Final technical report: Biomass energy: The climate-protective domain

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This is a three-year project initiated in 2008 and originally scheduled for completion at the end of February, 2011. Thanks to the availability of independent funds to support some of the project participants, we have been able to conserve some of the funds, which we used to support a no-cost extension through February, 2013. The original project plan emphasized four topic areas. Topic one used a new technology for interpreting remote-sensing data to quantify carbon and climate forcing from forested lands recently converted to biomass energy. Topic two extended this analysis to the global scale, using carbon-cycle modeling, combined with several kinds of observational data. Topic three focused on climate forcing from food-biomass interactions, with an emphasis on understanding indirect clearing that occurs as biomass for energy pushes food agriculture into other lands. Topic four looked at net climate forcing from biofuels-related direct and indirect conversions. It used climate models and satellite observations to quantify the component of climate forcing due to effects on albedo.

Over the course of the project, the team published paper in all four of these areas. In addition, we were able to devote substantial resources to some emerging areas. These included contrasting forest biomass in deforested and not deforested areas, the spatial velocity of climate change, consequences of alternative uses of biomass energy, and negative emissions energy technologies.

The project was very successful. The GCEP funds supported work that led to 12 papers, including papers in Science, Nature, and PNAS. Post-docs supported on the project went on to jobs at UC Merced, the California Academy of Sciences, Arizona State University, and a Fulbright NEXUS Scholarship.

The project was also successful beyond publishing papers and training scholars. It established Stanford as a center for creative research on biomass energy, and it played a key role in the emergence of an international dialogue about sustainability issues with biomass energy. For GCEP, the project demonstrated the value of thinking broadly about energy technologies. Its focus on understanding the limits of biomass energy and the environmental consequences of large-scale deployment of biomass energy broadened the program and provided useful reference points for the analysis of other energy systems.

The following sections of the report discuss the accomplishments in seven thematic areas that capture the full sweep of the published papers. The areas are:

1. Differing biomass consequences of past and future deforestation,
2. Global potential for sustainable biomass energy,
3. Efficient uses of biomass energy and the concept of miles per acre,
4. Conservation issues associated with land use and climate change,
5. Non-GHG forcing of climate,
6. Mapping pasture conversion,
7. Carbon-negative systems.

1. Differing biomass consequences of past and future deforestation

Loarie, S. R., G. P. Asner, and C. B. Field. 2009. Boosted carbon emissions from Amazon deforestation. Geophysical Research Letters 36:L14810.

Deforestation represents about 10% of the carbon released to the atmosphere by anthropogenic activities. Changes in the rate of deforestation vary dramatically from region to region. Over the past several years, the rate of clearing in the Brazilian Amazon has fallen dramatically. Area cleared is, however, only one determinant of carbon loss from deforestation. The other is biomass per unit of cleared area. This study (Loarie et al. 2009a) combined optical and radar data to assess whether there was a temporal trend in biomass per unit of land area deforested in Brazil from 2001 to 2007. The answer is that there was (Figure 1), with higher biomass per unit of area in the plots deforested at the end of the time interval. As a consequence, estimates of deforestation based on the assumption of constant biomass are biased low. Even more important, the remaining Brazilian Amazon has biomass per unit of area that is substantially higher than the pre-deforestation biomass in the regions that have been cleared. Thus, any future deforestation will represent carbon releases that are more intense than those in the historical era, heightening the conservation value of these not yet deforested regions. The findings in this paper are important for biomass energy, because new biomass plantations often come at the expense of tropical forest, either directly or through a series of indirect transfers.

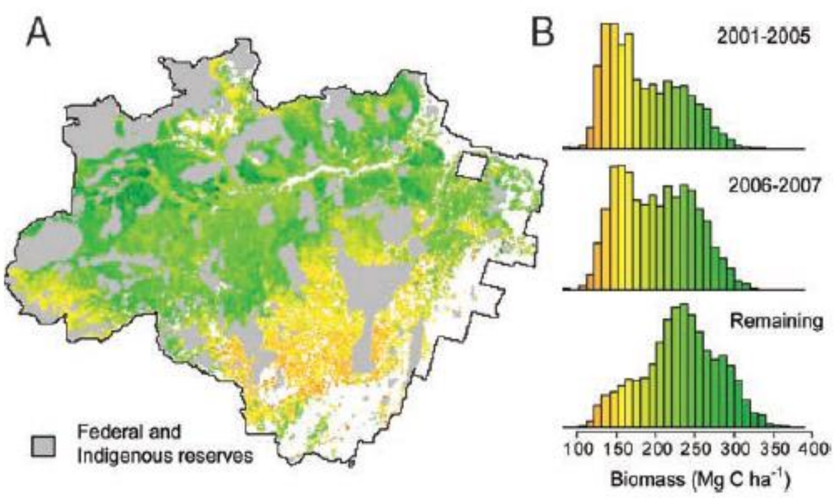


Figure 1: (a) Pre-deforestation biomass (Mg C ha^{1}) in the Brazilian Amazon. Federal and indigenous reserves are in gray. The color code for Figure 2a is the orange-to-green scheme shown in Figure 2b. (b) Histograms of biomass previously cleared (top) in 2001–2005, (middle) in 2006–2007, and (bottom) biomass in remaining forests in 2007. Y-axis represents the frequency of 100 km2 areas.

2. Global potential for sustainable biomass energy

Field, C. B., J. E. Campbell, and D. B. Lobell. 2008. Biomass energy: the scale of the potential resource. Trends in Ecology & Evolution 23:65-72.

Over the last few decades, several papers have estimated the potential for biomass energy production. The results vary widely, with major sources of variability due to the areas assumed to be available, the plant growth potential in those areas, and the projection for future changes in growth. For this study (Field et al. 2008), we adopted a strong sustainability filter and estimated potential biomass energy subject to the condition that land not be switched from food agriculture to biomass energy and that new biomass energy production not go into forested areas. The latter criterion was intended to avoid carbon debts and protect biodiversity. These criteria led to a search for land that was in agriculture at some point in the last 300 years but is currently abandoned. Building from estimates of past agriculture, we developed a map of abandoned lands, and then estimated that plant growth on these lands under natural conditions (Figure 2). Based on the argument that plant growth under natural conditions represents the maximum feasible without extensive inputs of fertilizer or water, we used this as the estimate of the sustainable domain for biomass energy. The number, 27 EJ/y, represents about 5% of current global primary energy demand.

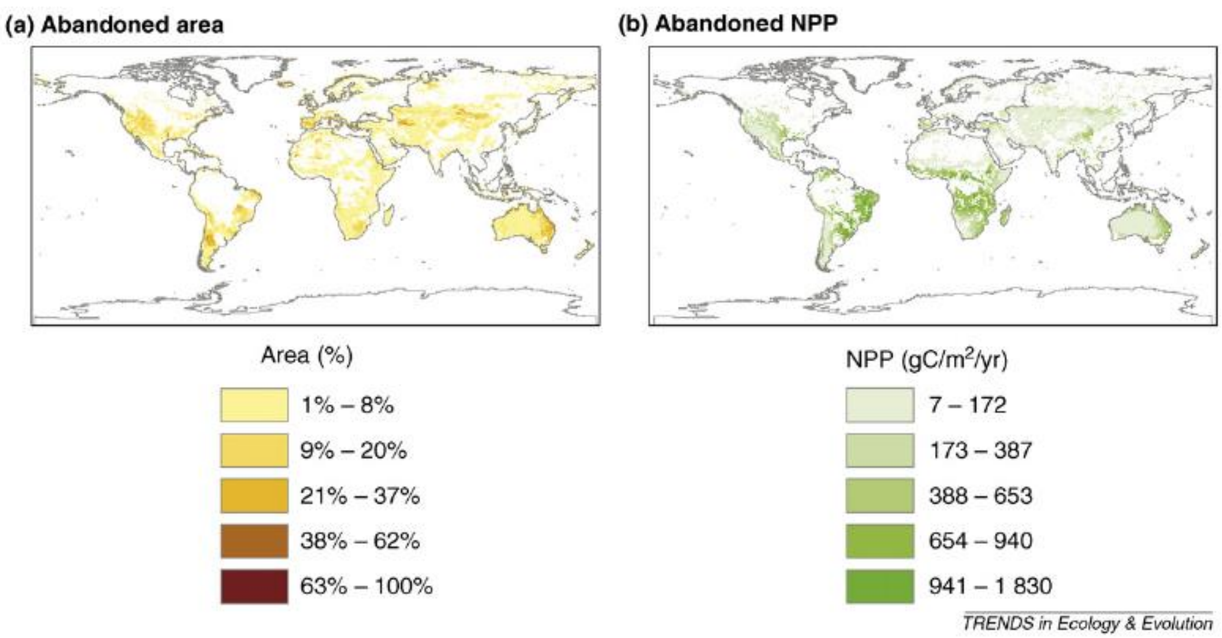


Figure 2: (a) Total abandoned land area (abandoned from crops and grazing) and (b) the projected net primary production of natural vegetation on those areas.

Campbell, J. E., D. B. Lobell, R. C. Genova, and C. B. Field. 2008. The global potential of bioenergy on abandoned agriculture lands. Environ. Sci. Technol., http://pubs3.acs.org/acs/journals/doilookup?in_doi=10.1021/es800052w

This paper (Campbell et al. 2008) extended the results of Field et al. (Field et al. 2008) to address country-by-country access to sustainable biomass energy. The conclusion was that The Unites States, Brazil, and Australia are the three countries with the most access to potentially sustainable biomass resources. Still, sustainable biomass potentially represents only a small fraction of current primary energy demand in most developed countries (Figure 3). But for Brazil, Australia and many developing countries, sustainable biomass could play a large role in meeting primary energy demands.

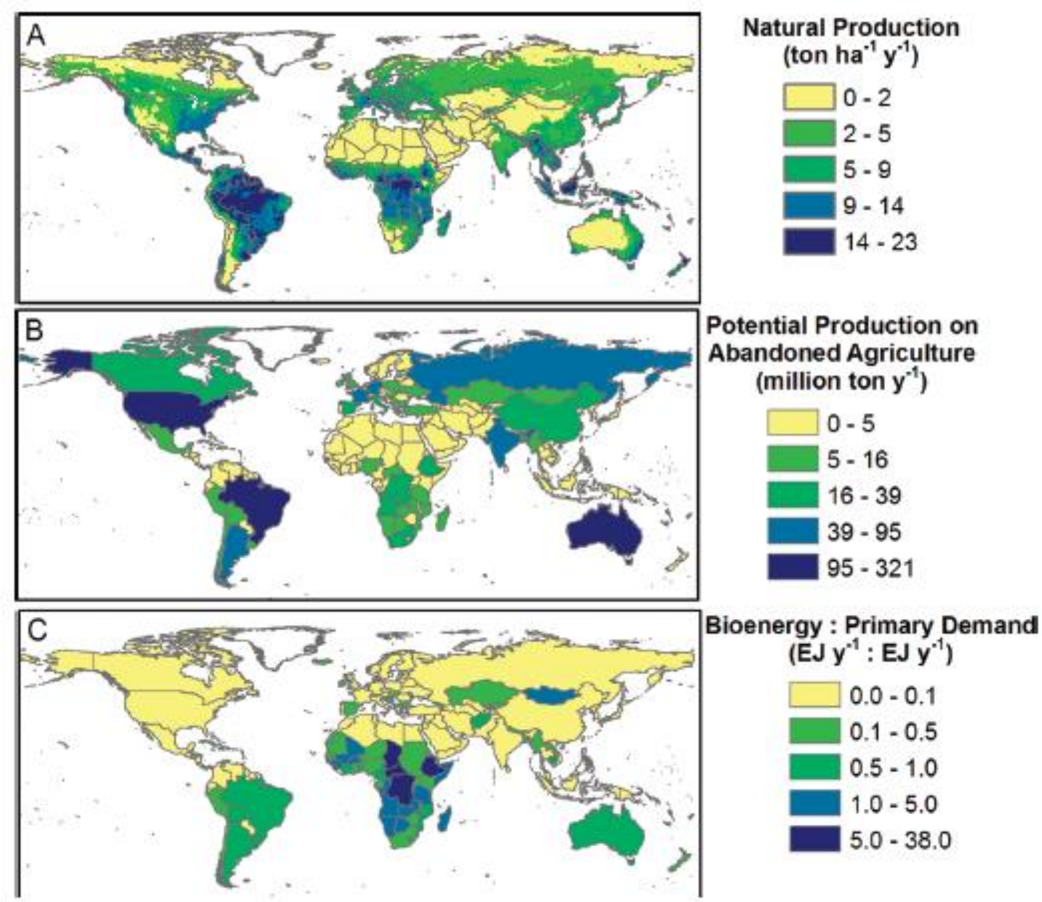


Figure 3. Biomass production potential on abandoned agriculture lands. (A) Natural above-ground production of biomass on all lands determined from the CASA model, assuming 50% of the biomass is above-ground and the ratio (by mass) of biomass to carbon is 2.2. (B) Potential above-ground production of biomass on abandoned agriculture lands at the country level. (C) Ratio of the energy content of the biomass on abandoned agriculture lands relative to the current primary energy demand at the country level. The energy content of biomass is assumed to be 20 kJ g^{-1}.

3. Efficient uses of biomass energy and the concept of miles per acre

Campbell, J. E., D. B. Lobell, and C. B. Field. 2009. Greater transportation energy and GHG offsets from bioelectricity than ethanol. Science 324:1055-1057.

The quantity of land available to grow biofuel crops without impacting food prices or greenhouse gas emissions from land conversion is limited. Therefore, bioenergy should maximize land use efficiency when addressing transportation and climate change goals. Biomass could power either internal combustion or electric vehicles, but the relative land use efficiency of these two energy pathways is not well quantified. Here (Campbell et al. 2009) we show that bioelectricity outperforms ethanol across a range of feedstocks, conversion technologies, and vehicle classes. Bioelectricity produces an average 81% more transportation kilometers and 108% more emissions offsets per unit area cropland than cellulosic ethanol (Figure 4). These results suggest that alternative bioenergy pathways have large differences in how efficiently they use the available land to achieve transportation and climate goals.

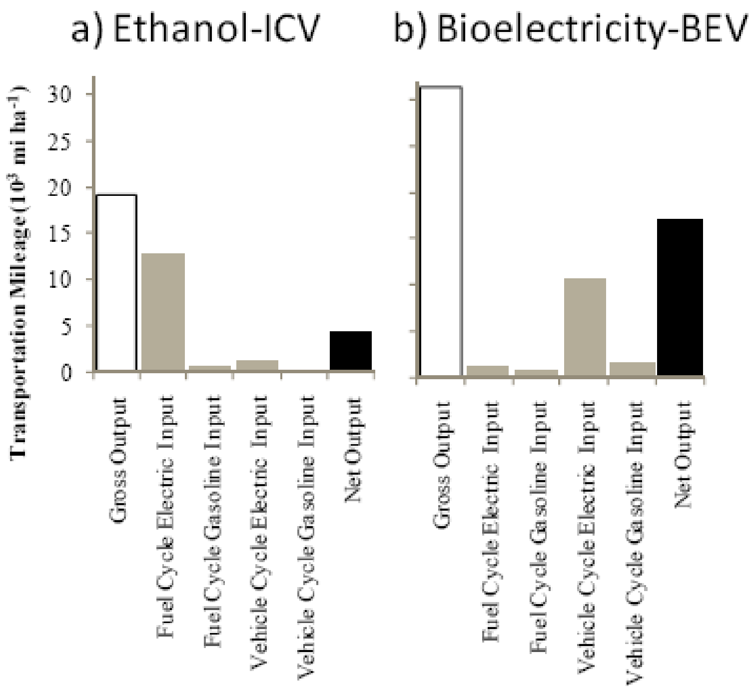


Figure 4. Transportation and GHG offsets from bioelectricity and ethanol based on a range of vehicle classes, agriculture systems, and energy conversion technologies. Net output accounts for co-products as well as input in the fuel cycle and vehicle cycle. Results are not plotted for cases when more kilometers could be traveled with input energy than with gross output energy.

4. Conservation issues associated with land use and climate change

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009. The velocity of climate change. Nature 462:1052-1055.

The ranges of plants and animals are moving in response to recent changes in climate. As temperatures rise, ecosystems with ‘nowhere to go’, such as mountains, are considered more threatened. However, species survival may depend as much on keeping pace with moving climates as the climate’s ultimate persistence. Here (Loarie et al. 2009b), we present a new index of the velocity of temperature change (km yr^{-1}), derived from spatial gradients ($^{\circ}C$ km^{-1}) and multimodel ensemble forecasts of rates of temperature increase ($^{\circ}C$ yr^{-1}) in the 21st century. This index represents the instantaneous local velocity along Earth’s surface needed to maintain constant temperatures, and has a global mean of 0.42 km yr^{-1} (A1B emission scenario). Due to topographic effects, the velocity of temperature change is lowest in mountainous biomes such as tropical and subtropical coniferous forests (0.08 km yr^{-1}), temperate coniferous forest, and montane grasslands. Velocities are highest in flooded grasslands (1.26 km yr^{-1}), mangroves, and deserts (Figure 2). High velocities suggest that the climates of only 8% of global protected areas have residence times exceeding 100 years (Figure 5). Small protected areas exacerbate the problem in mediterranean-type and temperate coniferous forest biomes. Large protected areas may mitigate the problem in desert biomes. These results suggest management strategies for minimizing biodiversity loss from climate change. Montane landscapes may effectively shelter many species into the next century. Elsewhere, reduced emissions, a much expanded network of protected areas, or efforts to increase species movement may be necessary.

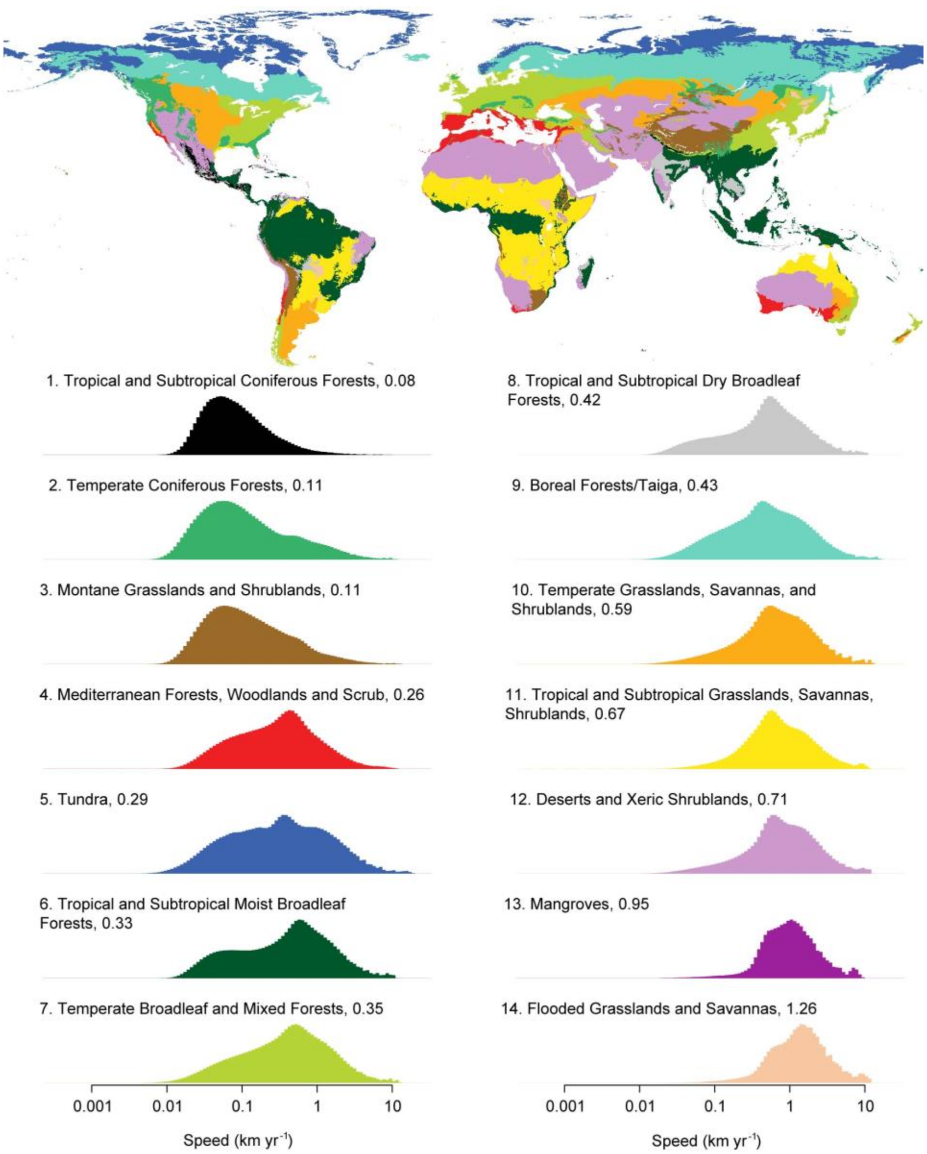
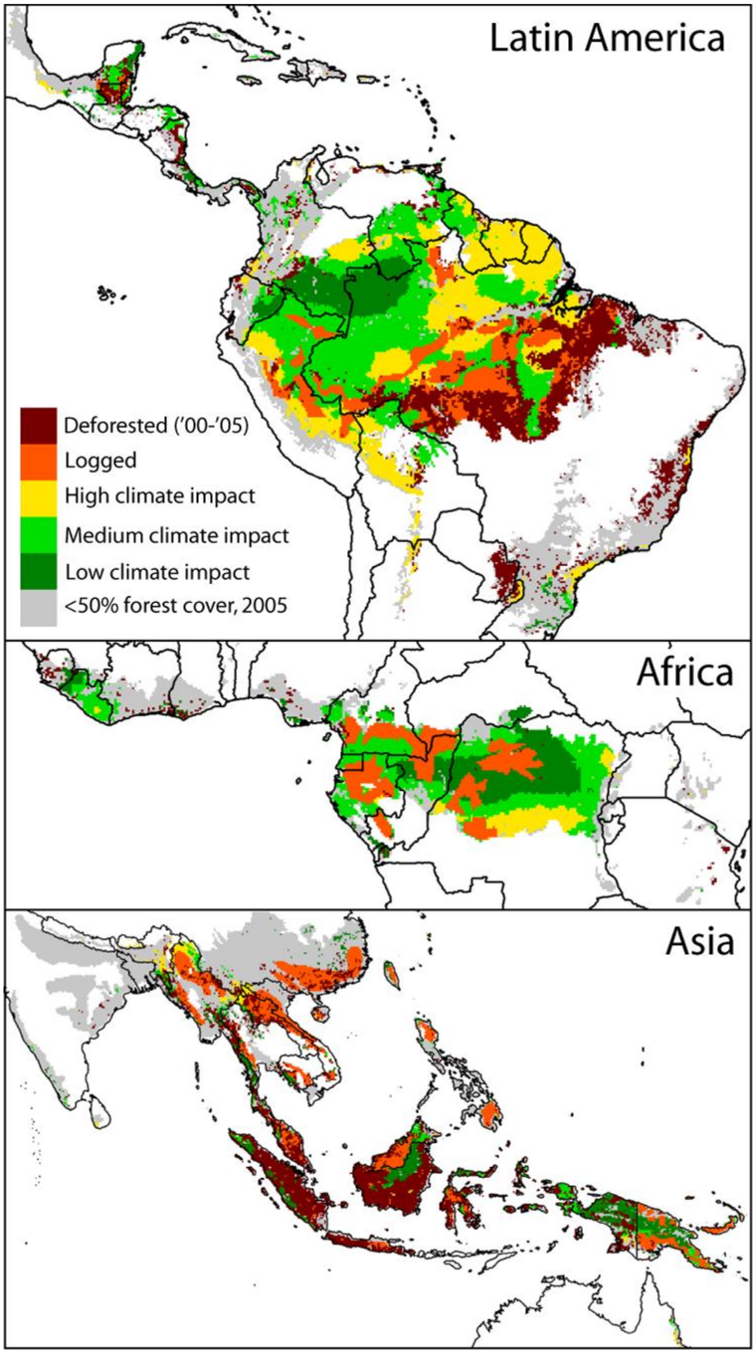


Figure 5. The velocity of temperature change by biome. A map of biomes and histograms of the speed of temperature change within each biome. Histograms are ordered by increasing velocity according to their geometric means.

Asner, G. P., S. R. Loarie, and U. Heyder. 2010. Combined effects of climate and land-use change on the future of humid tropical forests. Conservation Letters 3:395-403.



New deforestation and selective logging data and climate change projections suggest that biodiversity refugia in humid tropical forests may change more extensively than previously reported. However, the relative impacts from climate change and land use vary by region (Asner et al. 2010). In the Amazon, a combination of climate change and land use renders up to 81% of the region susceptible to rapid biodiversity change. In the Congo, logging and climate change could negatively affect the biodiversity in 35-74% of the basin. Climate-driven changes may play a smaller role in Asia-Oceania compared to that of Latin America or Africa, but land use renders 60-77% of Asia-Oceania susceptible to major biodiversity changes. By 2100, only 18-45% of the biome will remain intact (Figure 6). The results provide new input on the geography of projected climate change relative to ongoing land-use change to better determine where biological conservation might be most effective in this century.

Figure 6. The footprint of deforestation, selective logging and climate change in the humid tropical forest biome.

5. Non-GHG forcing of climate

Georgescu, M., D. Lobell, and C. Field. 2009. Potential impact of US biofuels on regional climate. Geophysical Research Letters 36:L21806.

Our research has extended recent work assessing indirect impacts of landscape change associated with bioenergy expansion through a biogeochemical lens by focusing on the direct biogeophysical climate effects on local and regional climate.

Aided by the Weather Research and Forecasting Model (WRF), a coupled land-atmosphere modeling system, we conducted a suite of midsummer, continental-wide, sensitivity experiments by imposing realistic biophysical parameter limits appropriate for bio-energy crops in the Corn-Belt of the United States. Our intention was two-fold: first, to isolate the maximum regional climate impact due to land-use change resulting from bioenergy crops and second, to quantify the relative importance of biophysical parameters relative to one another. The full breadth of albedo and minimum canopy resistance specification resulted in the largest simulated local changes in 2 m temperature (order of 1°C). The tendency of greater leaf area index (LAI) and rooting depth for perennial rather than annual bioenergy crops highlight their local cooling contribution of 1-2°C, notwithstanding any changes in albedo and minimum canopy resistance (Georgescu et al. 2009).

Georgescu, M., D. B. Lobell, and C. B. Field. 2011. Direct climate effects of perennial bioenergy crops in the United States. Proceedings of the National Academy of Sciences 10.1073/pnas.1008779108

Biomass-derived energy offers the potential to increase energy security while mitigating anthropogenic climate change, but a successful path toward increased production requires a thorough accounting of costs and benefits. Until recently, the efficacy of biomass-derived energy has focused primarily on biogeochemical consequences. In this paper (Georgescu et al. 2011), we showed that the biogeophysical effects that result from hypothetical conversion of annual to perennial bioenergy crops across the central U.S. impart a significant local to regional cooling with considerable implications for the reservoir of stored soil water (Figure 7). This cooling effect is related mainly to local increases in transpiration, but also to higher albedo. The reduction in radiative forcing (RF) from albedo alone is equivalent to a carbon emissions reduction of 78 t C ha^{-1}, which is six times larger than the annual biogechemical effects that arise from offsetting fossil fuel use. Thus, in the near-term, the biogeophysical effects are an important aspect of climate impacts of biofuels, even at the global scale. Locally, the simulated cooling is sufficiently large to partially offset projected warming due to increasing greenhouse gases over the next few decades. These results demonstrate that a thorough evaluation of costs and benefits of bioenergy-related land-use change must include potential impacts on the surface energy and water balance to comprehensively address important concerns for local, regional, and global climate change.

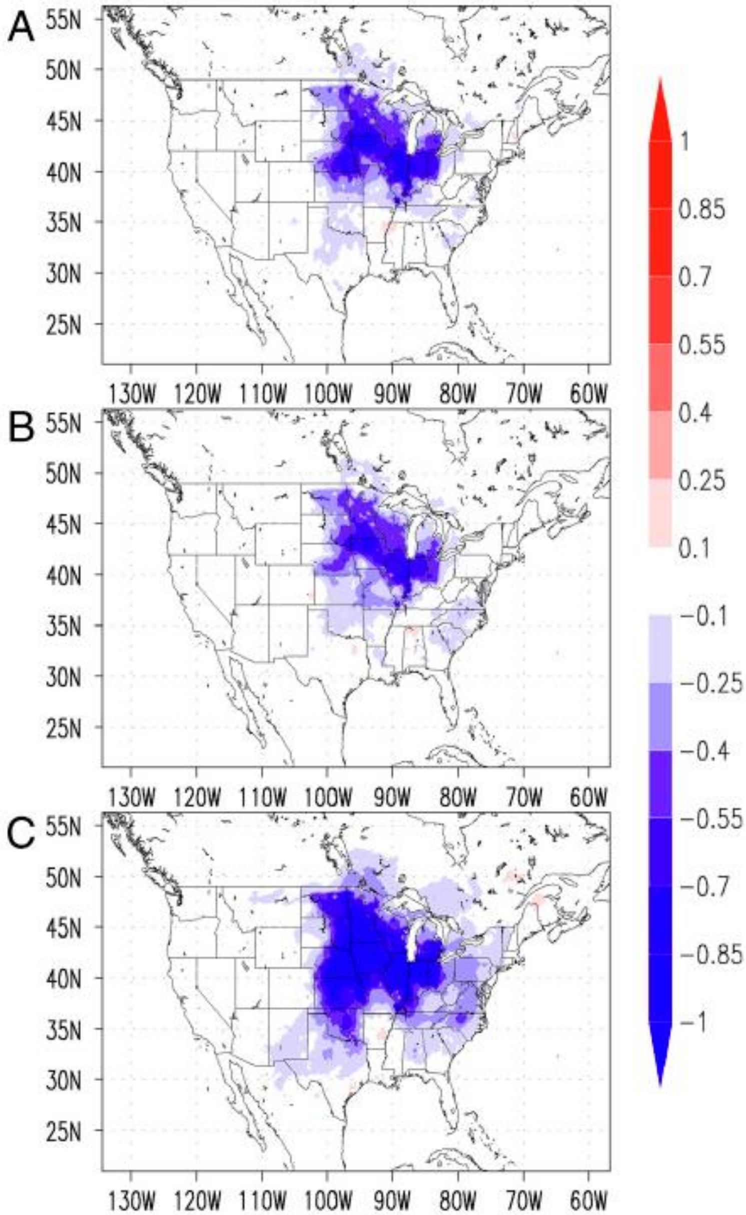


Figure 7. Simulated time mean (APR-OCT) difference in **(a)** 2 meter temperature [°C] (Perennials minus Annuals); **(b)** as (a) but perennial crop representation does not include albedo modification; **(c)** as (a) but perennial crop representation includes rooting depth of 2m.

Loarie, S. R., D. B. Lobell, G. P. Asner, and C. B. Field. 2011. Land-Cover and Surface Water Change Drive Large Albedo Increases in South America*. Earth Interactions 15:1-16.

Albedo is an important factor affecting global climate, but uncertainty in the sources and magnitudes of albedo change has led to very simplistic treatment of albedo in climate models. Here (Loarie et al. 2011a) we examined nine years of historical 1-km MODIS albedo estimates across South America to advance understanding of the magnitude and sources of large scale albedo changes. We use the magnitude of albedo change from the Brazilian Amazon arc-of-deforestation (+2.8%) as a benchmark for comparison. Large albedo increases (>+2.8%) are 2.2 times more prevalent than similar decreases throughout South America. Changes in surface water drive most large albedo changes that are not caused by vegetative cover change. Decreased surface water in the Santa Fe and Buenos Aires regions of Argentina is responsible for albedo increases exceeding that of the arc-of-deforestation in magnitude and extent (Figure 8). The mechanism driving changes in surface water is a combination of natural flooding and human manipulations through dams and other agriculture infrastructure. This study demonstrates the substantial role that land cover and surface water change can play in continental-scale albedo trends.

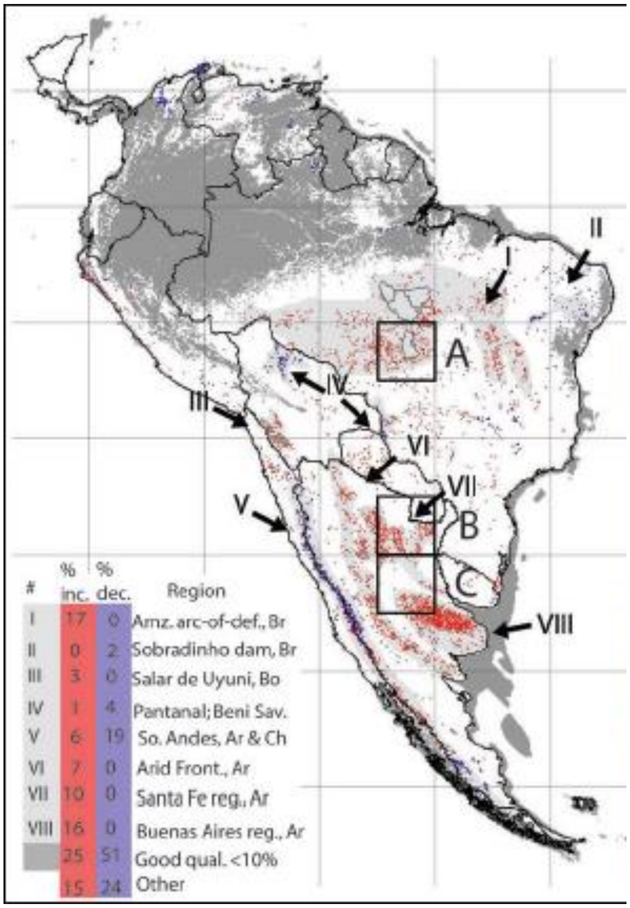


Figure 8. Large Increases (>+2.8%, red) and decreases (<-2.8%, blue) in albedo across South America. The legend shows the percentage of these large changes within regions of interest (light gray areas) labeled by roman numerals. Dark gray areas have scarce good quality data (<10%). Black outlines are country boundaries. Gray outlines indicate a sample of indigenous reserves in Brazil, including the Parque Nacional Indigena do Xingu. The gray grid shows 1200 x 1200 km MODIS tiles. A-C are quarter MODIS tiles that intersect three regions of interest.

Loarie, S. R., D. B. Lobell, G. P. Asner, Q. Mu, and C. B. Field. 2011. Direct impacts on local climate of sugar-cane expansion in Brazil. Nature Clim. Change 1:105-109.

The increasing global demand for biofuels will require conversion of conventional agricultural or natural ecosystems. Expanding biofuel production into areas currently used for agriculture reduces the need to clear natural ecosystems, leading to indirect climate benefits through reduced greenhouse gas emissions and faster payback of carbon debt. Biofuel expansion may also cause direct, local climate changes by altering surface albedo and evapotranspiration, but these effects have been poorly documented. This study (Loarie et al. 2011b) quantifies the direct climate effects of sugarcane expansion in the Brazilian cerrado, based on maps of recent sugarcane expansion and natural vegetation clearance combined with remotely sensed temperature, albedo, and evapotranspiration over a 1.9 million km^2 area. On a regional basis and clear sky day time conditions, conversion of natural vegetation to a crop/pasture mosaic warms the cerrado by an average of 1.55 (1.45 – 1.65) °C, but subsequent conversion of that mosaic to sugarcane cools the region by an average 0.93 (0.78 – 1.07) °C resulting in a mean net increase of 0.6 °C (Table 1). Our results suggest that expanding sugarcane into existing crop and pasture land has a direct local cooling effect that reinforces the indirect climate benefits of this land-use option.

MODIS variable	Land-use transition	Slope	s.e.	p.val	c.i.	Int.	N	R^2
Temp (°C)	from nat. veg. to crop/past.	1.55	0.05	<0.001	1.45 - 1.65	0.03	8507	0.11
Temp (°C)	from crop/past. to sugarcane	-0.93	0.07	<0.001	-1.07 - -0.78	-0.67	2376	0.06
ET (mm/day)	from nat. veg. to crop/past.	-0.60	0.02	<0.001	-0.67 – -0.53	0.08	8495	0.08
ET (mm/day)	from crop/past. to sugarcane	0.43	0.04	<0.001	0.30 – 0.56	0.01	2354	0.05
Albedo (%)	from nat. veg. to crop/past.	1.73	0.04	<0.001	1.65 - 1.80	0.48	8507	0.19
Albedo (%)	from crop/past. to sugarcane	0.20	0.05	<0.001	0.09 - 0.31	0.43	2376	<0.01

Table 1: Results of linear regressions fit through scatter plots of fractional change in land-use against change in MODIS variables. A subset of pixels separated by at least 5 km was used to minimize spatial autocorrelation. For each row, fractional change in landcover represents the abscissa and the MOIDS variables represent the ordinate. n refers to the number of 1 km^2 pixels in each regression and reflects the restricted subset of pixels >=5 km apart. Standard error of the slope parameter is referred to as s.e., the p-value of the slope parameter is p.val., and c.i. is the 95% confidence interval for the slope estimate. R^2 is the fit of the regression. All regressions were significant with p-values < 0.001.

Georgescu, M., D. B. Lobell, C. B. Field, and A. Mahalov. 2013. Simulated hydroclimatic impacts of projected Brazilian sugarcane expansion. Geophysical Research Letters 10.1002/grl.50206

This paper (Georgescu et al. 2013) took a climate-modeling approach to the same topic addressed by Loarie et al. (Loarie et al. 2011b). The conclusion based on the regional climate model was similar. During the growing season, sugarcane tends to run about 1C cooler than the previous vegetation, largely because it has a higher albedo. During the dry season, sugarcane areas tend to be warmer by about the same amount (Figure 9), such that annual effects are modest.

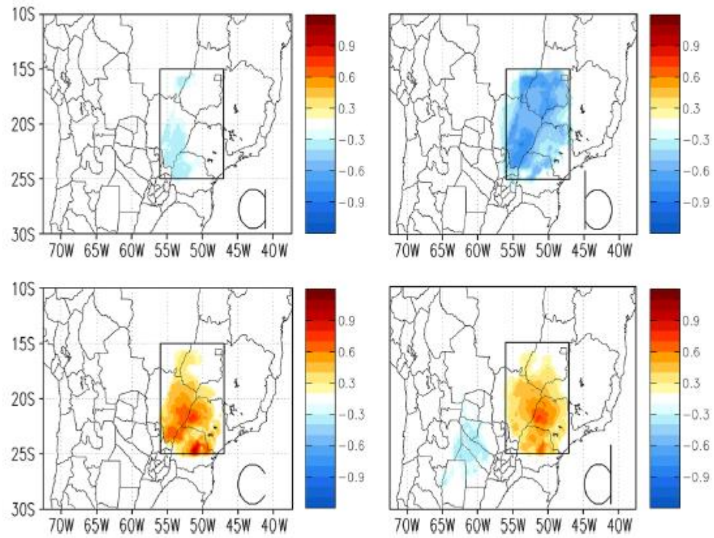


Figure 9. Simulated ensemble averaged 2m air temperature difference (°C) between Sugar and Control simulations for: (a) March–April–May, (b) June–July–August, (c) September–October–November, and (d) December–January–February, for entire length of simulations (2004–2008).

6. Mapping pasture conversion

Ferreira, L. G., L. E. Fernandez, E. E. Sano, C. Field, S. B. Sousa, A. E. Arantes, and F. M. Araújo. 2013. Biophysical Properties of Cultivated Pastures in the Brazilian Savanna Biome: An Analysis in the Spatial-Temporal Domains Based on Ground and Satellite Data. Remote Sensing 5:307-326.

One of the goals of this GCEP project is developing additional clarity on the topic of indirect deforestation, defined as clearing for crops in response to conversions elsewhere of lands from agriculture for food production to agriculture for fuel production. Indirect deforestation is incredibly difficult to quantify, because it is in fact indirect. The putative mechanism is that reduction in the supply of food lead to increases in price, and that increases in food prices increase the attractiveness of clearing forest lands in order to use them for food production. The situation is even more complicated in Brazil, where deforestation results from a combination of factors potentially involving a chain of interlinked processes. The hypothesis is that expansion of sugarcane displaces soy, and the displaced soy expands in areas that had been used for cattle ranching. This pushes the cattle into areas that had been cleared for subsistence agriculture, potentially pushing the small-scale farmers to expand forest gaps related to selective logging. All of these steps are influenced by a wide range of market and policy practices. They also occur over huge spatial scales.

To contribute to the assessment of indirect deforestation, we have been carefully mapping pastures and the changes. The pasture mapping effort was managed as a collaboration, with Brazilian scientists, including students, in the field. The paper from this collaboration (Ferreira et al. 2013) focused on using LANDSAT data to understand the relationship between pasture quality and water availability (Figure x). It also explored the sensitivity of pasture sensitivity to drought.

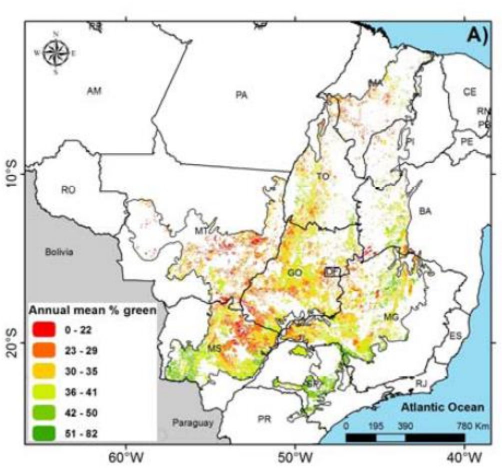


Figure X. Annual mean % greenness in the pasture regions of Brazil. Reds and yellows are regions with pronounced dry seasons.

8. Carbon-negative systems.

PhD student Lena Perkins (Mechanical Engineering) is nearly completed with her thesis on carbon negative energy systems. The core of the work is an exergy-based analysis comparing direct air capture of CO2 (DAC) with biomass energy with carbon capture and storage BECCS) as alternative systems that combine net energy generation with decreased atmospheric CO2. The core result of the exergy analysis is that BECCS provides a huge efficiency starting advantage as a consequence of the much higher starting concentration of CO2. The exergy advantage of BECCs provides a compelling motivation for further study and perhaps deployment, but the optimism about BECCS needs to be moderated by the results of the other results indicating constraints on the maximum sustainable level at which biomass can be moved to the energy system (Campbell et al. 2008, Field et al. 2008).

9. Post-docs and Students Supported by this project

J. Elliott Campbell: Current position: Assistant professor, School of Engineering, University of California, Merced.

Scott Loarie: Current position: Scientist, California Academy of Sciences, iNaturalist creator.

Matei Georgescu: Current position: Senior Sustainability Scientist, Global Institute of Sustainability, Assistant Professor, School of Geographical Sciences and Urban Planning, Adjunct Professor, School of Mathematical and Statistical Sciences, Arizona State University.

Sharon Gourdji: Current position: Fulbright Nexus Scholar, Stanford University.

Lena Perkins: Current position: Completing PhD in 2013, Stanford University.

10. GCEP-Supported Publications

Asner, G. P., S. R. Loarie, and U. Heyder. 2010. Combined effects of climate and land-use change on the future of humid tropical forests. Conservation Letters **3**:395-403.

Campbell, J. E., D. B. Lobell, and C. B. Field. 2009. Greater transportation energy and GHG offsets from bioelectricity than ethanol. Science **324**:1055.

Campbell, J. E., D. B. Lobell, R. C. Genova, and C. B. Field. 2008. The global potential of bioenergy on abandoned agriculture lands. Environ. Sci. Technol.:doi. 10.1021/es800052w

Ferreira, L. G., L. E. Fernandez, E. E. Sano, C. Field, S. B. Sousa, A. E. Arantes, and F. M. Araújo. 2013. Biophysical Properties of Cultivated Pastures in the Brazilian Savanna Biome: An Analysis in the Spatial-Temporal Domains Based on Ground and Satellite Data. Remote Sensing **5**:307-326.

Field, C. B., J. E. Campbell, and D. B. Lobell. 2008. Biomass energy: the scale of the potential resource. Trends in Ecology & Evolution **23**:65-72.

Georgescu, M., D. Lobell, and C. Field. 2009. Potential impact of US biofuels on regional climate. Geophysical Research Letters **36**:L21806.

Georgescu, M., D. B. Lobell, and C. B. Field. 2011. Direct climate effects of perennial bioenergy crops in the United States. Proceedings of the National Academy of Sciences:10.1073/pnas.1008779108.

Georgescu, M., D. B. Lobell, C. B. Field, and A. Mahalov. 2013. Simulated hydroclimatic impacts of projected Brazilian sugarcane expansion. Geophysical Research Letters:n/a-n/a.

Loarie, S. R., G. P. Asner, and C. B. Field. 2009a. Boosted carbon emissions from Amazon deforestation. Geophysical Research Letters **36**:L14810.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009b. The velocity of climate change. Nature **462**:1052-1055.

Loarie, S. R., D. B. Lobell, G. P. Asner, and C. B. Field. 2011a. Land-Cover and Surface Water Change Drive Large Albedo Increases in South America*. Earth Interactions **15**:1-16.

Loarie, S. R., D. B. Lobell, G. P. Asner, Q. Mu, and C. B. Field. 2011b. Direct impacts on local climate of sugar-cane expansion in Brazil. Nature Clim. Change **1**:105-109.