Linking Historical and Future Land-Use Change to the Economic Drivers and Biophysical Limitations of Agricultural Expansion in the Brazilian Cerrado

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The potential for expansion of intensive agriculture onto land currently occupied by degraded, low-productivity cattle pastures (i.e. land that has already been deforested, but is underutilized) is often touted as a means to avoid further deforestation in the Cerrado and reduce environmental degradation, while increasing agricultural productivity. However, the capacity and suitability of land for this transition has not been evaluated or quantified on a regional basis. This proposal aims to quantify the extent of these degraded lands and evaluate their potential to mitigate future environmental impacts as global demand for agricultural commodities continues to rise.

The specific project objectives are to:

1) Quantify the area of low productivity pastures using multiple resolution satellite sensors.
2) Assess the impacts of a range of scenarios for sugarcane expansion on future land use changes in the Cerrado.
3) Evaluate inter-regional shifts in agricultural production within Brazil and the impact they have on deforestation pressure on the Cerrado.
4) Estimate historical and potential future changes in carbon stocks and emissions of N_2O and CH_4 resulting from conversion to agricultural production.
5) Assess the hydrological impacts of historical and potential future scenarios of deforestation and conversion to intensive agriculture.

Below is a brief summary of the project accomplishments under each objective. All figures referenced in the text are contained in the Supplementary Information (SI) file accompanying this document (SI_AnnualReport2013_NNX11AE56G.pdf). To date, twenty scientific publications have been produced with the support of this grant (see SI Bibliography).

1) Quantify the area of low productivity pastures using multiple resolution satellite sensors.

We are approaching this objective using a combination of moderate-resolution optical (MODIS) and high-resolution radar (ALOS/PALSAR) – as well as very high-resolution WorldView2 data.

MODIS: During the third year of the project, our collaborators at the Federal University of Goiás (LAPIG-UFG) spearheaded the following activities:

1. Improved LAPIG Maps platform. With support from this grant, we have developed new tools to facilitate data retrieval and analysis. The updated satellite time series for biophysical variables (vegetation indexes, evapotranspiration, precipitation, net primary productivity, and equivalent water thickness) and vector data for the Cerrado are publically available on the LAPIG Maps website (www.lapig.iesa.ufg.br).

2. Processed, organized, and analyzed ancillary databases. Following are the highlights of this year's accomplishments:
    - Disseminated 2012–2013 early warnings of Cerrado deforestation. These were based on MODIS, Landsat, and Resourcesat data for deforestation polygons > 25 ha (**Figure 1**).
    - Assessed Cerrado burned areas in 2013, based on both the MODIS MCD45A1 and MCD64A1 products.
    - Validated the MCD45A1 product within the major Cerrado land-cover and land-use classes (**Figure 2**).

3. Completed ground-based measurements of dry- and wet-season pasture biophysical parameters. We measured total biomass, green biomass, % green cover, and reflectance in the Rio Vermelho Basin (Goiás state) – a landscape dominated by exotic and natural grasses under a range of management practices and degradation levels (**Figure 3**). We are also conducting monthly field campaigns in Cerrado areas near Uberlândia (Minas Gerais state) during the 2013-2014 hydrological cycle (beginning in October 2013; **Figure 4**). We expect significant improvements in the biome scaling of pasture properties and conditions, initially attempted with 2010-2011 ground estimates (Ferreira et al., *Remote Sensing*, 2012), based on this longer and more (geographically) representative time series.

RADAR: During the third year of the project, collaborators at the Woods Hole Research Center (WHRC) have focused on the following activities:

4. Developed methods for high-resolution mapping of riparian forests in the Cerrado. Over the past year, we have focused on developing the methods to generate a detailed 15-m resolution map of 2010 riparian vegetation spanning the entire Cerrado biome (~2 million km^2). Toward this end, we are conducting a pilot study in the ~11,000 km^2 Rio Vermelho watershed (**Figure 5**). We selected this region due to the availability of field data and high-resolution imagery (including sub-meter WorldView-2 data from the NASA-NGA program), which will facilitate testing various calibration and validation strategies. This biome-scale mapping effort represents a refinement, as well as an update, of the ca. 2007 ALOS-based map of forest probability generated previously **(Figure 5)**. Our mapping approach emphasizes distinguishing riparian forest corridors from adjacent land-cover types, most notably pasture. Wall-to-wall ALOS/PALSAR (15-m) Fine-Beam Dual Polarization (FBD) data are available for the Cerrado (~833 scenes) from the Alaska Satellite Facility DAAC for ca. 2010. The methods developed for the Rio Vermelho watershed (~9 scenes) will be used to scale up the riparian mapping and pasture quality data to the entire Cerrado biome.

2) Assess the impacts of a range of scenarios for sugarcane expansion on future land use changes in the Cerrado AND 3) Appraise inter-regional shifts in agricultural production within Brazil and the impact they have on deforestation pressure on the Cerrado.

Accomplishing these project objectives requires a flexible modeling platform capable of simulating a complex range of future land use and policy scenarios. During the third year of this grant, project collaborators at the Federal University of Minas Gerais (CSR-UFMG) took the lead on developing and refining this modeling capability. They focused on the following activities:

1. Developed and validated the OTIMIZAGRO modeling platform. OTIMIZAGRO is a spatially-explicit model for Brazil capable of simulating land cover, land-use change, forestry, deforestation, regrowth, and carbon emissions under various scenarios of agricultural land demand, and domestic land-use policies. This cellular automata model is based on empirically-derived equations governing the likelihood of each cell becoming one of sixteen crops, native forest, forest plantations, pastures, or forest regrowth. Suitability is based on a wide range of biophysical (slope, elevation, soil, climate) and socioeconomic (accessibility, transport, logistical costs) factors. Our preliminary analyses evaluate the aptitude of existing pasturelands for growing crops, and examine the current and potential future distributions of key commodity crops under different scenarios (**Figure 6**).

2. Evaluated the implications of Brazil's New Forest Code for the carbon budget. Using OTIMIZAGRO and the Dinâmica EGO modeling platform, we completed a spatially-explicit analysis of the changes in conservation requirements under Brazil's New Forest Code (enacted in October, 2012). The analysis quantified the conservation "deficits" (i.e. areas where restoration is legally required) and "surpluses" (i.e. areas where deforestation is legally allowed) in all Brazilian biomes. Our analysis indicates that over 50% of the Cerrado has already been deforested and just 7% of the remaining vegetation is protected in public conservation areas. We estimate that an additional ~40 Mha (million hectares) of the Cerrado may be legally deforested under the Forest Code. Results from this analysis were submitted as a *Science Policy Forum* article and are currently under review. We are currently working on a companion analysis of the implications of these legal changes for the water cycle (*Objective 5*), which will be completed in the coming year.

4) Estimate historical and potential future changes in carbon stocks and emissions of N_2O and CH_4 from conversion to agricultural production.

During the third year of the grant, project collaborators at the University of Vermont (UVM) have taken the lead on the following activities:

1. Developed GHG book-keeping model. For this project objective, we have focused on the three main sources of anthropogenic greenhouse gas (GHG) emissions in the Cerrado: 1) wild fires, 2) deforestation, and 3) agricultural management (e.g. tillage and fertilization). To estimate GHG emissions, we developed a bookkeeping model, using recently-published data on carbon storage, as well as carbon, methane, and nitrous oxide fluxes under different land uses in the Cerrado. Baseline land covers were defined by existing land-cover data products and emissions were calculated from land-cover datasets derived in this project. Preliminary results of this effort were presented as an oral presentation at the AGU Fall Meeting (Dec. 2012). We are currently developing a spatially-explicit, stand-alone bookkeeping model and preparing a publication summarizing our results.

2. Estimated emissions from increased deforestation. Deforestation datasets produced by our project partners at LAPIG (*UFG, Objective 1*) indicate that deforestation in the Cerrado has increased dramatically in recent years. This may be evidence of displacement of deforestation (leakage) from the Amazon to the Cerrado, as pressure to reduce Amazon deforestation mounted in the late 2000s. On the other hand, it may simply be the combined result of lower legal protection of the Cerrado, suitability of land for agricultural production, and cheaper costs of clearing (*UFMG, Objectives 3&4*). Regardless of the cause, our estimates suggest that recent increases in Cerrado deforestation have doubled carbon

emission rates since 2007. Roughly half of total carbon emissions came from belowground carbon stocks (**Figure 7**), underscoring the importance of belowground stores in the region.

3. Estimated emissions from fires in the Cerrado. Our analysis indicates that fires were the largest source of GHG emissions from land-cover and land-use change in the Cerrado. In 2010 – an anomalously dry year preceded by a wetter-than-average wet season – an estimated 750,000 ha of the region burned, compared to a cumulative burned area of 2.5 Mha from 2007-2012 (this estimate includes areas that burned more than once). The largest emissions from these fires were due to carbon losses from aboveground and belowground carbon stocks, or biomass burning. The smoldering process creates smaller, but more potent, emissions of GHGs such as methane and nitrous oxide (**Figure 8**).

5) Assess the hydrological impacts of historical and future scenarios of deforestation and conversion to intensive agriculture.

During the third year of the grant, project collaborators at WHRC have focused on the following activities:

1. Evaluating the impact of past deforestation and land-use change on regional hydrology. This analysis used available data on rainfall (CRU), land use (Otimizagro, MCD12Q1), and evapotranspiration (MOD16) to quantify the impact of historical and potential future land-use changes on the regional water and energy balances. As a first step, we summarized long-term monthly and annual averages of the ET and rainfall datasets, and calculated runoff for the Cerrado (**Figure 9**). We then identified pure pixels that were invariant throughout the time series, using a combination of the MCD12Q1 product and Brazilian government data to separate pasture and savanna. Using theses pixels and the MOD16 time series, we evaluated the effect of land cover on monthly ET (latent energy) from 2000-2012 (**Figure 10**). Preliminary results were presented at the AGU Fall Meeting (Dec. 2013).

2. Calibrating the IBIS Model for Cerrado vegetation. IBIS model simulations compare favorably with observed discharge in watersheds dominated by moist or seasonally-dry tropical forests (e.g. the Amazon biome), but initial analyses indicate that the model consistently overestimates discharge in the Cerrado biome (**Figure 11**). Using the MODIS ET product for comparison, we have traced the source of this bias to the ET estimates, which appear to be unrealistically high in the dry season. Preliminary results from the Cerrado-based Aruanã basin confirm that IBIS tends to overestimate ET in this region, leading to underestimation of runoff. We are currently working on improving IBIS to better capture vegetation dynamics in dry environments, and thus the water and energy dynamics for Cerrado.

3. Estimating monthly ET responses under future land-use scenarios. Together with our project partners at UFG, we evaluated evapotranspiration responses over the dominant Cerrado land-cover and land-use classes. We then conducted a preliminary assessment of the potential impacts of future pasture expansion on the water cycle (**Figures 12 and 13**), which we are currently preparing for publication (Arantes, Ferreira, and Coe, *In Prep.*, *Brazilian Geophysical Journal*).