidge, & Pitman, 1995; Swann, Fung, Levis, Bonan, & Doney, 2010). These studies tend to produce robust signals and shed light on the role that those ecosystems play in the climate system. Another class of studies examines realistic estimates of past land use change (Betts, Falloon, & Goldewijk, 2007; Findell, Shevliakova, Milly, & Stouffer, 2007; Kvalevåg, Myhre, Bonan, & Levis, 2009; Lawrence & Chase, 2010; Pitman et al., 2009), while only a few studies have examined plausible future scenarios of land use change (Arora & Montenegro, 2011; Feddema et al., 2005). Gaps remain in distinguishing the detailed mechanisms by which LUC causes observed changes in climate. For instance, none of these studies compared coupled model surface flux responses to offline surface fluxes with fixed atmospheric forcing, which could illuminate the role of atmospheric feedback mechanisms.

By examining two scenarios that follow identical atmospheric forcing trajectories from GHG and aerosols, but with different policy prescriptions and thus different patterns of land use change, this study uniquely examines the role that policy design can have in influencing climate via the biophysical effects of land use change. By placing crops in very cold or dry regions of the globe, our alternative RCP4.5 scenario pushes the boundary of realism. However, it does so while making self-consistent assumptions regarding yields on those lands – yields that are required to meet large demands for biofuels in a world where carbon concentrations are constrained but deforestation is not directly controlled. Agricultural expansion in the alternative RCP4.5 scenario is both widespread and intense, but the net result avoids the total removal of whole ecosystems explored by previous studies. Global forest cover is reduced by 52% relative to the standard RCP4.5. Thus, our alternative scenario can be thought of as a hypothetical upper bound on agricultural expansion and an example of the importance of policy design details.

We supplement our core simulations with a series of offline radiative transfer and offline land model simulations to isolate forcing and feedback mechanisms that contribute to the coupled earth system response to land use change. These simulations allow us to compare changes to surface and planetary energy budgets conditioned on the inclusion or exclusion of atmospheric feedback mechanisms. That is, we are able to determine the first-order changes in surface latent and sensible heat fluxes as well as the initial change in top-of-atmosphere radiation balance that result from land use change in the absence of changes in clouds, water vapor, or atmospheric circulation. Breaking the climate system response down into component mechanisms provides insight into the drivers of the observed signals and can generate hypotheses regarding the response to different kinds of land surface change. It also creates new opportunities for validating model results against observational data. For instance, offline surface fluxes are more directly comparable to eddy flux observations in circumstances where the scale of land use change is not large enough to induce the atmospheric feedbacks predicted by coupled models examining hypothetical large-scale land use change. The use of offline radiative transfer simulations also allows us to compute the radiative forcing associated the modeled pattern of land use change, a metric that plays an important role in climate policy as it is used to weigh the magnitude of climate perturbation by different forcing agents. While some of the aforementioned studies have computed the radiative forcing from various patterns of land use change, e.g., (Betts, 2000), this study is unique in its side-by-side comparison of offline and coupled surface flux responses and so is able to provide new insight into the mechanisms of large-scale land use change influences on climate.

2.3 Methods

2.3.1 Scenarios

The scenarios of anthropogenic activity examined in this study are generated by the Global Change Assessment Model (GCAM), one of the integrated assessment models used to generate scenarios as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). Each scenario describes future emissions and land use activities for the period of 2005 to 2100. The baseline scenario in our study is the standard CMIP5 reference concentration pathway 4.5 (RCP4.5), in which a universal carbon tax (UCT) is applied in order to stabilize radiative forcing from greenhouse gases and aerosols at 4.5 W/m^2 (Thomson et al., 2011). For the purposes of scenario generation, radiative forcing is calculated within GCAM by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC), version 5.3. Radiative forcing from changes in surface physical properties – i.e., alterations to the land-surface albedo – is not accounted for, nor are forcing from mineral dust and nitrate. In this scenario, agricultural technology improvements combined with the high price of emitting terrestrial carbon lead to modest amounts of afforestation worldwide with a corresponding contraction in global crop area. Biofuels play a relatively small role in both the energy and land use mix.

In the alternative scenario, the same target of 4.5 W/m^2 is reached via a fossil fuel and industrial carbon tax (FFICT), under which deforestation is not penalized directly for the resultant increases in CO_2 from disturbance of forest soils and reduction in woody carbon storage. However, since the target is based on atmospheric radiative forcing, terrestrial carbon emissions do count against the target. As a result the fossil fuel and industrial sectors must work even harder to meet the target. Because biofuels combined with carbon-capture and storage on biofuel processing plants are a low cost technology for displacing fossil fuel emissions in this scenario, there is a positive feedback whereby deforestation for biofuels induces a need for more biofuels in order to meet the policy target. As biofuel production expands, both biofuels and traditional crops are pushed to ever more marginal land where greater areas are required to produce the same yields. The net effect of these dynamics is a dramatic expansion of agriculture, replacing roughly 50% of global forest area by the final decade of the century (see Figure 1). However, it should be noted that the footprint of bioenergy could be smaller if one assumes greater increases in future agricultural productivity (Thomson et al., 2010). Agricultural expansion is rather rapid in this scenario, with 33% loss of forest occurring in the decade from 2010-2019.

2.4 Coupling to the earth system model

The present study is part of a larger effort to create an Integrated Earth System Model (iESM), which aims to couple the economic portions of the GCAM integrated assessment model to the Community Earth System Model (CESM), a physical earth system model featuring component models for the atmosphere, ocean, land, and sea ice. The eventual goal is to implement a two-way coupling within a single integrated system whereby economic decisions in GCAM translate directly into trace gas fluxes and land use changes in CESM while changes in climate within CESM feed back onto crop yields, heating and cooling demands, etc. in GCAM.

This study utilizes the one-way iESM coupling procedure from GCAM to CESM, which relies on a third model – the Global Land-use Model (GLM) (Hurtt et al., 2011; 2006)– to downscale land use change values from the 14 economic regions in GCAM to a 0.5 degree latitude-longitude grid. GLM computes estimates of secondary land area, and spatially allocates wood harvest values (in carbon units) to areas of primary and secondary ecosystems. It also "harmonizes" the data to ensure a continuous transition from historical land-use data. These values are then translated into changes to the areas occupied by the plant functional types implemented in the Community Land Model (CLM), the land model component of CESM, following the procedure developed by Lawrence et al. (2012), and upscaled to the 0.9 x 1.25 degree latitude-longitude grid used in CLM. This entire procedure is consistent with that utilized in the CMIP5. Thus we are able to reproduce the land use change dataset used by the National Center for Atmospheric Research (NCAR) as input to CESM for the standard RCP4.5 scenario, which we refer to as UCT.

In order to isolate the biophysical climate effect of reaching the same atmospheric forcing target with different patterns of land use, we force CESM with identical concentrations of atmospheric greenhouse gases and aerosols derived from the UCT scenario. Aerosol concentrations and deposition rates were computed from emissions as part of the CMIP5 process utilizing an offline atmospheric chemical transport model (Lamarque et al., 2011). We adopt this procedure despite differences in the trajectory and mix of greenhouse gas and aerosol forcing agents between the GCAM versions of the UCT and FFICT scenarios. The original FFICT scenario has greater forcing from methane and nitrous oxide due to greater agricultural activity as well as transiently higher levels of forcing from black carbon from biomass burning. The trajectory of forcing differs as well, with the FFICT scenario overshooting then declining to the target value of 4.5 W/m^2 and the UCT scenario gradually building up to the same target. However, CO_2 concentrations are equal in the two GCAM scenarios. Thus by adopting the UCT concentrations for all atmospheric constituents, we eliminate variation in the behavior of non-CO_2 forcing agents.

While it is possible to run CESM with an active chemical transport model forced by emissions from GCAM rather than concentrations derived from an offline run as we do here, this approach would confound the biophysical effects of land use change with differences in the mix and trajectory of atmospheric forcing agents. A follow-up study could examine these additional effects; however, it should be noted that the chemical transport model in CESM adds considerable computational cost. 95% of the UCT forcing in 2100 and 94% of the FFICT forcing in 2100 comes from well-mixed GHGs. Thus, we expect that differences in forcing trajectory would be more important than differences in the mix of forcing agents.

We run CESM at approximately 1 degree (0.9 x 1.25) resolution in a fully coupled transient mode with a dynamic ocean, Community Atmosphere Model 4 (CAM4) physics, and an active carbon-nitrogen biogeochemical model within CLM. The full carbon cycle is not active since atmospheric concentrations of greenhouse gases and aerosols are prescribed as discussed above. We use the standard CLM configuration in which all crops are represented as C3 grasses. Initial conditions for the component models are taken from a 20th century NCAR simulation beginning from equilibrium pre-industrial conditions.

We use a version of CESM that differs from the official release version 5 used for the CMIP5 in a handful of ways, most of which do not materially alter the climate simulation. The most notable difference is that the beta version 15 we have adopted corrects the orbital forcing observed by the sea ice model to be consistent with the other model components. Previous versions held the orbital forcing of the sea ice constant. As discussed further below, we compare our simulation of the UCT scenario (standard RCP4.5) to an ensemble of 5 simulations performed at NCAR using CESM release version 5 for CMIP5. Despite the differences between the version that we use and that used for CMIP5, the mean global temperature response and spatial pattern of temperature response as revealed by fingerprinting methods (discussed further below) from our simulation fall within or near the 95% confidence interval around the ensemble mean taken from the 5 CMIP5 runs. Thus we are confident that we can reasonably replicate the standard RCP4.5 scenario using the model version and configuration options chosen.

2.4.1 Use of CMIP5 Data

As part of CMIP5, researchers at NCAR have made available the outputs of 5 simulations of the RCP4.5 scenario (our UCT scenario), each with varying initial conditions. These were performed at 0.9 x 1.25 degree resolution using identical configurations, but a slightly different model version than the one that we used for UCT and FFICT as discussed above. We analyze these data to derive estimates of model internal variability in order to evaluate whether differences observed between the UCT and FFICT scenarios are statistically significant. We also evaluate whether our UCT scenario is statistically indistinguishable from the standard CMIP5 RCP4.5 scenarios.

In addition, we utilize 3-hourly atmospheric history outputs from one of the CMIP5 RCP4.5 simulations to drive our offline CLM simulations discussed below.

2.4.2 Fingerprinting Method

We estimate the spatial pattern or “fingerprint” of the warming trend within each simulation using a method based on empirical orthogonal function (EOF) analysis, which has been employed in the climate change detection and attribution literature, e.g., (Santer et al., 2004). First we aggregate the temporally and spatially varying surface temperature data to annual time steps at approximately 8° x 8° resolution. We take the fingerprint to be the first EOF obtained from the anomalies of this aggregated data set. The first EOF describes the dominant mode of variance within the data – in this case the overall warming trend over time.

2.4.3 Offline Land Model Simulations

To isolate the first-order land surface response to changes in vegetation due to land use change, we perform an offline land model simulation in which atmospheric conditions are held fixed at the conditions exhibited in the UCT scenario, but the pattern of land use change is matched to that in the FFICT scenario. Thus the effect of rising GHG concentrations are present in the atmosphere, but the effects of land use change on water vapor, clouds, radiation etc. are deliberately omitted. We call this the FFICT-offline scenario. The atmosphere is forced with 3 hourly data taken from one of the NCAR RCP4.5 simulations performed for CMIP5. CLM has built-in algorithms for interpolating the 3-hourly atmospheric data to the 30-minute timestep that we use, including an adjustment to the incoming solar radiation that accounts for the cosine of the zenith angle at each timestep. In order to verify that our offline technique adequately reproduces the UCT climate, we also perform an offline UCT scenario (UCT-offline) that forces the atmosphere as above while maintaining the UCT pattern of land use change. Our finding of congruence between the UCT and UCT-offline scenarios indicates that we have successfully reproduced the UCT climate in the offline simulations.

2.4.4 Offline Radiative Transfer Calculations

To calculate the radiative forcing due to land use change, we utilize an offline version of the CESM atmospheric model, the Community Atmosphere Model (CAM). This offline version of CAM, known as PORT (REF?), runs only the radiative transfer calculations and is forced with instantaneous 3-dimensional state information saved from our UCT scenario at a rate of 240 samples per model year. The samples are evenly distributed over seasonal and diurnal timescales. By substituting surface albedos from the FFICT-offline scenario into PORT driven by the UCT atmospheric states, we obtain an estimate of the change in top-of-atmosphere net absorbed solar radiation that is free from atmospheric feedbacks.

2.5 Results

2.5.1 Global and Regional Temperature Trends

The simulated globally averaged warming trend over the 21st century differs by 0.5 °C between the UCT and FFICT scenarios, which exhibit warming trends of 1.2 and 0.7 °C per century respectively. The temperature divergence between the scenarios is apparent by 2030 (Figure 2) corresponding with the early divergence in land use patterns between the scenarios. Considering the ensemble mean and 95% confidence intervals surrounding this mean taken from the five RCP4.5 scenarios run at NCAR for CMIP5 (Figure 2) it is clear that the FFICT scenario lies well outside the range of internal variability exhibited by the model, indicating that the temperature differences are statistically significant. Meanwhile, the fact that the UCT scenario lies mostly within the confidence interval around the CMIP5 ensemble mean indicates that we have successfully replicated the RCP4.5 scenario at this scale despite minor differences in model version.

Figure 3 shows the spatial pattern of the temperature trends in the two scenarios, calculated by subtracting the mean of the first simulation decade (2005-2014) from the last (2090-2099) for each scenario. The UCT pattern of warming is typical of greenhouse gas-induced climate change with greater temperature change at high latitudes and over land. The FFICT pattern, however, actually shows a cooling trend in some regions, particularly near areas of boreal deforestation in eastern Siberia and portions of Canada. Other regions show no trend or trends that are similar to those found in the UCT scenario.

The differences between the scenarios are more clearly shown in the seasonal June-July-August (JJA) and December-January-February (DJF) temperature differences between the scenarios for the final simulation decade (Figure 4). There is a clear pattern of relative cooling (i.e., less warming) in the FFICT scenario over much of the land area above 50 degrees latitude. This reduction in warming is strongest over the boreal forests and the Barents Sea and extends to the northeast of Finland, particularly during the northern hemisphere winter when the relative cooling is more than 6 °C in some locations. There is also a widespread but modest cooling on the order of 1 °C present over much of the Arctic Ocean during northern hemisphere winter and over mid-latitude oceans during northern hemisphere summer.

While smaller in spatial extent, there are also regions of the tropics at the edges of the Amazon and Congo forests where the FFICT scenario exhibits higher temperatures than the UCT scenario. These are on the order of 1 °C.

Stippling in Figure 4 indicates those gridcells for which the FFICT value lies outside of the 95% confidence interval around the NCAR RCP4.5 ensemble mean. We avoid the problem of underestimating variance due to temporal autocorrelation by using the ensemble variance rather than a time-series of values from a single simulation. However, due to spatial autocorrelation and the finiteness of our sample, it is still likely that more than 5% of the gridcells would display significance even if the FFICT scenario were drawn from the same distribution as the RCP4.5 ensemble (Livezey & Chen, 1983). Indeed, 20% of our UCT scenario (identical to RCP4.5 modulo differences in model version) gridcells are found to be significant using this test for the end-of-century decadal mean temperature difference (not shown). However, many more (71%) of the FFICT gridcells are significant (panel A).

2.5.2 Spatial Fingerprint of the Warming Trend

Our fingerprint analysis provides an alternative way to characterize the spatial significance of the pattern of warming present in the FFICT vs. the UCT scenario. The fingerprints of the UCT and FFICT warming trends are shown in Figure 3. Because rising GHG concentrations and land use change trends are correlated in our scenarios (i.e., they are not orthogonal processes), their combined effect on surface temperature is mixed, at least partly, in the fingerprint obtained from EOF analysis. As might be expected, the fingerprints fairly closely track the decadal temperature difference between the first and last simulation decade (also shown in Figure 3). The effect of Boreal deforestation in the FFICT fingerprint is evidenced by diminished warming at high latitudes and a patch of cooling over Eastern Siberia.

We can readily show that the differences between the UCT and FFICT fingerprints are statistically significant and probably do not result from internal variability of the models. The demonstration follows by comparing the FFICT fingerprint against the fingerprints obtained from each of the NCAR RCP4.5 ensemble members. The analytical approach treats each fingerprint as a vector in n-dimensional space where n is 864, the number of gridcells present at the resolution chosen for this analysis. We then compute the angle between each fingerprint and the fingerprint obtained from the RCP4.5 ensemble mean in that n-dimensional space. The ensemble members cluster near the ensemble mean at a mean angle of 7.0° with a standard deviation of 1.3°. The FFICT fingerprint, on the other hand, is rotated by 19.5° from the ensemble mean. Since this angle differs from the corresponding angles for the RCP4.5 ensemble by more than 9 standard deviations, the differences between the FFICT and ensemble mean are therefore highly statistically significant. Thus, even if we are agnostic about the functional form of the distribution of angles around the ensemble mean, we can conclude from Chebyshev's inequality that it is very unlikely to obtain the FFICT fingerprint from model internal variability.

2.5.3 Surface Energy Budget Changes

Our FFICT-offline simulation, which holds atmospheric conditions fixed at UCT values, indicates that the first order effect of changing vegetation from the UCT to FFICT scenario is an increase in reflected solar radiation of 2.2 W/m^2 averaged over the global land surface during the final simulation decade. As shown in Figure 5, this increase in reflected solar radiation is balanced by decreases in sensible (-2.0 W/m^2) and latent (-0.7 W/m^2) heat fluxes, as well as a small increase in emitted longwave radiation (0.5 W/m^2).

Allowing the atmosphere to respond to these changes results in feedback processes that further alter each term of the surface energy balance. In the fully coupled case, altering land use from the UCT to FFICT scenario results in an even larger increase in reflected solar radiation of 4.0 W/m^2. The corresponding changes in sensible (-1.4 W/m^2) and latent (-1.8 W/m^2) heat fluxes are shifted more heavily to decreases in latent heat flux, and there is a large decrease in emitted longwave radiation (-4.1 W/m^2), reflecting the decrease in surface temperature. The increase in reflected solar radiation is partly explained by an increase in surface insolation of -1.7 W/m^2, which appears as a negative term in the energy budget in order to maintain the sign convention that all fluxes are positive upward. Likewise, the large decrease in emitted longwave is offset by an even larger decrease in downward longwave radiation of 4.8 W/m^2, which we show later is related to changes in the greenhouse effect of water vapor. Both the offline and coupled surface energy budgets balance at the 0.05 W/m^2 level. We do not account for changes in ground heat storage and the latent heat of fusion in this analysis.

Figure 6 shows the equivalent regional energy budgets averaged over the boreal and tropical forest areas. We define boreal as all land area from 45 to 65 degrees N and tropical as all land area from 15 degrees S to 10 degrees N. While the general pattern of flux changes is similar to the global pattern in each region, the scale of change in the boreal zone is much larger despite similar levels of deforestation in each region (9.6 M km2 in the Boreal zone vs. 10.2 M km2 in the tropics).

The most notable qualitative difference between regions relates to the emitted longwave flux changes, which are strongly negative in the Boreal region and essentially neutral in tropics for the coupled simulations. In the tropics, decreases in latent and sensible heat fluxes outweigh increases in shortwave reflectivity, requiring that the surface temperature and corresponding upward longwave fluxes increase to compensate. This may indicate that the decrease in latent and sensible heat flux in the tropics is dominated by a decrease in surface roughness, which reduces the efficiency of turbulent energy fluxes, rather than the albedo change that dominates in the Boreal forest.

2.5.4 Feedback Mechanisms

Lower temperatures in the FFICT scenario relative to the UCT scenario are associated with greater snow and ice extent (Figure 7), which contribute to the coupled increase in reflected solar radiation (Figure 8) and represent a positive feedback on temperature reductions. The increase in reflected solar radiation in the coupled simulation is also due in part to an increase in incident solar radiation. Changes in water vapor and atmospheric dynamics combine to reduce cloud cover in many regions (Figure 7), particularly at high latitudes. This increase in insolation is partially reflected, but also provides more energy to drive latent, sensible, and long wave energy fluxes. The increase in sensible heat flux from the offline to coupled simulation is consistent with increased insolation, but the corresponding decrease in latent heat also indicates a shift in Bowen ratio, probably due to lower surface temperatures and so lower vapor pressure deficit.

Indeed, reductions in latent heat flux and cooler air temperatures contribute to lower atmospheric water vapor, both in the tropics and at high Northern latitudes (Figure 9). Because the baseline level of atmospheric water vapor is quite low to begin with at high latitudes, this change leads to a significant change in the local greenhouse effect, defined as the difference between emitted surface longwave radiation and the top-of-atmosphere outward radiation flux. However, this effect is diminished in the tropics where the greenhouse effect of water vapor is more highly saturated. The spatial pattern of greenhouse effect changes is shown in Figure 10, which corresponds closely with the spatial pattern of temperature change shown in Figure 4. In the high latitudes, this cycle suggests a strong positive feedback effect – albedo and transpiration changes cool the air and reduce water vapor, which leads to lower long wave surface insolation, further cooling the surface and further reducing transpiration and water vapor. The decrease in emitted long wave and latent heat fluxes in the coupled simulation (Figure 6) is consistent with this mechanism. However, to definitively isolate the role of snow, ice, cloud, and water vapor feedbacks on the surface energy budget would require additional simulations targeting each mechanism individually.

Figure 11 shows changes in the planetary energy budget over the 21st century that result from greenhouse gas and albedo effects in both the UCT and FFICT scenario. Because the radiative forcing from anthropogenic GHGs is held fixed at approximately 4.5 W/m^2 for each scenario, deviations in the greenhouse effect from this level are due to changes in atmospheric water vapor. In the UCT scenario, water vapor feedback effects increase the greenhouse effect from 4.5 W/m^2 to 5.6 W/m^2, while in the FFICT scenario, land use change effects on water vapor reduce this to 4.2 W/m^2, which is below the anthropogenic forcing level.

Both scenarios exhibit positive albedo feedbacks that result from loss of snow of and ice over the 21st century, however these effects are reduced in the FFICT scenario (0.5 W/m^2) compared to the UCT scenario (1.2 W/m^2).

2.5.5 Radiative Forcing

Using the offline radiative transfer model to hold the 3-dimenstional atmospheric conditions fixed at UCT scenario values while altering surface albedos according to the FFICT-offline scenario, we obtain a shift in top-of-atmosphere net downward shortwave flux of -0.96 W/m^2 for the period 2091-2100. Thus, the globally averaged forcing from land use change in the FFICT scenario relative to UCT is on the same order of magnitude as forcing from anthropogenic GHGs in these scenarios.

2.6 Discussion

Our results indicate that under plausible scenarios, the biophysical climate effects of land use change play an important role in determining the outcomes of climate policy at both global and regional scales. Thus policies that do not consider these effects may result in unintended consequences. In general, the climate outcomes of achieving atmospheric GHG targets depend on the specific policy mechanisms employed insofar as those different mechanisms impact the pattern and scale of land use change.

In the context of the CMIP5 simulations, our findings challenge a fundamental assumption underlying the “parallel process” (Moss et al., 2010) for generating alternative technological and socio-economic pathways for meeting the RCP targets, namely the assumption that there is a unique relationship between the trajectory of radiative forcing and subsequent climate change impacts as predicted by any given CMIP5 climate model. Furthermore, our results indicate that the RCP scenarios, which vary unsystematically in their levels and patterns of land use change, may exhibit important differences in terms of regional and global climate outcomes that are not directly linked to the chosen GHG target. As a result, the transient climate sensitivity– i.e., the magnitude of temperature change in 2100 per unit of quantified forcing – exhibited by each CMIP5 model is likely to differ by scenario as well.

In addition to influencing the global mean temperature response, we show that land use change can influences the spatial pattern or “fingerprint” of warming that is exhibited over time as derived from EOF analysis. This result has implications for the use of pattern scaling techniques for generating new climate change scenarios, (e.g., (Mitchell, 2003)). While it is possible to generate and scale separate response signals for GHG, aerosols, land use change etc., the response signal for land use change is highly dependent on geography and is likely to interact with GHG forcing. For example, the albedo response from Boreal deforestation depends on snow cover, which in turn is influenced by GHG-induced warming.

Clearly, the forcing effect of land use change is an important consideration for climate policy, both real and simulated. Land use change is similar in some regards to sulfur aerosols, which are important despite their short atmospheric lives and geospatially heterogeneous effects on the Earth's energy balance. Depending on the specific objectives of individual policies, it may or may not make sense to incorporate the forcing effect of aerosols or albedo change into targets and accounting frameworks. If this is deemed appropriate, our work points to the inadequacy of globally averaged radiative forcing as the metric for doing so. As noted by others (Pielke et al., 2002), due to the geographically specific and spatially heterogeneous effect of land use change on climate, globally averaged metrics belie the climate effects of land use change on the regional scales where they matter most to humans. The global cooling effect of deforestation in our simulations is strongly concentrated in the high northern latitudes, whereas a radiatively equivalent reduction in GHG would be more evenly distributed across the globe, impacting society in different ways. Indeed, the cooling effect of Boreal deforestation is so concentrated that some regions experience net cooling over the 21st century in our FFICT scenario despite a global mean warming of 0.7° C.

Consistent with a growing body of evidence, our work demonstrates the significant regional cooling effect of Boreal deforestation, which results from strong albedo change coupled with a regional water vapor greenhouse effect. Our offline land model simulations demonstrate that reduced water vapor flux from the surface is only partially due to the first order effect of vegetation change. Atmospheric feedback processes further reduce this flux. While our experiment was not designed to separate different atmospheric processes from one another, a plausible explanation is that regional cooling driven by albedo change reduces the capacity of the atmosphere to retain water vapor and drives down latent heat fluxes, suggesting that albedo change can activate a high latitude water vapor feedback independently of changes in stomatal conductance.

The scale of surface energy and hydrological flux changes from tropical deforestation predicted by our model is smaller than that indicated by eddy covariance studies (Randow et al., 2004). Despite this, we find significant temperature increases – on the order of 1 °C – in some regions of the tropics. Other modeling studies have found significant changes in precipitation resulting from tropical deforestation (McGuffie et al., 1995; Nepstad, Stickler, Filho, & Merry, 2008). However, there is substantial disagreement among models on the magnitude and sometimes the sign of climatic effects from land use change (Pitman et al., 2009). Thus, more work is needed to constrain model parameterizations with observational data before they can be used to make specific recommendations for programs such as REDD, which are likely to induce biophysical climate perturbations directly over large areas of the tropics and potentially indirectly outside the tropics via leakage mechanisms (Watson, 2000).

The integrated assessment model scenarios that our simulations are based on assume that the biogeochemical climate effects of land use change – that is, the associated CO_2 source and sink changes – are perfectly compensated for by reductions or increases in fossil carbon emissions. This assumption allows us to isolate the biophysical forcing and explore the implications of idealized policy scenarios. However, in practice it will be difficult to perfectly account for and trade the CO_2 fluxes from terrestrial sources – particularly those involving changes in soil carbon stocks – with those from fossil fuels. Many studies have examined the relative climate effects of biogeochemical and biophysical forcing from land use change. Their results are mixed, but generally point to a stronger biogeochemical signal except for the case of Boreal deforestation where biophysical effects can dominate (Bala et al., 2007; Betts, 2000; Molen, Hurk, & Hazeleger, 2011). Regardless of which signal dominates, if the CO_2 flux from deforestation in our FFICT scenario were not totally compensated for through carbon trading, the apparent cooling signal from deforestation would be reduced.

In our simulations we have not accounted for non-CO_2 emissions from biomass burning, such as black carbon and organic carbon, and ozone precursors, which could have significant climate effects on short time scales, as well as impact ecosystem function and human health directly.

We treat all crops and grasses identically in our simulation and do not prescribe special crop phenology or management practices. Thus we only capture the gross energy flux changes associated with going from forest ecosystems to non-forest ecosystems. A recent effort to incorporate crop-specific parameterizations into CESM (Levis et al., 2012) indicates that the high amplitude annual cycle in crop leaf area compared to grasses contributes to important seasonal effects on precipitation and surface energy fluxes. Future work on the land use effects of climate policy would benefit from using such parameterizations. Indeed, crop phenology has been identified as a major source of variance across model predictions of climate effects of land use change (Pitman et al., 2009).

2.7 Figures

Figure 1: Change in a) crop cover and b) forest cover from 2005 to 2100 for the FFICT scenario.

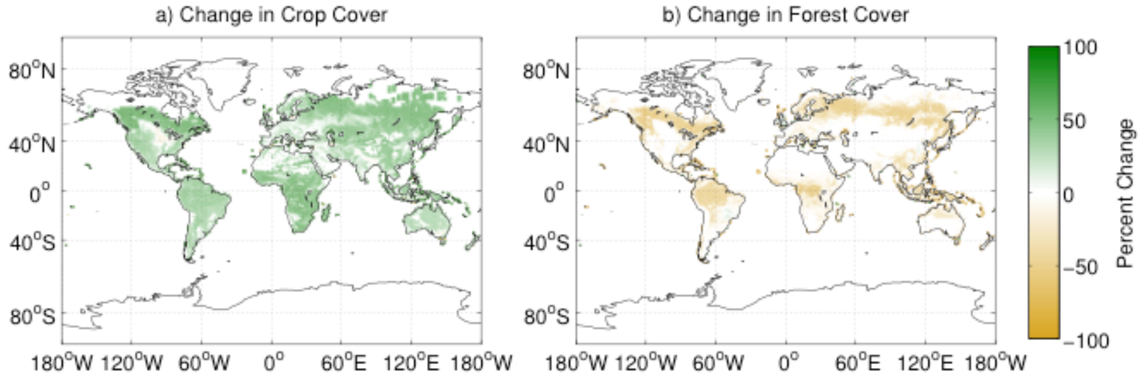


Figure 2: Global mean surface temperature anomaly relative to the first decade of each simulation (2005-2014). Dashed lines indicate the 95% confidence interval around the RCP4.5 ensemble mean.

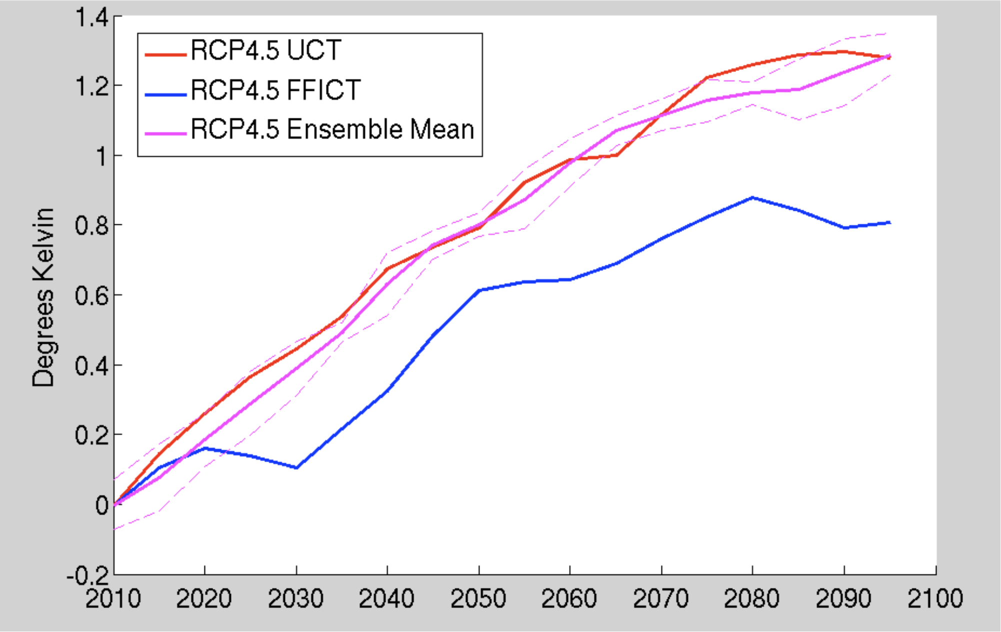
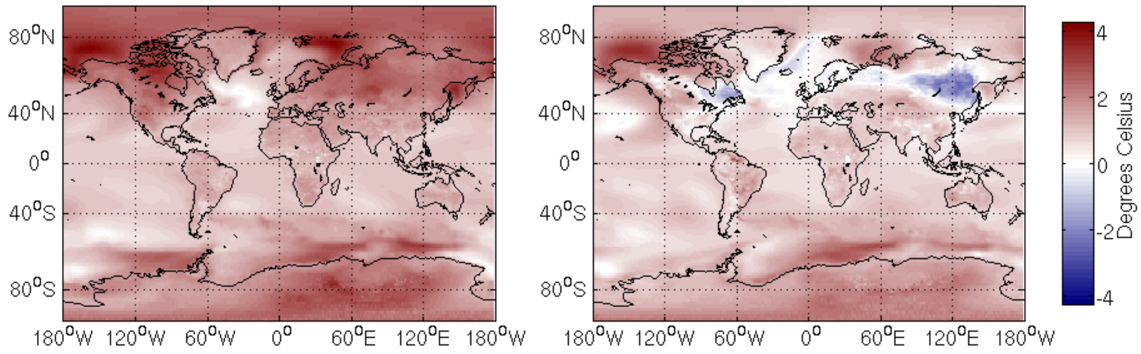
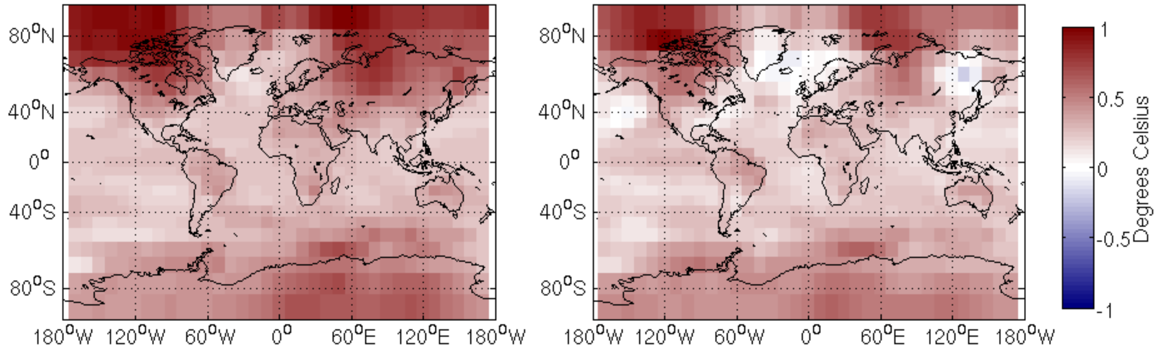


Figure 3: Spatial pattern of temperature change over the 21st century calculated using decadal differences (mean of the last simulation decade (2090-2099) minus the first (2005-2014)) for a) the UCT scenario and b) the FFICT scenario, as well as using EOF-based spatial fingerprint method for c) the UCT scenario and d) The FFICT scenario. The fingerprints have been scaled to fit within the range -1 to 1 °C.



a) UCT Temperature Difference

b) FFICT Temperature Difference

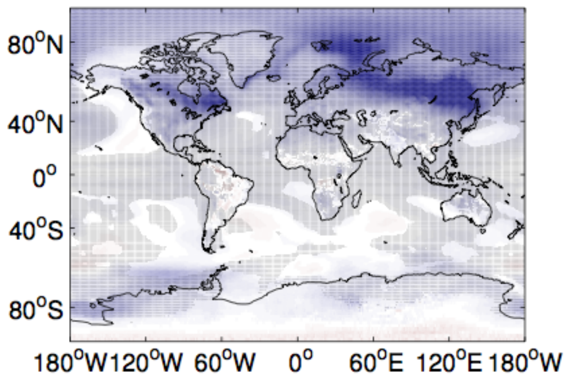


c) UCT Fingerprint

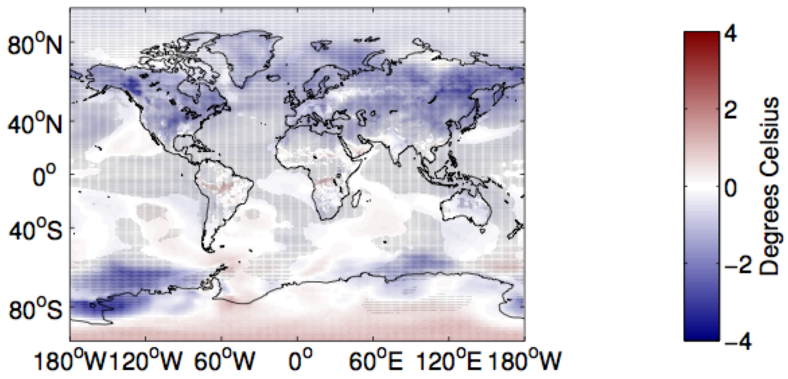
d) FFICT Fingerprint

Figure 4: Spatial pattern of mean surface temperature difference between the UCT and FFICT scenarios (FFICT minus UCT) for the final simulation decade (2090-2099), calculated a) annually, b) for the northern hemisphere summer: June, July and August (JJA), and c) for the northern hemisphere winter: December, January, and February (DJF). Stippling indicates those gridcells for which the FFICT value lies outside of the 95% confidence interval around the NCAR RCP4.5 ensemble mean.

a) Annual



b) JJA



c) DJF

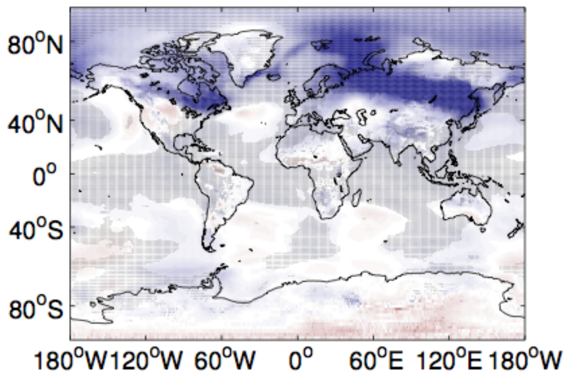


Figure 5: Changes in the global land surface energy budget between the UCT and FFICT scenarios (FFICT minus UCT) for the final simulation decade (2090-2099) obtained from both offline land model simulations and fully coupled earth system simulations that include atmospheric, ocean, and sea ice feedbacks. All fluxes are positive upward such that a negative value for incident solar radiation designates an increase in insolation in the FFICT scenario relative to UCT. To the right of the dashed line are terms of the surface energy budget that are held fixed in the offline simulations.

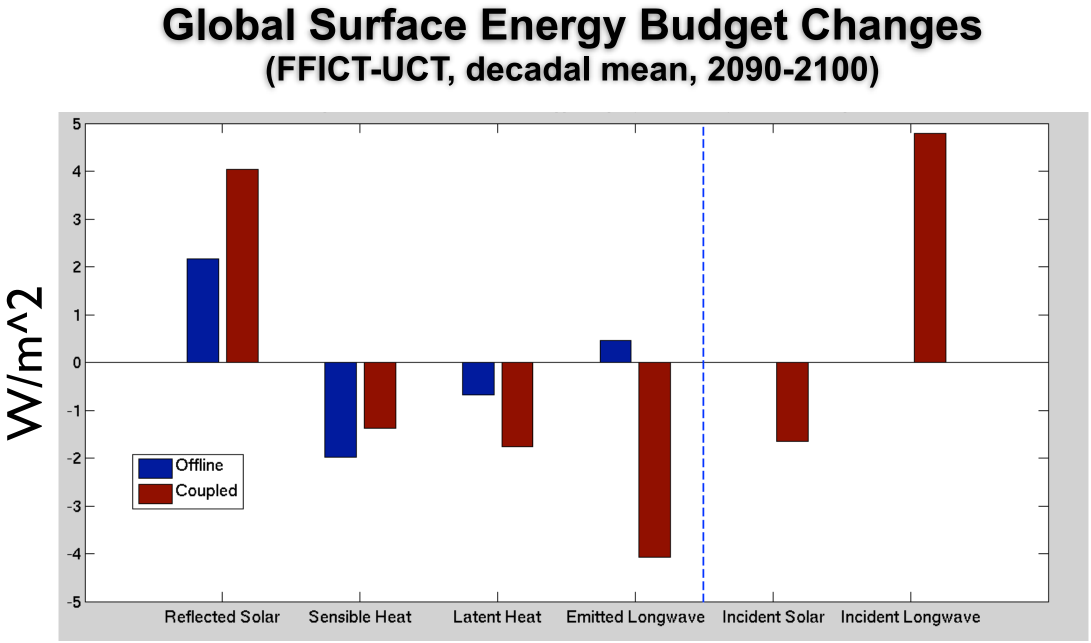


Figure 6: Changes in the regional land surface energy budget for boreal ecosystems (upper panel) and tropical ecosystems (lower panel) between the UCT and FFICT scenarios (FFICT minus UCT) for the final simulation decade (2090-2099) obtained from both offline land model simulations and fully coupled earth system simulations that include atmospheric, ocean, and sea ice feedbacks. All fluxes are positive upward such that a negative value for incident solar radiation designates an increase in insolation in the FFICT scenario relative to UCT. To the right of the dashed line are terms of the surface energy budget that are held fixed in the offline simulations.

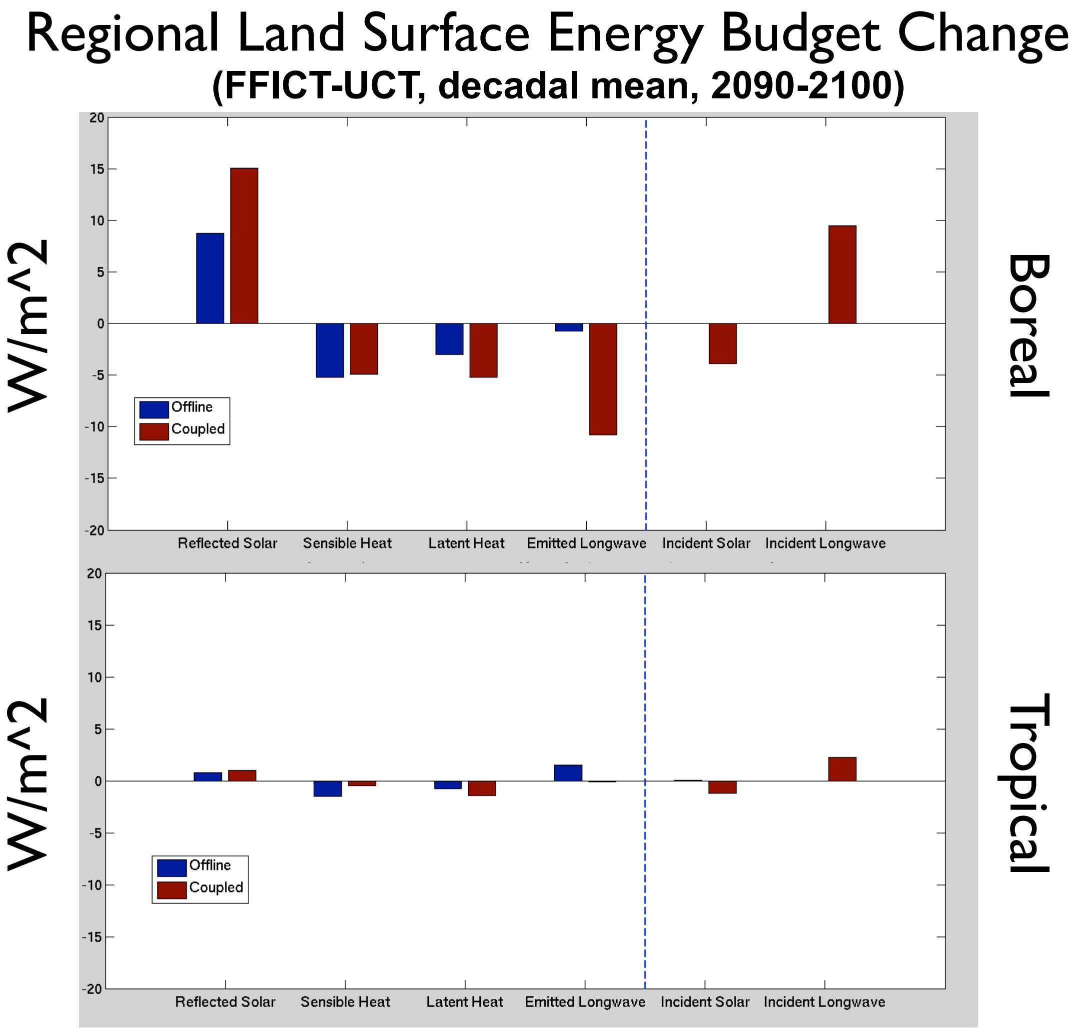
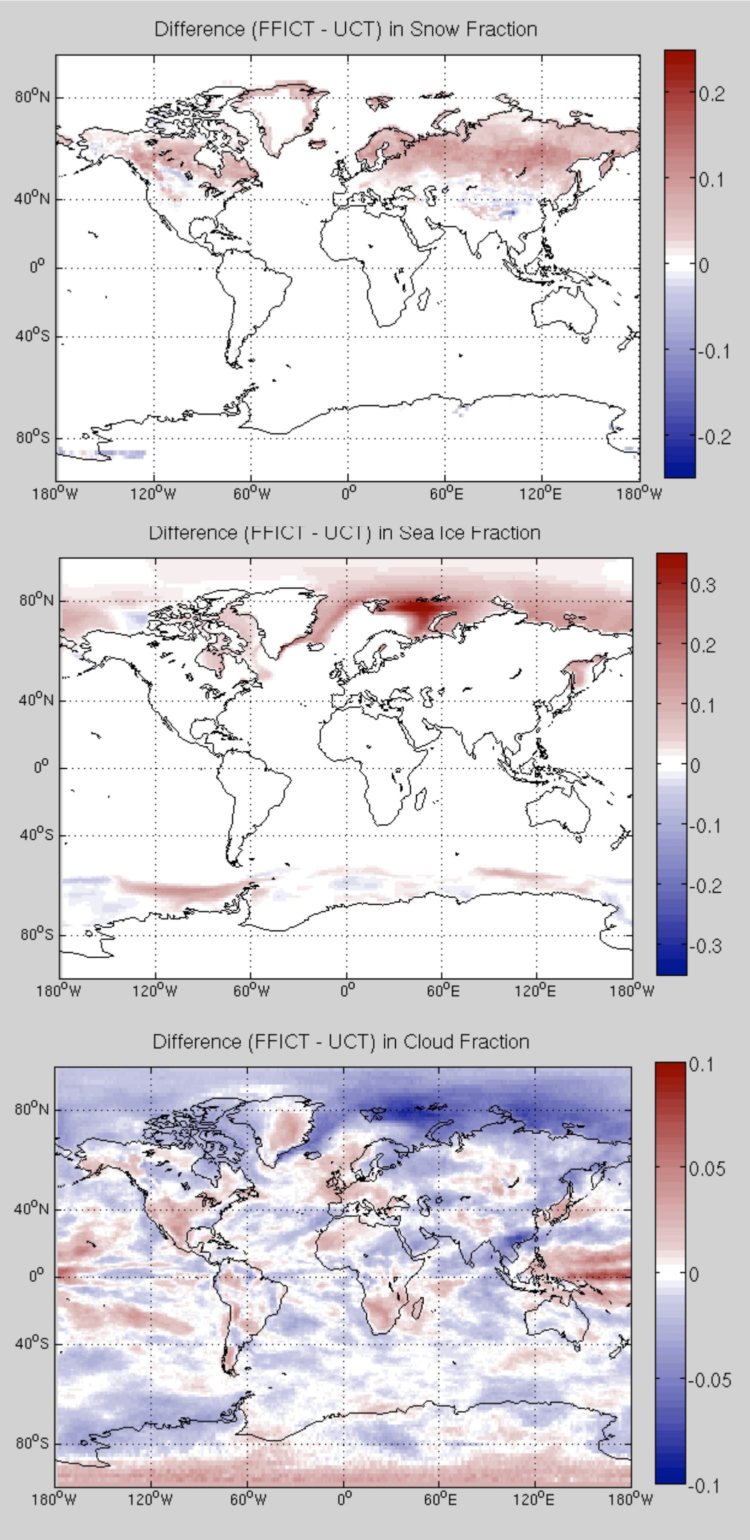


Figure 7: Fractional changes in snow cover (upper panel), sea ice (middle panel), and cloud cover (lower panel) between the coupled UCT and FFICT scenarios (FFICT minus UCT) for the final simulation decade (2090-2099).

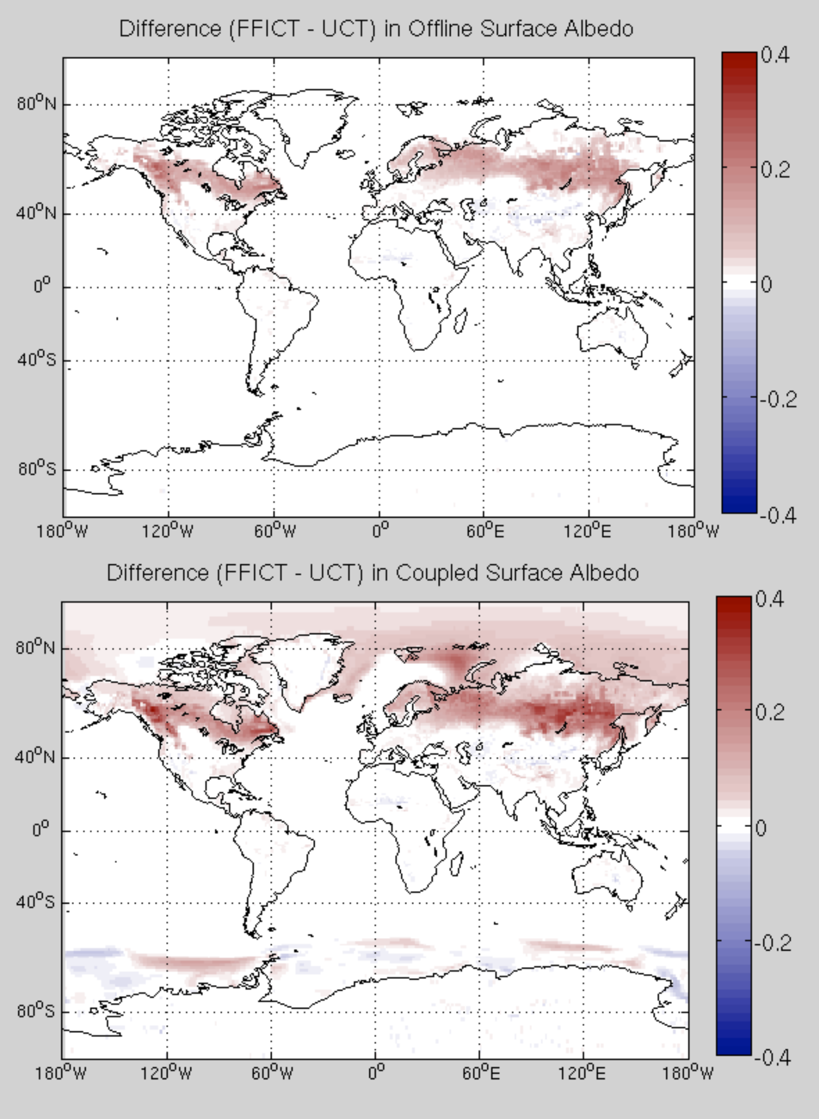


Difference (FFICT - UCT) in Snow Fraction

Difference (FFICT - UCT) in Sea Ice Fraction

Difference (FFICT - UCT) in Cloud Fraction

Figure 8: Surface albedo changes between the UCT and FFICT scenarios (FFICT minus UCT) for the final simulation decade (2090-2099) based on offline land model simulations (upper panel) and fully coupled earth system model simulations (lower panel) that account for atmospheric, ocean, and sea ice feedbacks.



Difference (FFICT - UCT) in Offline Surface Albedo

Difference (FFICT - UCT) in Coupled Surface Albedo

Figure 9: Mean atmospheric water vapor content in the final simulation decade (2090-2099) by latitude and height (measured in pressure units) for the UCT scenario (left panel) and the difference between UCT and FFICT scenarios (FFICT minus UCT, right panel)

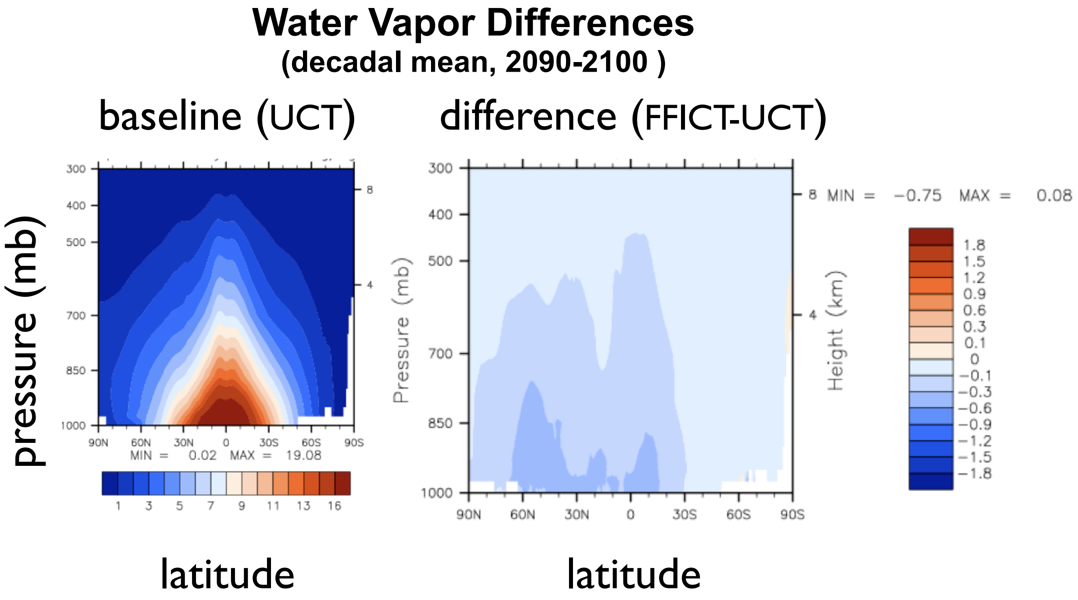


Figure 10: Spatial pattern of difference in the greenhouse effect during the final simulation decade (2090-2099) between the UCT and FFICT scenarios (FFICT minus UCT).

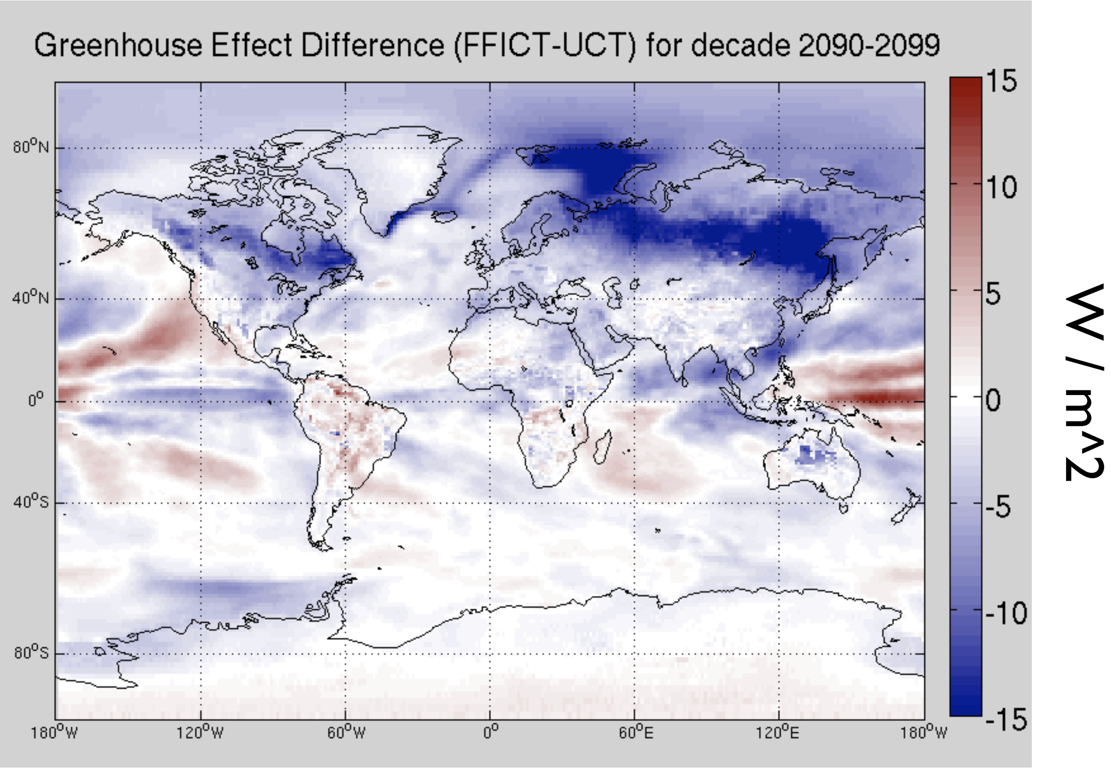
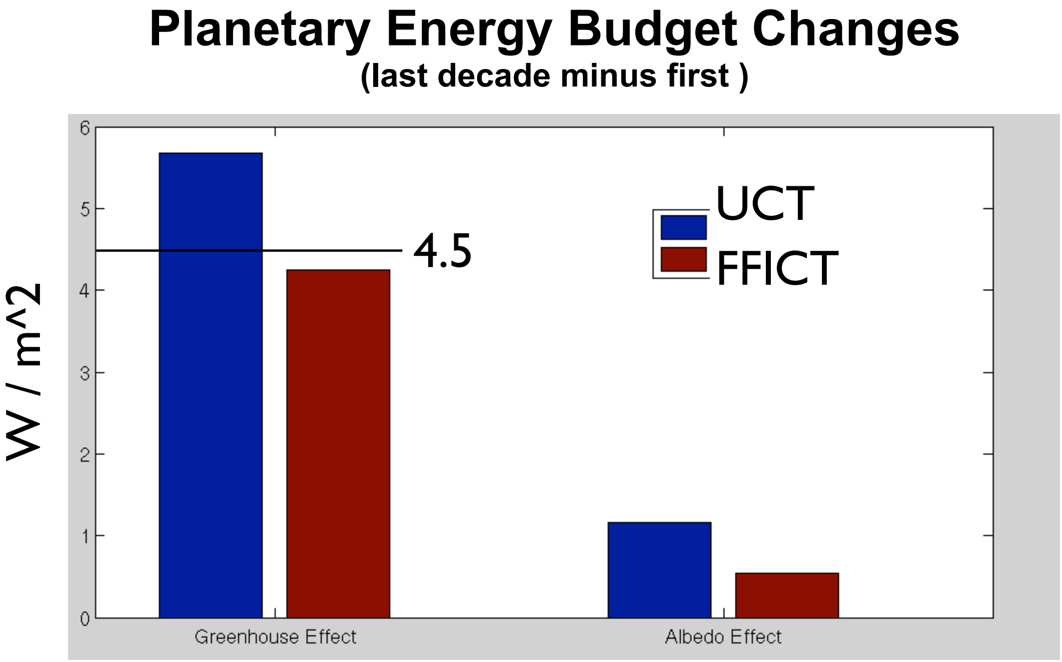


Figure 11: Mean planetary energy budget changes from the first simulation decade (2005-2014) to the last (2090-2099) (last decade minus first) for both the UCT and FFICT scenarios. The greenhouse effect designate the decrease in top-of-atmosphere longwave radiation relative to surface longwave radiation and the albedo effect refers to the increase in net absorbed shortwave radiation. The bar at 4.5 W/m^2 indicates the nominal greenhouse gas and aerosol forcing target present in both simulations.



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3 Differential climate impacts of equivalent forcing from land use change and carbon dioxide: Implications for including albedo effects in carbon trading schemes

3.1 Abstract

The albedo effect of land use change can theoretically be incorporated into carbon accounting and trading schemes using radiative forcing as a common metric for weighing the magnitude of both biophysical and biogeochemical climate disturbances. However, radiative forcing associated with albedo change is regionally concentrated whereas greenhouse gases are transported in mixed in the atmosphere. Thus their forcing is more widespread, leading to different spatial patterns of climate change and potentially different mean equilibrium responses from each of these sources of climate perturbation, even with equal globally averaged radiative forcing. To explore the potential magnitude of this discrepancy, we conduct three simulations within the Community Climate System Model 4 (CCSM4), utilizing a slab ocean model. Each simulation examines the effect of a stepwise change in forcing relative to a 4th pre-industrial control simulation: 1) widespread conversion of forest land to crops resulting in approximately -1 W/m^2 global radiative forcing from albedo change, 2) an increase in CO_2 concentrations that exactly balances the forcing from land use change at the global level, and 3) a simulation combining the first two effects, resulting in net zero forcing as would occur in an idealized carbon cap-and-trade scheme that accounts for the albedo effect of land use change. We find differences in both the mean equilibrium temperature response as well as the spatial pattern of climate change from each of these forcing agents, such that even in the net zero forcing simulation, the earth warms slightly overall while cooling significantly in the northern latitudes where the albedo effect of land use is strongest. This work indicates that commonly used metrics, such as Global Warming Potential, that are based on radiative forcing may not be appropriate for equating the non-GHG climate effects of land use change with well-mixed GHG's.

3.2 Introduction

Changes in terrestrial carbon stocks via increased forest cover and soil carbon sequestration have the potential to offset anthropogenic greenhouse gas (GHG) emissions, as does the offset of fossil fuel use from large-scale deployment of biomass crops for bioenergy. However, changes in land surface physical properties, such as albedo and stomatal conductance, associated with these activities influence climate as well (Bonan, 2008; Georgescu, Lobell, & Field, 2011) and may help or hinder efforts to stabilize climate depending on the nature and location of the land use change (Bala et al., 2007). Thus carbon offset programs and efforts to pay for the climate value of forests, such as the UN Reduced Emissions from Deforestation and Degradation (REDD) program, as well as life-cycle accounting frameworks, fail to capture the full climate effects of land use change if they only account for changes in carbon stocks.

Radiative forcing has been suggested as a metric for equating biophysical climate disturbances from land use change with equivalent levels of atmospheric carbon dioxide in the literature on land use change impacts (Betts, 2000; Bright, Cherubini, & Strømman, 2012; Schwaiger & Bird, 2010), an approach that is similar to the global warming potential (GWP) metric used to express non-CO_2 greenhouse gases in terms of CO_2-equivalents. However, this approach has been critiqued elsewhere on theoretical grounds because not all climate changes associated with land use change are principally radiative in nature (e.g. changes in hydrology or the vertical distribution of heat within the atmosphere (Boucher, Myhre, & Myhre, 2004)), and because the spatial scale of land use change forcing differs from that of well-mixed greenhouse gases (Pielke et al., 2002). This latter point implies that perfectly offsetting the radiative forcing from land use change with an equivalent amount of greenhouse gases would still induce climate change in the form of spatially concentrated heating or cooling in the region of land use change with more widespread temperature change of the opposite sign outside the sphere of influence of land use change. Such temperature gradient perturbations are likely to induce additional changes in circulation, moisture and heat transport.

Furthermore given that different feedback mechanisms are likely to be activated by radiative forcing applied in different geographic locations, it is not clear *a priori* that the climate system should exhibit the same equilibrium climate sensitivity from land use change forcing as from GHG. Hansen et al. find an efficacy factory, defined as the ratio of climate sensitivity for a given forcing agent to that of doubled pre-industrial CO_2, close to 1 for historical land use change (2005).

The efficacy of biophysical climate forcing from potential future land use change has not been well characterized. Furthermore, no study has evaluated the adequacy of radiative forcing as a metric for incorporating the biophysical effects of land use change into carbon accounting frameworks. Here we do this by modeling a scenario in which land use change forcing is offset by a radiatively equivalent change in greenhouse gas concentrations.

This study addresses these gaps via a series of model simulations beginning with pre-industrial conditions, each of which apply a stepwise change in forcing, summarized in Table 1. In the land use change (LUC) scenario, approximately 50% of global forest cover is replaced with crops, leading to a radiative forcing of -1.0 W/m^2 from albedo change. In the CO_2 scenario,

CO_2 levels increase by 57 ppm relative to the pre-industrial level of 285, yielding a positive radiative forcing of 1.0 W/m^2 that compensates for the albedo change present in the LUC scenario. A third scenario (the TRADE scenario) examines the combined effect of albedo change and an equivalent rise in CO_2 concentrations, such as would occur in an idealized carbon cap-and-trade scheme that takes into account albedo effects using radiative forcing, or if REDD were funded by forestry carbon credits and accounted for albedo in a similar manner. We perform the simulations with a simplified slab ocean model, which represents only the mixed layer of the ocean, in order to simulate equilibrium climate responses at reasonable computational cost.

3.3 Methods

3.3.1 Climate Simulations

We conduct simulations at approximately 1 degree resolution with release version 8 of the Community Climate System Model 4 (CCSM4), using standard configurations for the atmosphere and sea ice components, a slab ocean model, and prognostic carbon-nitrogen biogeochemistry within the land model. The control simulation extends by 40 years a publicly available pre-industrial equilibrium control simulation (case name b40.1850.track1.1deg.006) performed at the National Center for Atmospheric Research (NCAR) using an identical model configuration. The control simulation is forced with 1850 greenhouse gas, land use, aerosol, and orbital data. Each of the perturbed forcing simulation begins with the same initial conditions as the control simulation, but applies a stepwise change in boundary conditions (either vegetation cover, greenhouse gas concentrations, or a combination of the two) that is held constant for 60 model years. The time scale of equilibration for the slab ocean model is on the order of 10-30 model years, so the final 30 years of each perturbed forcing simulation reflect a new equilibrium climate.

The pattern of land use change in the LUC and TRADE scenarios is based on the relative difference between the standard Representative Concentration Scenario 4.5 (RCP4.5), developed as part of the 5th Coupled Model Intercomparison Project (CMIP5), and an alternative implementation of the same scenario in which large-scale biofuel deployment is induced by a tax on fossil fuel and industrial carbon emissions (Chapter 2). For each model gridcell, we compute a vector of transitions among various plant function types between the two scenarios in 2100, typically a decrease in natural vegetation types and a corresponding increase in crop area. We apply these vectors to the 1850 control vegetation distributions, scaling the vector as needed for a small percentage of gridcells (<5%) in which the decrease in one or more natural vegetation types would otherwise exceed the pre-industrial abundance of that vegetation type. For instance, the transition vector may call for a 0.35 fractional decrease in temperate deciduous trees in a particular location, but that gridcell might only have a 0.30 fractional coverage of temperate deciduous trees in 1850. In this case, we scale the entire transition vector for that cell by 0.3/0.35, converting all of the temperate deciduous trees but no more.

3.3.2 Radiative Forcing and Equivalent CO_2 Calculations

We obtain the radiative forcing from albedo change via a two-step process designed to isolate the first-order effect of land use change on the net shortwave flux at the top of the atmosphere. First, we perform an offline land model simulation for 20 model years in which the atmospheric forcing variables passed to the land model are held at pre-industrial conditions obtained from a control simulation performed at NCAR. This step eliminates atmospheric feedbacks on snow cover and vegetation growth dynamics that might influence land surface albedos. The surface albedos from this simulation are then used to drive an offline radiative transfer simulation where, again, atmospheric state variables (e.g., water vapor, GHG, and cloud distributions) are held at pre-industrial values drawn from the first 20 years of our control simulation. We compute radiative forcing as the difference between the net top-of-atmosphere shortwave flux from this simulation and the control simulation.

We compute the increase in CO_2 concentrations over pre-industrial levels required to offset the albedo forcing of -1 W/m^2 with the following relationship (G. Myhre, Highwood, Shine, & Stordal, 1998):

$F = 5.35 \ln(C / C_0)$

where F is radiative forcing, C is the perturbed CO_2 concentration, and C_0 is the baseline CO_2 concentration prior to perturbation. This yields a required increase of 57 ppm over the pre-industrial level of 285 ppm.

3.4 Results

3.4.1 Mean Temperature Responses

The time evolution of mean global surface temperature from each simulation is shown in Figure 12. The equilibrium temperature responses, calculated from the final 30 years of each simulation, are -0.57 °C and 0.74 °C for the LUC and CO_2 scenarios respectively, implying an efficacy factor of 0.78 for the radiative forcing present in the LUC scenario. Dotted lines indicate 95% confidence intervals based on an estimate of model internal variance obtained from the control simulation. Despite net neutral radiative forcing, the TRADE scenario converges to a new equilibrium temperature that is 0.21 °C above control, reflecting the different sensitivities of the climate system to biophysical forcing from land use change versus CO_2.

The equilibrium temperature response in the TRADE scenario is larger than the linear combination of temperature responses from the LUC and CO_2 scenarios (0.17 °C), reflecting interactions between the two climate change processes. Warming from CO_2 is likely to reduce snow cover, and consequently the magnitude of albedo change from converting forests to cropland, leading to higher temperatures. That is, the snow albedo feedback associated with CO_2 warming is likely to be enhanced with lower forest cover. The sign of the interaction term is consistent with this mechanism.

A notable feature of these simulations is that a good deal of change takes place even in the first model year. More than 50% of the equilibrium temperature change present in the LUC scenario is evident in the very first year, indicating that fast timescale feedback processes dominate this response. On the other hand, only 12% of the equilibrium temperature change occurs in the first year of the CO_2 scenario. These differences are likely due to the lower heat capacity of continents versus oceans – all of the LUC forcing is concentrated over land where temperatures are able to adjust rapidly to a given change in energy fluxes.

Figure 13 shows the surface air temperature responses over land and ocean for the LUC and CO_2 scenarios. The fast temperature response in the LUC case is driven by changes over land, whereas the ocean response is both smaller and slower, leading to an equilibrium change in land-sea contrast. In the CO_2 case, air temperatures over both land and oceans respond more slowly and in tandem with one another. Interestingly, the equilibrium land temperature responses are similar in both scenarios, but the ocean response is diminished in the LUC case.

The TRADE scenario exhibits both the rapid decline in temperature evident in the LUC scenario and the slow build-up evident in the CO_2 scenario (Figure 12). We expect that with a more realistic dynamic ocean model (recall that our use of the slab ocean model artificially decreases the timescale of ocean equilibration for computational reasons), the TRADE scenario would spend a longer time below control initially, followed by an eventual rise to the level above control indicated.

3.4.2 Planetary Energy Budget

Insight into the dynamics of the climate system response to forcing can be gained by examining the evolution of the planetary energy budget over time, as depicted in Figure 14. When the net absorbed shortwave radiation (blue line) exceeds the net outgoing longwave radiation (red line), the planet is a net energy sink and average temperatures must increase in order to boost the longwave flux and restore equilibrium. The converse is true when the planet is a net source of radiation; temperatures must cool to restore equilibrium.

CO_2 forcing causes a decrease in outgoing longwave radiation that is gradually restored as the planet warms. Meanwhile, feedback processes (e.g. snow and ice feedbacks) cause a decrease in albedo and corresponding increase in absorbed shortwave such that both shortwave and longwave fluxes eventually equilibrate at a level approximately 0.5 W/m^2 above control. The albedo feedbacks are slow in this case and correspond with the rise in mean temperature.

Albedo forcing in the LUC scenario causes a rapid decrease in absorbed shortwave radiation followed by a slower decline to an equilibrium level approximately 1 W/m^2 below control. The slow decline coincides with the decrease in ocean temperatures and indicates the presence of ice albedo feedbacks. Outgoing longwave radiation tracks the shortwave decline closely and reflects both the rapid decline in temperature in the first time step and the more gradual temperature decline to equilibrium over the next several years.

The TRADE scenario (Figure 14, panel B) exhibits a rapid decline in absorbed shortwave, like the LUC case but smaller in magnitude. The shortwave decline is exceeded by an even larger initial decline in longwave radiation. Thus, the planet is a net energy sink within the first model year, indicating that elevated CO_2 levels are already counteracting the initial decline in temperature from albedo change in this scenario. Albedo feedbacks eventually reverse some of the initial shortwave decline.

3.4.3 Spatial Pattern of Temperature Responses

Consistent with the results presented in Chapter 2, the temperature decrease in the LUC scenario is concentrated in the northern latitudes where albedo increases are strongest due to the contrast between Boreal forests and snow-covered croplands (Figure 15). The warming in the CO_2 scenario, on the other hand, is widespread. In the TRADE scenario, which includes both LUC and CO_2 forcing, the southern hemisphere and tropics warm even as the northern mid and high latitudes cool, altering global scale temperature gradients. Thus while overall temperatures are slightly warmer in the TRADE scenario relative to the pre-industrial control, many regions experience cooling while others experience warming.

3.5 Discussion

We show that the equilibrium climate response differs in important ways between land use change and GHG forcing. The mean temperature response per unit of forcing, i.e. the equilibrium climate sensitivity, is smaller by 22% for the spatial pattern of land use change that we examine compared to an elevated CO_2 scenario with equivalent forcing, indicating that different feedback processes are activated by each of these types of forcing. This result is in contrast to the Hansen et al. (2005) efficacy factor for historical land use change that is much closer to 1. This discrepancy could be due to the specific pattern of land use change that we examine and/or differences in model structure. However, given strong variation in the climate effects from deforestation at different latitudes (Bala et al., 2007; Bonan, 2008), we expect that the efficacy of land use change forcing varies significantly as a function of geography.

Climate policies are set in a context of human activities, forcing, climate response, and societal damages from climate change (Figure 16). The utility of radiative forcing as a policy metric for judging the climate value of different activities relies on there being a strong relationship between forcing and damages. However, when the climate system response to equivalent forcing from different activities is itself different, this relationship breaks down. If we take equilibrium temperature response to be our measure of climate system response, then one could imagine applying an adjustment factor for forcings with different efficacies, as in Hansen et al. (2005); in our case, we would discount the forcing from albedo change by approximately 25%. However, the damages from climate change certainly depend on the spatial pattern of temperature change, which differs substantially between LUC and CO_2 forcing, particularly considering changes in hydrology and atmospheric circulation that are likely to accompany changes in global temperature gradients. In addition, we find that a greater portion of the temperature response to land use change compared to GHG is dominated by fast timescale feedbacks, which has implications for societal damages as well.

Treating climate forcings as equivalent for policy purposes, and in particular including biophysical aspects of land use change in global carbon trading and offset strategies using metrics such as GWP that are based on radiative forcing, risks significant climate distortion.

However, ignoring biophysical effects altogether would also lead to unintended consequences (Chapter 2). As mitigation strategies evolve, decision-makers must weigh the costs of ignoring biophysical effects against those of using imperfect metrics that do not adequately characterize the full climate system response to land use change. An alternative class of policies (discussed in Chapter 1) would focus on regional scale climate effects of land use change using regional scale metrics.

3.6 Figures

Figure 12: Global mean surface air temperature response of each perturbed forcing simulation relative to the pre-industrial control. Dotted lines indicate the 95% confidence interval around the mean equilibrium responses for each simulation.

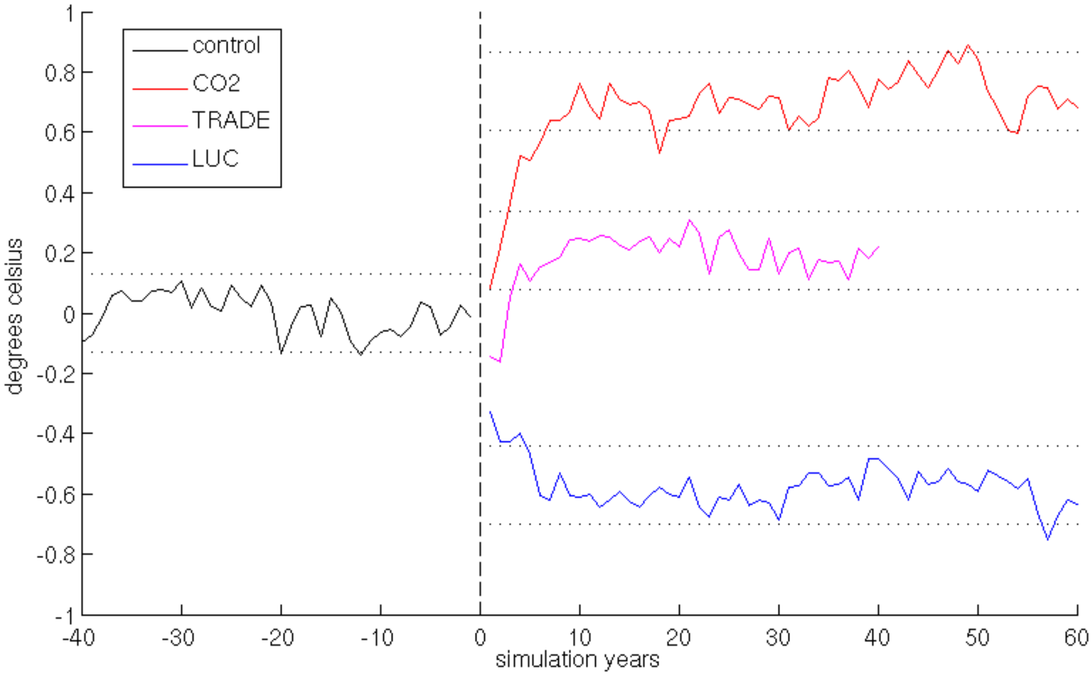

Figure 13: Global mean surface air temperature responses over land and oceans respectively for the LUC and CO_2 scenarios.

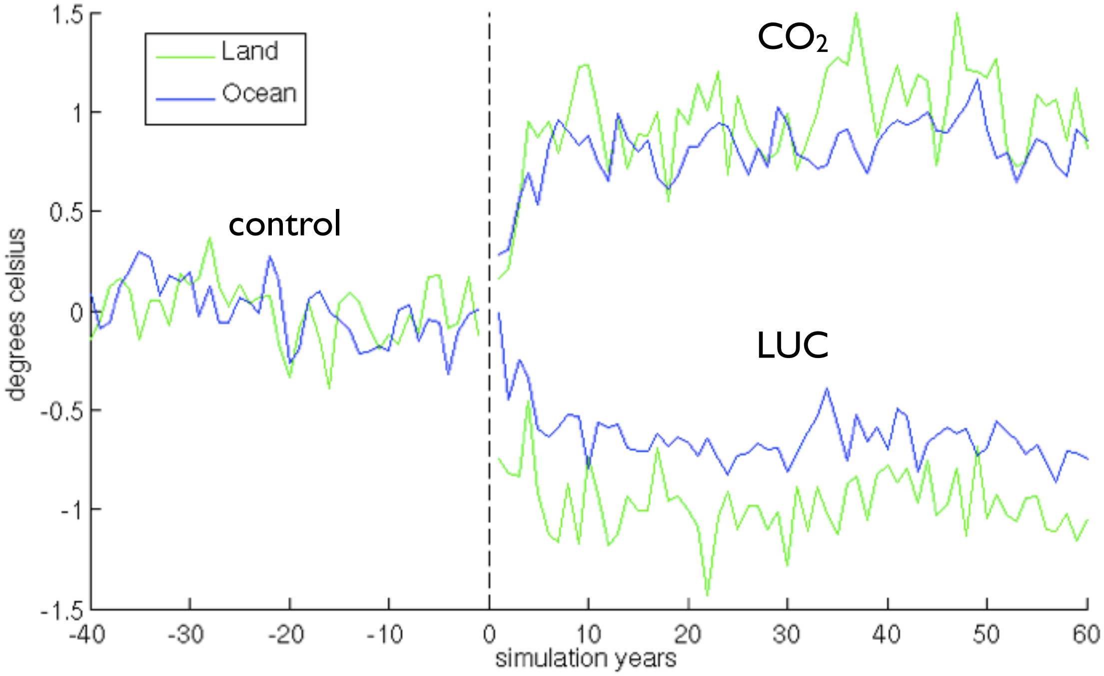

Figure 14: Time evolution of planetary energy balance changes for each of the perturbed forcing simulations relative to the pre-industrial control. Blue lines indicate net top-of-atmosphere absorbed shortwave radiation and red lines indicate net top-of-atmosphere outgoing longwave radiation.

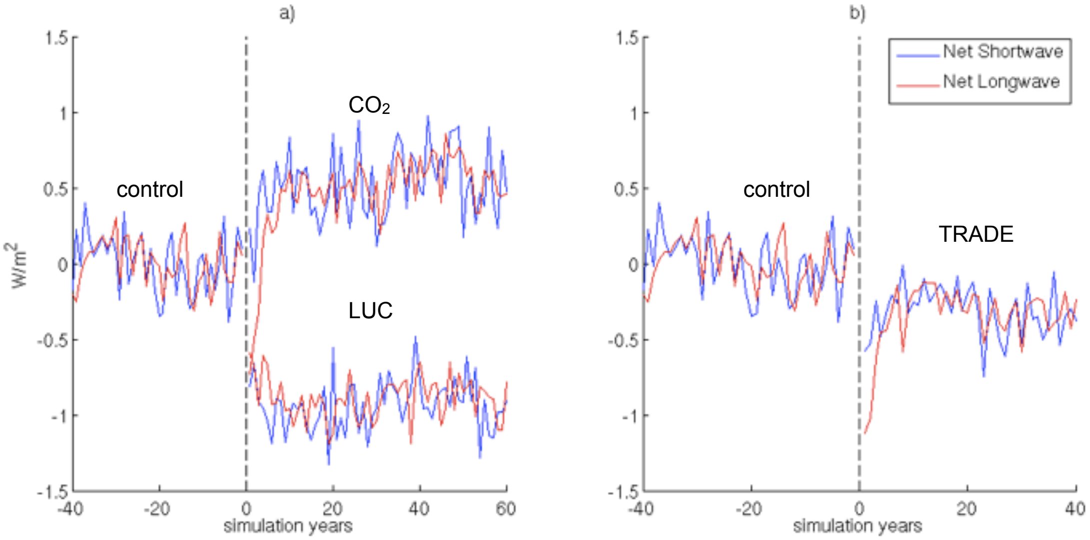

Figure 15: Spatial pattern of equilibrium surface air temperature change relative to control for each perturbed forcing simulation.

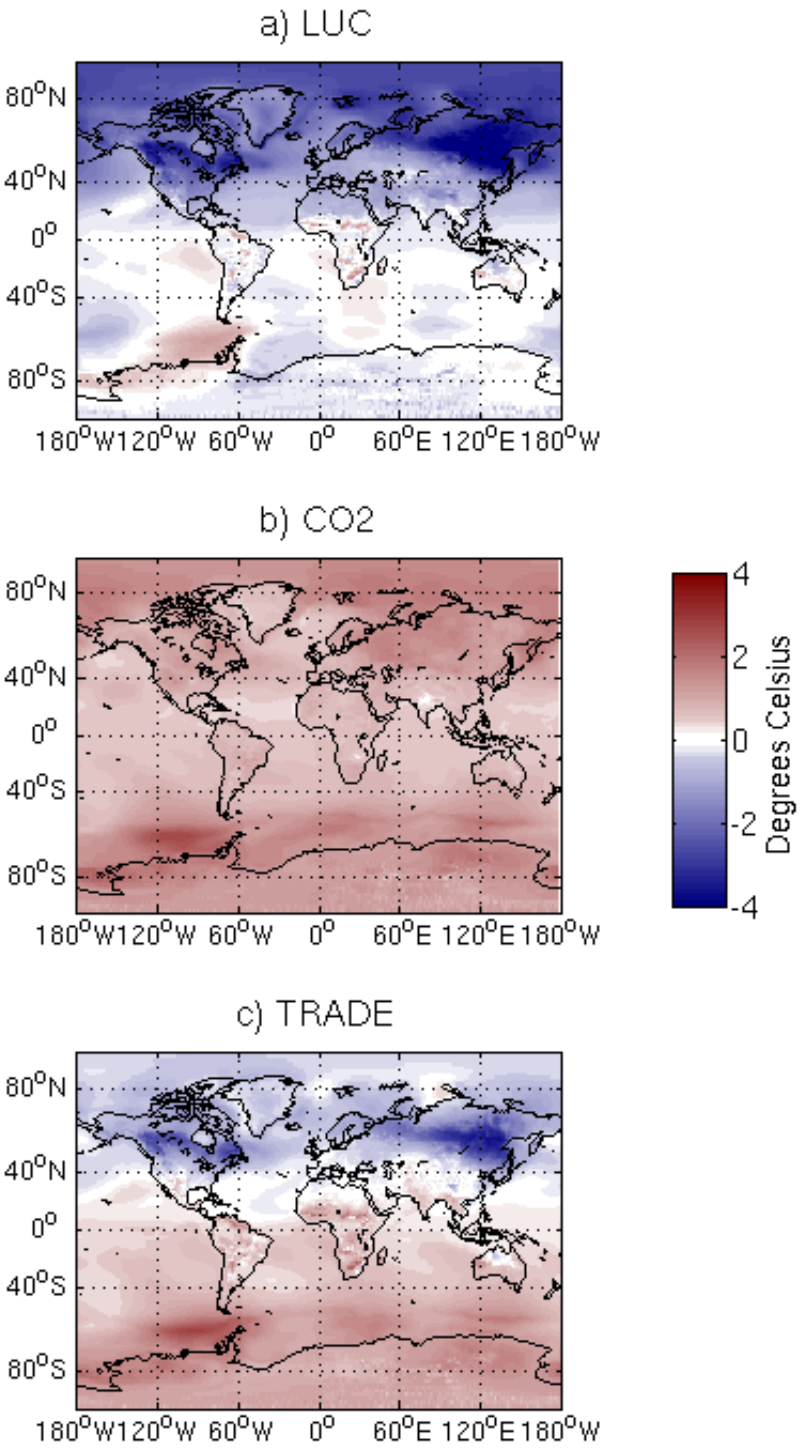

Figure 16: Schematic showing relationship between anthropogenic climate forcing, climate change, and societal damages from climate change. Radiative forcing is a good proxy for comparing the societal damages from different activities only if the feedback processes and pattern of climate change induced by equivalent forcings are themselves equivalent.

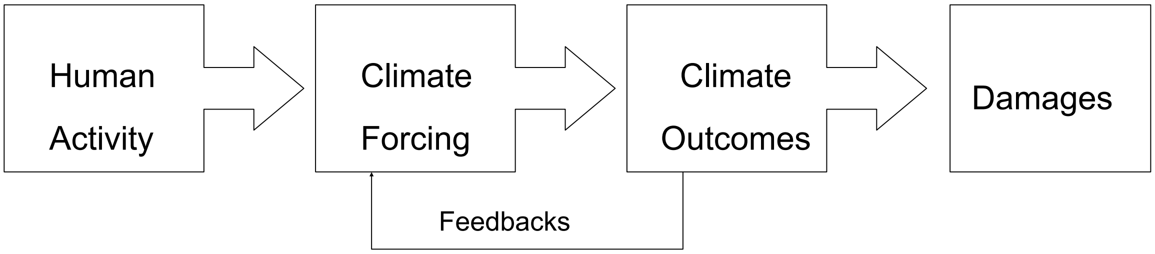

Table 1: Radiative forcing by simulation.

Scenario	Albedo forcing	CO_2 forcing	Net forcing
	W/m^2	W/m^2	W/m^2
LUC	-1	0	-1
CO_2	0	1	1
TRADE	-1	1	0

3.7 References

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4 Conclusions

Anthropogenic influences on the terrestrial carbon cycle have the potential to mitigate climate change by slowing the rise in atmospheric CO_2 concentrations. To accomplish this, policies that place value on terrestrial carbon could lead to large-scale increases in forest cover relative to business-as-usual or to expansion of cropland for biofuel production. The foregoing chapters examine an important consideration for such policies, namely that land use change also influences climate via biophysical processes that have the potential to reinforce or thwart climate mitigation efforts at regional and perhaps global scales.

In Chapter 1, I summarize relevant policies and programs, categorizing them into three groups: those that use market mechanisms to explicitly value terrestrial carbon, those that include terrestrial carbon in life-cycle assessments, and those focused on regional scale land use planning. For the first two types of policies, metrics based on radiative forcing, such as Global Warming Potential (GWP) have been employed to weigh the relative climate influence of different well-mixed greenhouse gases (GHGs). I argue on theoretical grounds that biophysical effects of land use change do not fit neatly into this paradigm. The climate effects of biophysical change are not distributed spatially in the same way as well mixed GHGs, and land use change influences climate in important ways that do not result in radiative forcing at all.

I examine several alternative metrics, locating them within a framework that describes human influences on climate, climate feedbacks, and subsequent social costs. Regional scale forcing metrics may provide valuable, but nonetheless incomplete, information about both GHG and biophysical aspects of land use change within regional land use planning policies. Metrics that measure climate outcomes rather than forcing have the potential to integrate different forcing mechanisms across different scales of climate influence. However they require more sophisticated modeling capability as well as a method for weighing the relative importance of different kinds of climate outcomes such as temperature versus precipitation change or extreme change versus mean change, in different places. A damage function, which maps climate outcomes into units of social value, provides a theoretic benchmark that would properly evaluate the costs and benefits of any climate perturbation activity.

Given the imperfection of any metric that can be computed in practice, Chapter 1 raises several questions about the physical climate system response to land use change that could help to inform the conditions under which biophysical considerations are important as well as the magnitude of the climate distortion – the unintended climate outcomes – that would result from policies designed to maximize various metrics. Subsequent chapters address some of these questions using an earth system model to probe the climate system response to land use change.

In Chapter 2, I show that failure to account for the biophysical aspects of land use change in climate policy could lead to unexpected climate outcomes. Two different policies that reach the same global forcing target for GHG and aerosols yield significant differences in terms of both the mean and spatial pattern of temperature change. Using additional land model and radiative transfer model simulations in which atmospheric conditions are held fixed, I demonstrate that the feedback mechanisms triggered by land use change differ by region. For example, boreal deforestation is associated with a significant water vapor feedback that amplifies regional cooling initiated by albedo change. This effect is less apparent in the tropics where the greenhouse effect of water vapor is already saturated and so is insensitive to marginal changes in water vapor concentrations.

The results of these simulations also have implications for the scenario generation process of the 5th Coupled Model Intercomparison Project (CMIP5), which relies on the assumption that different socio-economic scenarios that follow the same forcing pathway lead to equivalent climate outcomes. To the extent that patterns of land use change differ – and in fact there are large differences – among scenarios, our work shows that the pattern of climate change will differ as well. The pattern scaling techniques that underlie this part of the CMIP5 process may need to be modified to account for the specific climate signals associated with land use change in different regions of the world.

In Chapter 3, I explore the implications of accounting for land use change using a globally averaged measure of radiative forcing. Simulations that apply equal and opposite globally averaged forcing from 1) increased albedo due to land use change and 2) elevated CO_2 concentrations do not lead to opposite equilibrium climate outcomes. The temperature response to land use change is smaller and more concentrated over land. In addition, a greater percentage of the land use change response occurs as a result of fast timescale processes. A simulation that includes both of these effects – resulting in net neutral forcing – yields a slight increase in global mean temperature. This modest temperature change is actually the mean of a significant temperature decrease in the high northern latitudes where the albedo effect is concentrated and an even stronger warming across the tropics and southern hemisphere.

These results indicate that the climate distortion, or unintended climate consequences, that would result from using radiative forcing as the metric to include albedo change in global carbon trading schemes is of the same order of magnitude as the climate signal that mitigation activities are meant to address. More generally, they support the notion that activities that are equivalent in terms of radiative forcing are not necessarily equivalent in their climate effects or consequent social costs.

Taken together, the results of Chapters 2 and 3 present a dilemma for global climate policy. Ignoring the biophysical aspects of land use change results in unintended consequences, but so does including these aspects within the radiative forcing-based paradigm. Meanwhile, there is no clear path to an alternative metric of global scale impacts, because the alternatives proposed thus far are either impractical to compute or suffer from similar theoretical critiques as radiative forcing.

One alternative strategy, discussed briefly in Chapter 1, would be to keep policies aimed at mitigating climate via land use change separate from policies aimed at reducing GHG emissions from fossil fuel use. While separating these activities is less efficient economically than allowing trade among them, it is also inefficient to trade in units that do not reflect the true costs of the externality that the regulated market intends to internalize. This disaggregated strategy would recognize that land use activities have multiple values for many actors and markets only internalize some of them. Regulation of climate, through both carbon cycle and biophysical processes, is just one of many ecosystem services affected by land use change.

Others include habitat for biodiversity, livelihoods for rural people, and the removal of pollutants from surface water. In many places, regional scale land use planning already takes into account the variety of competing interests that are difficult to weigh with a single metric. Considering all of the climate effects of land use change within this context could be accomplished with the use of sustainability indicators or other means of establishing acceptable constraints on certain kinds of land use change in order to avoid unwanted outcomes. One potential downside to this approach is that carbon cycle effects of land use change could be downplayed because much of their effect occurs outside of the regional jurisdictions where land use planning occurs.

The pattern of land use change examined in Chapters 2 and 3 is relatively extreme and much of the signal from land use change comes from boreal deforestation. More work – using different models and different scenarios – is needed to examine the extent and nature of the biophysical signal from less dramatic land use changes. In fact, while these chapters have established the importance of biophysical impacts of land use change for climate policy, they only begin to address the list of policy-relevant questions regarding the physical climate system response to land use change outlined in Chapter 1. A systematic examination of the climate consequences of different types of land use change, including management factors as well as landcover conversion, across many different regions would be a valuable step toward informing these questions. In addition to simulations, remote sensing and eddy covariance observations of energy, water, and greenhouse fluxes between land and atmosphere could provide useful empirical constraints as well. As knowledge of the role that ecosystems and land management play in the climate system evolves, it will enable more appropriate and efficient strategies for addressing land use change in climate policy