Integrated Dynamic Global Modeling of Land Use, Energy, and Economic Growth

Progress Report (May 2006 – April 2009)

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Final Report, 2006 – April 2009
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The overall objective of this collaborative project is to integrate an existing general equilibrium energy-economic growth model with a biogeochemical cycles and biophysical models in order to more fully explore the potential contribution of land use-related activities to future emissions scenarios. Land cover and land use change activities, including deforestation, afforestation, and agriculture management, are important source of not only CO2, but also non-CO2 GHGs. Therefore, contribution of land-use emissions to total emissions of GHGs is important, and consequently their future trends are relevant to the estimation of climate change and its mitigation.

This final report covers the full project period of the award, beginning May 2006, which includes a sub-contract to Brown University later transferred to the National Center for Atmospheric Research (NCAR) when Co-PI Brian O'Neill changed institutional affiliations.

(1) PET Related Tasks

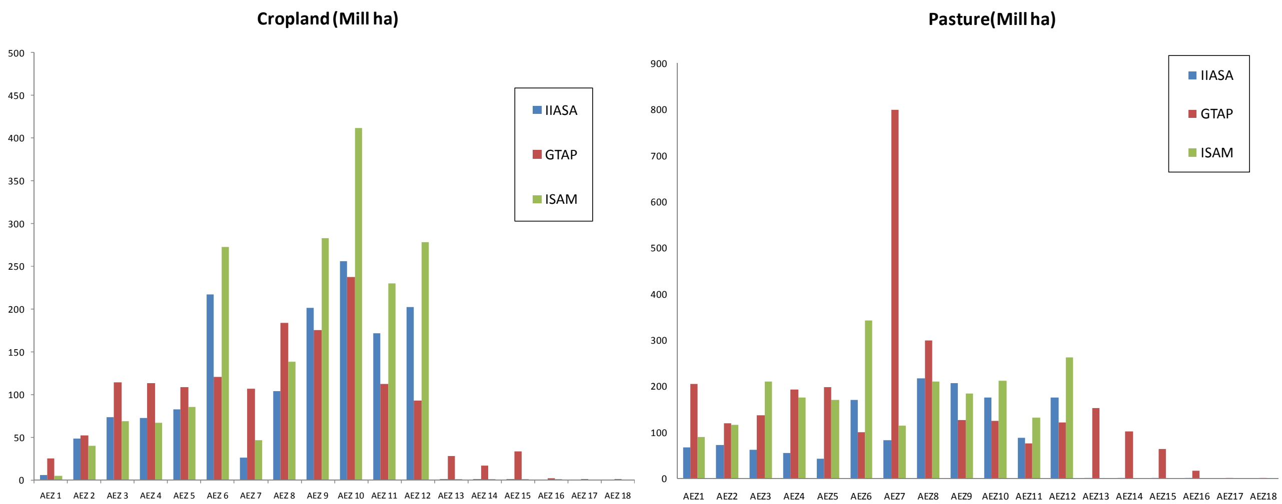
During the project period, the issue of data availability and analysis for use in the PET model grew in importance and required substantially more work than initially anticipated. In addition, a new task became necessary as the project developed: the development of an approach to modeling spatial land use at the grid cell level in a manner consistent with the regional PET model. Therefore, while the compilation and analysis of production data was completed, other tasks remain partially complete, with work continuing beyond the project period.

1.1 Production data for the PET model

The original proposal included plans to draw on production data from the SGM model at the Joint Global Change Research Institute, from national sources for key regions, and from the Global Trade Assessment Project (GTAP). Over time, it became clear that for inter-regional consistency the best strategy would be to rely on the GTAP data for all our model regions. We initially developed benchmark economic datasets (for the base year) for India and China based on national sources. These data were tested within the PET model structure in an analysis of emissions from energy use for these individual countries (Dalton et al., 2007), and further comparison to GTAP data is continuing. However, in the meantime, we have completed work using the GTAP 6 database to calibrate the production side of the PET model for all model regions (Fuchs et al., 2009). This analysis includes aggregating sectors and regions in the GTAP data to match the PET model structure, and developing a means to account for transport margins in the economic data characterizing trade flows. In addition, we used IEA energy quantity data to balance the GTAP data so that economic values are consistent with IEA energy quantities for the base year.

A substantial effort has been made to specify physical quantities of land that are consistent with the GTAP data by region and sector, disaggregated as well by 18 Agro-ecological zones (AEZs). We obtained quantity data from the GTAP Land Use Data Base (Lee et al., 2009). This data base provides both physical land cover and harvested area data for crops and pasture, by region and sector. For our model and scenario development purposes, these data have to be harmonized with both the historical land use data used in the ISAM model historical simulations, as well as future scenario data used as input to the PET model. As discussed in the Reference Scenarios task below, scenario data are obtained from the IIASA model. ISAM and IIASA data are spatial, while the GTAP data are aggregated for each region and AEZ. Ideally, the three data sets would be consistent with each other in the base year (2000), which is common to all.

Figure 1.1 shows a comparison we produced that aggregates the spatial ISAM and IIASA data to the PET model regions and to AEZ categories, and compares these totals to the GTAP data. Data are similar, concentrating agriculture and livestock in similar geographic regions, but still show noticeable differences, for example in the location of pasture in temperature regions (AEZ 1-6). These differences will have to be resolved in order to produce integrated scenarios spanning ISAM historical runs with PET model simulations that begin with GTAP data and are extended using the IIASA scenarios as

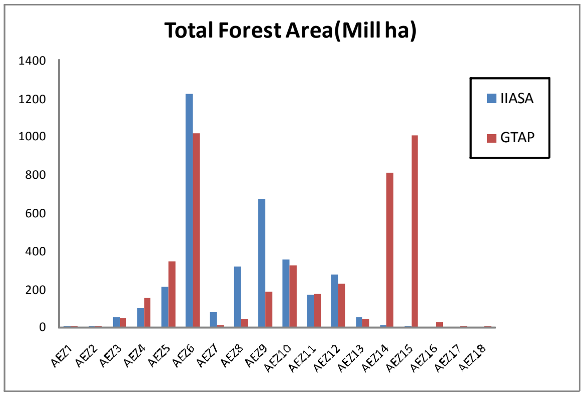


input.

Figure 1.1: Total hectares of land by AEZ category for the year 2000 for cropland (left) and pasture (right) according to the IIASA model, the GTAP land use data, and the ISAM model.

Specifying physical quantity data for forest land is still in progress. Figure 1.2, in the left panel, compares the total forest area distribution across AEZ category as estimated by

GTAP and as used in the IIASA model for 2000. While there are similar trends across AEZs, boreal forest area (AEZ 14 & 15) in GTAP shows the biggest difference from the IIASA forest area. In addition, the GTAP land use data base does not contain managed and unmanaged information (although not shown in the figure, the IIASA data base does include this distinction). The right panel of Figure 1.2 shows the total wood harvested area ca. 2000 from IIASA and ISAM (the GTAP data base does not include wood harvest data). Note that there is a sharp difference between the two sources for the harvest pattern in tropical region AEZ 6.



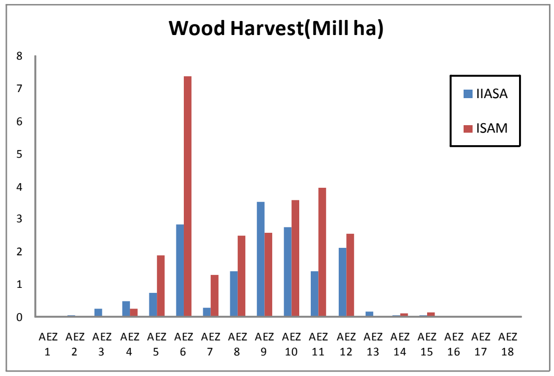


Figure 1.2: Total hectares of forest land by AEZ category for the year 2000 (left) and total wood harvest (right).

1.2 Modifications to the PET model

The proposed work included modifying the Population Environment-Technology (PET) model in order to explicitly incorporate land use. The PET model is an inter-temporal general equilibrium economic growth model that is used to project CO2 emissions from global use of fossil fuels over time horizons of decades to centuries. Land use is implicit in the original version of the model; land is aggregated into a single capital stock which is used as an input to production.

Plans for modifying the PET model as described in the original proposal have been fleshed out in a series of collaborators' meetings. The original plan remains the same, to treat land supply as exogenous and model the allocation across sectors. Specifically, we begin with an exogenously defined scenario over time for total land use in production by AEZ (taken, for example, from an existing IIASA model scenario),

$$\left\{\overline{S}_{jt}\right\}_{j=1,\ldots,18}^{t=1,\ldots,T}$$

where $\overline{S}$ can be thought of as specified in both physical units and in payments to land in base year dollars. To derive outcomes for land use by industry, we assume a single price for space within each AEZ and region, common to all industries:

$$MRPS_{ij} = P_i^y \frac{\partial F_i}{\partial S_i} \frac{\partial S_i}{\partial S_j} = P_j^S$$

where P_j^S is the common price, and it is equal to the marginal revenue product of space (*MRPS*) per unit of land in AEZ *j* and industry *i* (i.e., the additional revenue generated by adding one additional unit of land to production in industry *i* within AEZ *j*, given the prevailing price of output in industry *i* ($P^y{}_i$)). The amount of land used by each industry within each AEZ category over time (s_{ij}) is determined (internally to the PET model) based on the competitive market equilibrium price for space and the market clearing condition

$$\sum_{i=1}^{3} s_{ij}\left(P_i^y, P_j^S, y_i\right) = \bar{S}_j$$

which also determines the price for land P_j^S. This treatment of land is equivalent to the treatment of the supply-demand equilibrium in the labor market in the PET model (or capital in a static model).

We have compiled production data (see above) in preparation for this treatment of land by further disaggregating the production sectors in the model. In particular, we have separated agriculture from the original "Materials" sector and split it into six sub-sectors: Forestry, Rice, Other Crops, Animal Products, Fish, and Other Processed Food. Four of these sectors – Forestry, Rice, Other Crops, and Animal Products – will therefore have a separate input of land into production in the PET model.

Furthermore, we have made substantial progress on developing a scheme for producing spatial patterns of demand for land that are consistent with aggregate regional demand generated by the PET model. This scheme will allocate regional- and industry-specific payments to land to individual grid cells. While details have not been finalized, the approach is based on assuming that there is a production possibility frontier (PPF) in each grid cell that summarizes tradeoffs between using the land for production of crops, pasture, or forest. The shape of the PPF is assumed to be concave and is calibrated to base year data and represents the substitutability of land within that cell for different uses. An illustrative example is shown for three grid cells in the U.S. in Figure 1.3. Land use competition is then modeled as a revenue maximization problem from the perspective of households, who own all land in the PET model, subject to the constraint that total land use for each type of production must sum to the regional totals derived in the PET model. We anticipate completing regional and spatial PET model land use scenarios within the coming year.

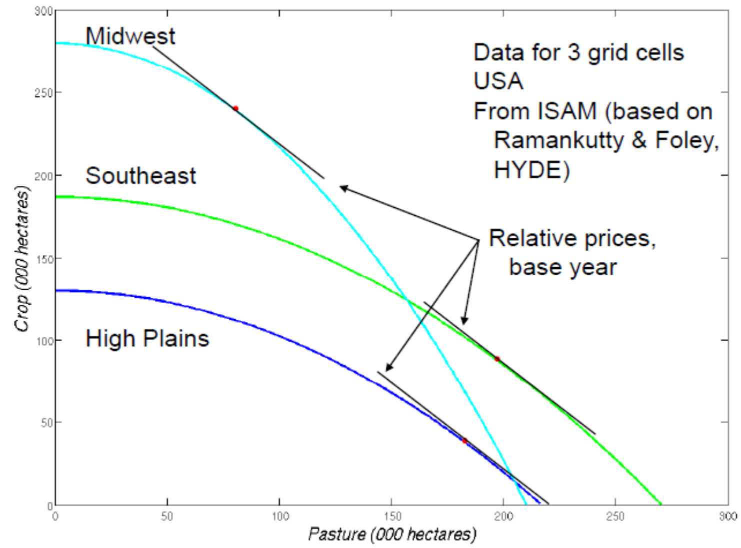


Figure 1.3: Example PPFs calibrated to ISAM grid cell-level land use data for three areas in the U.S. The figure shows the PPF between cropland and pasture; forest land is omitted for presentation purposes.

(2) ISAM Model Related Tasks

2.1 Potential Contribution of Regionally-Specific Land Use-Related Activities

As originally proposed, we have developed an algorithm to spatially distribute (at 0.5^{o} x 0.5^{o} resolution) future land cover change activities, such as harvest and urbanization, within each geopolitical region or nation. At each grid zone the supply and demand for each type of land is determined based socio-economic factors, such as population growth rates, prices of inputs and outputs and transportation costs, and biophysical and biogeochemical factors, such as land suitability and attainable crop yields, as well as terrain conditions. The land suitability is determined based on the "Length of the Growing Period" (LGP). We derive various categories of LGPs for each grid cell using biophysical and biogeochemical cycle components of the Integrated Science Assessment Model (Figure 2.1), which combine carbon and nutrient dynamics, climate change, soil characteristics, and topography data with a water balance model. Each LGP describes the number of days during a growing season with adequate temperature and moisture to grow crops. These LGPs roughly divide the world along humidity gradients, and are consistent with previous studies in global agro-ecological zoning. As for the economic activities, usually, data are not available at the grid zone level. For this reason we consider the history of changes in land use in every grid zone as a proxy for changes in the economic conditions over time.

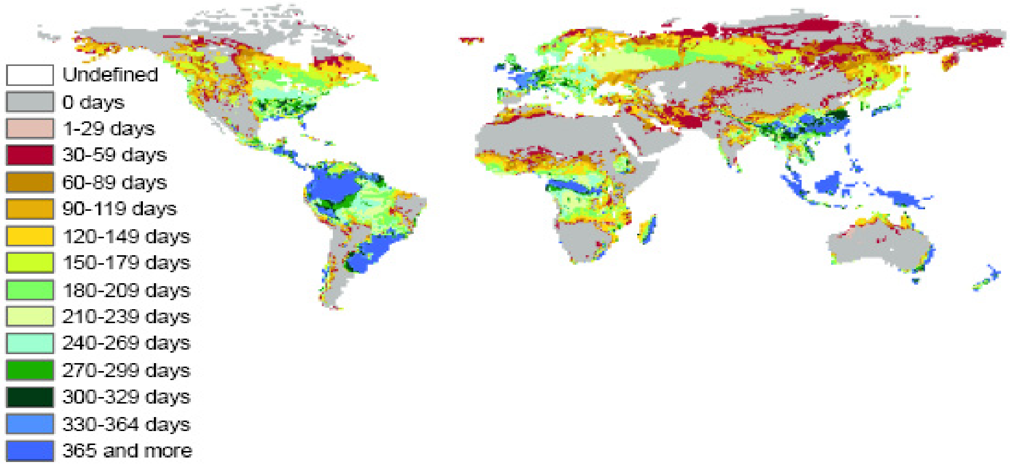


Figure 2.1: ISAM estimated length of growing period (LGP) for the year 2000. The LGP provides a standard framework for characterization of climate, soil, and terrain conditions relevant for agricultural production.

2.2 SRES A2 storyline for land use activities

We applied the above method to spatially allocate the regional land use changes for croplands and urbanization as outlined in IPCC SRES A2 scenario. In this practice we first determine time dependent LGP for each grid zones of the whole globe for the period 2000-2050, which we combined with regional distribution of croplands to determine spatially disaggregated land cover changes for cropland (Figures 2.2). Based on the spatially distributed population growth and economics activities, we also determine the spatially disaggregated land use changes for urbanization (Figure 2.3). We then used spatially disaggregated land use changes as an input in the ISAM model to generate emissions profile for various gases. Figure 2.4 compares the ISAM model estimated CO2 emissions due to land use changes with IPCC estimates.

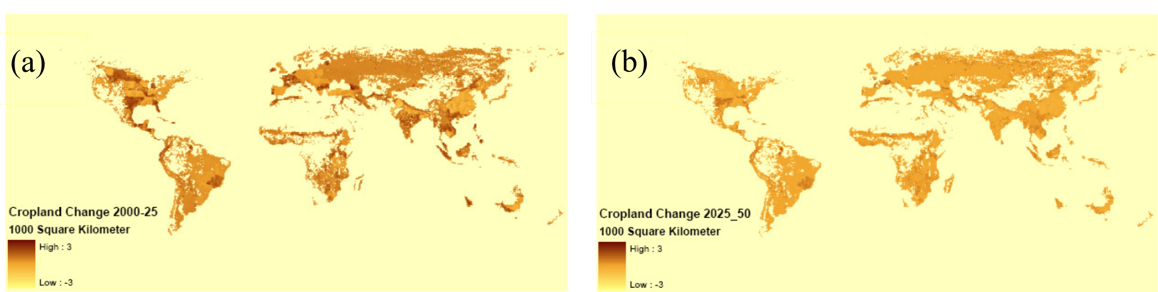


Figure 2.2: ISAM estimate changes for croplands (1000 km^2) for SRES A2 scenario. The changes are shown for the period 2000-2025 (a) and for the period 2025-2050 (b).

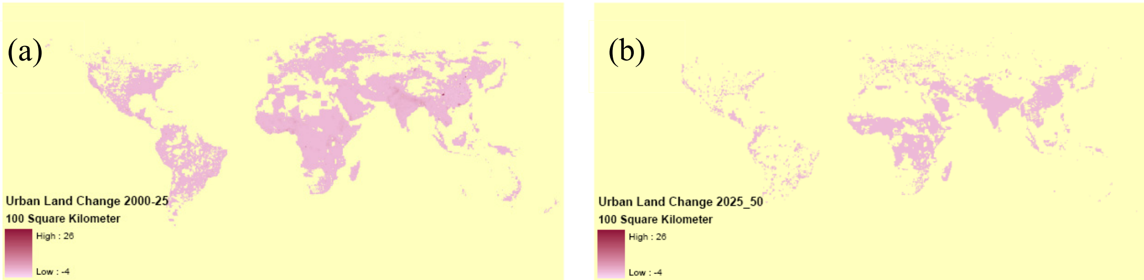


Figure 2.3: ISAM estimate land use changes for urbanization (100 km^2) for SRES A2 scenario. The changes are shown for the period 2000-2025 (a) and for the period 2025-2050 (b).

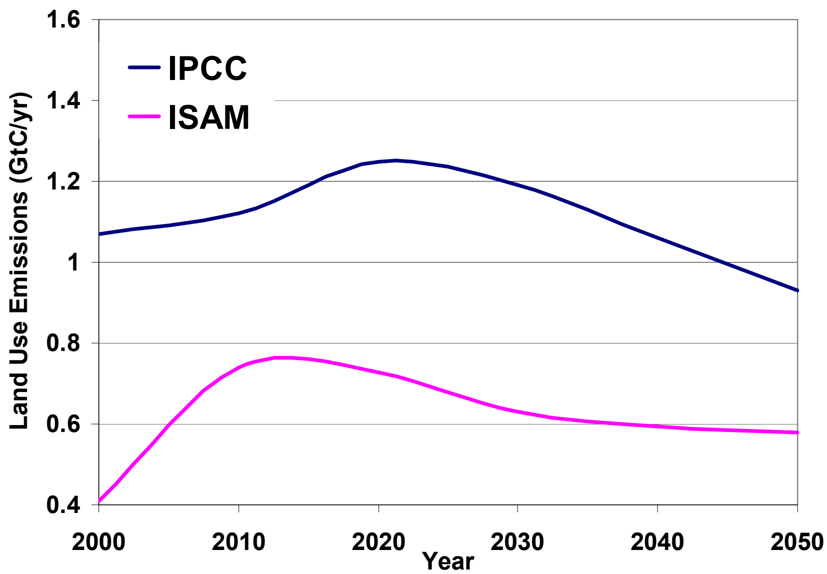


Figure 2.4: Comparison of ISAM estimated land use emissions for SRES A2 with IPCC estimates. As this figure shows the emissions uncertainty in year 2000 spans a factor of three. All SRES scenarios assume an emissions rate over the 1990s of 1.1 GtC/yr. According to our recent study (Jain and Yang, 2005) over the 1990s is about 0.5 GtC/yr. Other estimates also support lower rates of change (DeFries et al., 2001; Achard et al., 2001). If emissions are actually near the low end, then it is likely that SRES scenarios greatly overestimate the potential for land use emissions, at least over the next few decades.

2.3 Estimating the Land Suitability Using an Artificial Neural Networks (ANN).

We have developed a land use model to predict future cropland distributions or areas of land suitable for cultivation at a grid scale. Modeling the land suitability for cultivation and other usage at a grid scale requires implementation of a number of factors such as biophysical/biogeochemical processes and process interactions (feedbacks) and macro-socio-economic factors. In order to determine which biophysical factors are sensitive to the croplands, we carried out a series of sensitivity experiments using the ISAM biophysical model and conclude that the biophysical factors are non-linearly depended on the cropland area. As a result of this, we developed a nonlinear regression model for biophysical parameters to predict crop fraction (or crop area) at a grid scale. Artificial Neural Networks (ANN) was employed to perform nonlinear regression. The model has been calibrated and tested using the cultivation land area for the recent years. Our initial modeling analysis, which looks only biophysical parameters, suggests that the non-linear regression model predictions are statistically significant and robust. The findings of this modeling study were presented at the Fall 2007 AGU Fall meeting and at the NCAR's Climate Community System Model (CCSM) meeting in Boulder, CO. We plan to use this model coupled with PET socio-economic model to predict future land cover and land use changes for croplands for the IPCC's 5th assessment report.

2.4 Modeling of N_2O and NO Emissions from Soils in Terrestrial Ecosystems.

Nitrous oxide (N_2O) is not only one of the most important greenhouse gases, it is also involved in the depletion of stratospheric ozone. Nitric Oxide (NO) is a chemically active gas involved in tropospheric photochemistry and ozone regulation. Soils under natural vegetation and agriculture are one of the main sources of N_2O and NO through nitrification and denitrification processes. Current estimates of N_2O and NO emissions on regional to global scales are based on the upscaling of limited measurements from specific measurement sites, which have large uncertainty because of the heterogeneity of the soils and the seasonal and interannual variability in climate.

As originally proposed, we implement N_2O and NO emissions algorithm into a geographically explicit process-based terrestrial carbon-nitrogen cycle component of the Integrated Science Assessment Model (ISAM) with a fully dynamic nitrogen cycle to estimate emissions for N_2O and NO from terrestrial ecosystems..

The newly developed model includes all the major nitrogen dynamics processes such as immobilization, mineralization, leaching, nitrification, denitrification, volatilization and N uptake by plants (Yang et al., 2009a). Controls over nitrification and associated N_2O and NO emissions are soil texture, soil NH_4 content, soil moisture content, soil temperature and soil pH. Controls over denitrification and associated N_2O and NO emissions are soil heterotrophic respiration rate, soil NO_3 content, soil water content, and soil texture.

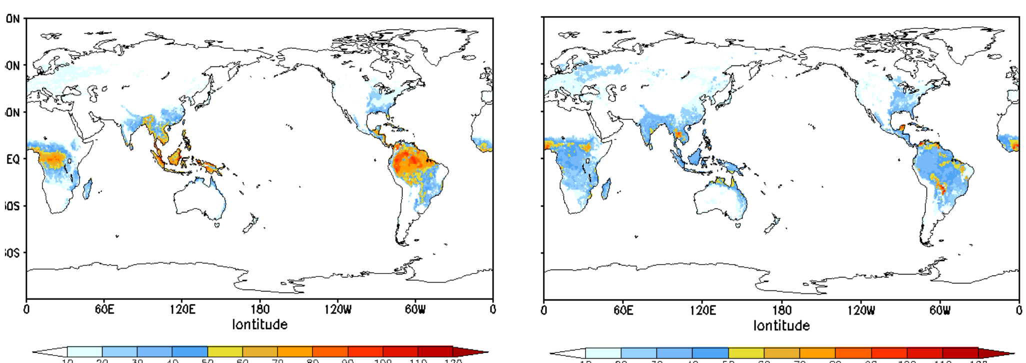


Figure 2.5: ISAM estimated global distributions of soil N_2O (top) and NO (bottom) emissions (mg/m^2/yr). These emissions do not account for any anthropogenic effects.

The N cycle submodel is calibrated and validated here with extensive field data from the Trace Gas Network (TRAGNET). TRAGNET includes N gas fluxes data from 29 sites in

United States, which include grassland, forest, and cropland areas encompassing a gradient of climate conditions and soil properties. In comparison to field measurements, the model is able to capture the temporal trends and magnitude of the N_2O emissions quite well (Figure 2.5). Generally the climate and soil moisture control on N_2O and NO emissions are reflected in the simulations, and well in accordance with the observations. The high emissions of N_2O during spring time at some sites however are not captured by the model. This could have been caused by the model's inability to capture the dramatic changes of soil water content when snow melts at that time. The calibrated and validated model was applied on the global scale to study the sources of N_2O and NO from terrestrial ecosystems. Our preliminary results show that global emissions from soils are 6.2 Tg N and 7.6 Tg N yr^{-1} for N_2O and NO respectively in pre-industrial time. Our results also show that tropical forest and tropical savanna are the major sources of N_2O and NO, while there are very low emissions at high latitude regions, which are consistent with both measurements and previous modeling studies. Our results also show that N_2O and NO emissions are sensitive to climate change, but not to CO_2. In addition, N deposition and land use change have led to the large increase of N_2O and NO emissions (Yang et al., 2009b).

(3) Linking the PET and ISAM models

The PET and ISAM models have been successfully linked using an energy-CO2-only version of the PET model and the 1-D version of the ISAM carbon cycle model. A least cost emissions path was solved for subject to the constraint that atmospheric CO2 not exceed 450 ppm. Linking was carried out through iterative calls to the PET and ISAM models, with the ISAM result providing information on whether the PET model solution satisfied the constraint.

Further progress on linking the two models awaits completion of a PET model version that generates regional land use, planned to be completed over the next year.

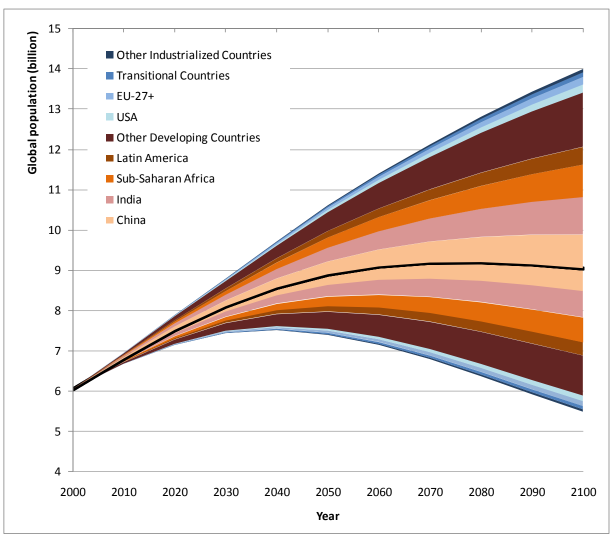
4 Reference Scenarios

While full reference scenario development was not completed during the project period, we did finalize two important components which will allow us to carry out scenario development in the near future.

4.1 Updated demographic scenarios

As proposed we developed updated global population projections to serve as input to the PET model in our analysis. The PET model uses the household as the demographic unit of analysis and therefore requires household projections, rather than more commonly used population projections, as input. We have pursued these updated projections through two separate tracks: development of our own population and household projection model, and development of scenarios based on existing projections from other institutions. On the first track, we have completed most of a new global population projection module to add to our integrated assessment modeling system. The model currently operates at the level of individual countries or regions, without being linked through migration. Tests against existing projections from the UN show an excellent match, indicating that our representation of changing age-specific fertility and mortality patterns corresponds to those in established models. Work toward completion of this model by adding international and rural-urban migration continues, but has not yet been finished.

In the interim period, in order to be able to continue PET modeling work, we have produced three new global household scenarios by combining existing population and urbanization projections with our own household projection model (Jiang and O'Neill, 2009; Figure 4.1). Our household projections are based on long-range population projections from the United Nations (UN, 2004), the most recent set of country-specific, long-term population scenarios available, which provide a substantially more up-to-date outlook for future population growth than those employed in the original SRES scenarios. We assume urbanization follows a medium path based on an extrapolation of UN urbanization projections to 2030 published recently by IIASA (Gruebler et al, 2007). These existing population and urbanization projections are supplemented by our own multi-state population and urbanization projections for China and India (Jiang and O'Neill, 2009). In addition, we used household survey data from 8 of our 9 model regions to calibrate a household model that we use to project population by household age, size, and urban/rural residence, simultaneously with the population projections.



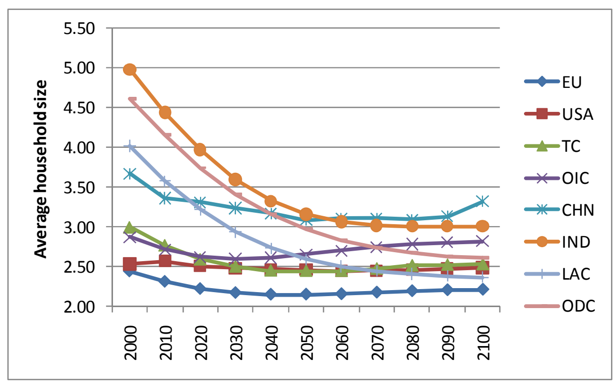


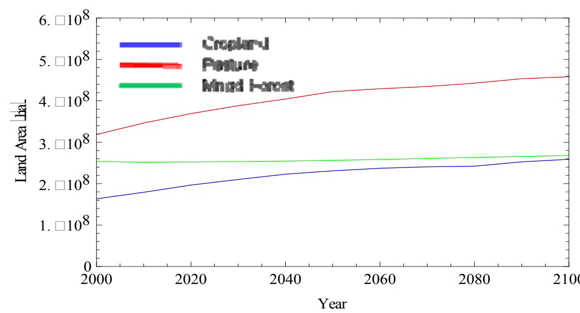
Figure 4.1: Left: Projected global population for the high (top of colored area), medium (black line), and low (bottom of colored area) population scenarios. Individual colored bands indicate contribution of each region to the difference between global scenarios, for each of 9 PET model regions. Right: Average household size for each region, projected with a size-, age-, and urban/rural-specific household headship rate model.

Exogenous land use scenario for SRES A2

As described above, our first step approach to the treatment of land in the PET model is to treat land as a factor of production in a manner similar to labor, in that total land supply is considered exogenous, but its distribution across sectors is endogenously modeled. Therefore, in developing a reference scenario, we must start with an exogenous scenario for total amount of land by region and AEZ that is in production for crops, pasture, or forestry.

We obtained such data for the IIASA MESSAGE model implementation of the A2 scenario (Riahi et al; Rokitayanski et al.), an updated version of the IPCC SRES A2 scenario that is based on more recent base year data, demographic projections, and outlooks for economic growth. It also incorporates new spatially explicit land use outcomes. We obtained the spatially explicit data, but substantial work was required to aggregate the spatial (0.5 x 0.5 degree) data into AEZ categories for each of the 9 PET model regions. Time varying calculations of the Length of Growing Period (LGP) for each grid cell were obtained from ISAM model analyses. We then calculated decadal average LGPs for each grid cell, to control for interannual variability, converted to AEZ categories, defined PET model regions within a GIS framework, and added up gridded land use in the IIASA scenario to the PET model regions by AEZ over time.

These aggregate outcomes are now ready to be used as PET model input in scenario analyses. Figure 4.2 shows an example of the IIASA gridded data for cropland, and the aggregation of three land use types for the example of the PET model Latin America region. This aggregation has also been done for the other eight model regions, specific to each of 18 AEZ categories (not shown).



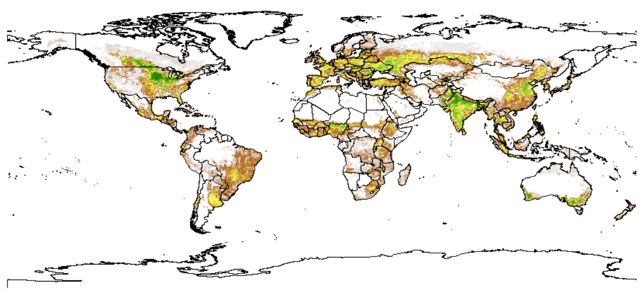


Figure 4.2: Left, gridded map of crop land as a percent of grid cell (0-100 as colors change from red to green), from the IIASA A2r scenario, for 2030. Right, aggregation of the IIASA gridded data over time for three land use types (crop, pasture, managed forest) for the PET model Latin America Region.

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