Biofuel Growth: Global Greenhouse Gas Emissions Impacts from Changes in Forest Carbon Stocks

by

Alla Golub[a], Thomas Hertel[a], Steven Rose[b] and Brent Sohngen[c]

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a Center for Global Trade Analysis (GTAP), Purdue University
b US Environmental Protection Agency
c The Ohio State University

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Abstract

There is significant policy interest in liquid biofuels with appealing prospects for energy security, farm security, poverty alleviation, and climate change. Large-scale commercial biofuel production could have far reaching implications for regional and global markets – particularly those related to energy and land use. As such, large-scale biofuels growth is likely to have significant impacts on global greenhouse gas (GHG) emissions. This paper utilizes a CGE model with explicit biofuel, land, and energy markets. The model is able to estimate the effects on the broad range of input and output markets potentially affected globally by biofuels policies. One of the most controversial issues within the biofuels debate is potential indirect changes in land use and, in particular, the resulting changes in forest carbon stocks. To uncover consequences of biofuel policies for forest carbon, we link our CGE model with a dynamic forward looking model of the forest sector. Within this framework, we evaluate the potential effects of US and multinational biofuels growth on changes in land use and emissions from changes in forest carbon stocks.

Introduction

There is significant policy interest in liquid biofuels with appealing prospects for energy security, farm security, poverty alleviation, and climate change. Large-scale commercial biofuel production could have far reaching implications for regional and global markets – particularly those related to energy and land use. As such, the growth in biofuels is likely to have significant impacts on global greenhouse gas (GHG) emissions. The objective of this paper is to inform understanding of the potential environmental consequences of historic and projected growth in biofuels supply.

Most of the attention devoted to GHG emissions associated with biofuels production has focused on the direct impacts – emissions associated with growing corn for biofuel, transporting it to market, milling it, and distributing the ethanol, as well as the emissions associated with the immediate conversion of the land for the corn production (Fargione *et al*., 2008). However, there is increasing interest in the potential *market-mediated* effects of biofuel programs (Kammen *et al*., 2008). Because biofuels have potentially large impact on agricultural and energy markets, they could induce price changes and these price changes could induce changes in other activities that give rise to additional changes in GHG emissions. Furthermore, it is suggested that biofuel subsidies could lower energy prices worldwide, and may in fact boost aggregate energy consumption sufficiently to offset any gains in displaced petroleum.

In addition, there is a concern about the potential global indirect land use impacts of biofuels (Searchinger *et al*., 2008). It is argued that the resulting increased supply of biofuels has stimulated the demand for cropland, worldwide, and led to the conversion of grazing and forest lands and increased global GHG emissions. Indeed, Searchinger *et al*. (2008) argue that a US corn-based ethanol program would double the associated GHG emissions worldwide.

However, this work has not considered the international competition for land and the changing opportunity costs of alternative land-uses, or the potential for the intensification of land-based production. Using a tool that explicitly models land-use market responses domestically and internationally across different land types and uses (food crops, energy crops, pasture, and forests), we investigate a particularly challenging and concerning aspect of the indirect land use change due to the growth in biofuels – the potential effects on global forests and the resulting GHG emissions from changes in forest carbon stocks.

We build on the existing work of Birur *et al.* (2008), Taheripour *et al.* (2007), Hertel *et al.* (2008) and Taheripour *et al.* (2008). Birur *et al.* (2008) develop a biofuels extension of the GTAP-E model (see Burniaux and Truong (2002) and McDougall and Golub (2008)). They capitalize on the new GTAP-biofuels data base developed by Taheripour *et al.* (2007), which disaggregates three new commodities: 1) ethanol from coarse grains (mainly corn), 2) ethanol from sugarcane, 3) and biodiesel from oilseeds, all within the global GTAP framework. The model is validated over the 2001-2006 period (Birur *et al*., 2008). Hertel *et al.* (2008) use this model to examine the impacts of increased biofuel demand in the US and EU on the pattern of global agricultural production, land use and international trade. They conclude that these mandates are likely to have significant impacts on global land use. Taheripour *et al.* (2008) explicitly introduce biofuel by-products (BYPs) – Dried Distillers' Grains with Solubles (DDGS) and oilseed meals, major BYPs of grain based ethanol and biodiesel – into the GTAP data base and the Hertel *et al*. (2008) model to analyze the economic and environmental impacts of the US-EU biofuel growth. They show that incorporation of BYPs into the model significantly changes the land use consequences. All these studies, however, do not estimate the implications of the biofuel market developments for global GHG emissions.

Methods

To investigate the GHG emissions from forest land-use change due to growth in biofuels, we begin with a model of Hertel *et al*. (2008), add BYPs as it is described in Taheripur *et al*. (2008), and then link resulted CGE model with forward looking forestry model of Sohngen and Mendelsohn (2007). The key feature of the CGE model for purpose of analyzing changes in land use is described below, while for other details a reader is referred to Birur *et al*. (2008) and Hertel *et al*. (2008). A feature unique to this work and central for this paper – the link with the Global Timber Model – is presented in detail. To better capture interactions between land-using sectors, primary and secondary commodity markets, and regions, we have added more sectoral details to the aggregation used in Hertel *et al*. (2008). The number of regions used in this work is 18 – same as in Hertel *et al.* (2008). However, the grouping is different. While Hertel *et al.* (2008) break out net energy exporters, our aggregation allows to focus on regions where forestry is economically important. Our model has 18 regions and 34 production sectors, three of which are ethanol from corn, ethanol from sugarcane and biodiesel (see Appendix Table A1), and 36 produced goods which include DDGS and oilseed meals, by-products of corn based ethanol and biodiesel, respectively.

Heterogeneous land

Following earlier work on land-use modeling within GTAP framework (see, for example, Darwin *et al.* (1995), Lee *et al.* (2008), and Golub *et al.* (2008)) we introduce Agro-Ecological Zones. This facilitates analysis of the competition for land within and across regions and the potential for changes in land use driven by biofuel policies. The importance of this explicit treatment of global land use competition and different land types should not be understated. Corn, for example, competes with different crops in different AEZs. The expansion of corn in the US for ethanol use has had a much larger impact on soybeans than on other crops. This, in turn, has had an impact on the incentive to grow soybeans in particular AEZ in other regions (e.g., Brazil), which can lead to shifts in land use (e.g., livestock and forestry) in other AEZs within the same region or other regions. Disaggregating the global land endowments by AEZ in an economy-wide global economic modeling framework allows us to take account of this stream of effects and feedbacks.

We distinguish 18 AEZs, which differ along two dimensions: growing period (6 categories x 60 day intervals), and climatic zones (3 categories: tropical, temperate and boreal). Following the work of the FAO and IIASA (2000), the length of growing period depends on temperature, precipitation, soil characteristics and topography. The suitability of each AEZ for production of alternative crops and livestock is based on currently observed practices, so that the competition for land within a given AEZ across uses is constrained to include activities that have been observed to take place in that AEZ.

As in the standard GTAP model (Hertel, 1997), there is a single, national production function for each commodity. However, unlike the standard GTAP model, which treats land as a homogenous endowment, in our model the heterogeneous AEZs are inputs to the national production function. With a sufficiently high elasticity of substitution between AEZs, we are assured that the return to land across AEZs, but within a given use (or sector), will move closely together, as would be the case if we had modeled production of a given homogeneous commodity on each AEZ separately.

Land does not move freely between alternative uses within an AEZ. It is constrained by a Constant Elasticity of Transformation (CET) frontier. Thus, within an AEZ, the returns to land in different uses are allowed to differ. With this structure, we can calibrate the partial equilibrium land supply response to remain in line with the econometric literature. The absolute value of the CET parameter represents the upper bound (the case of an infinitesimal share for that use) on the elasticity of supply to a given use of land in response to a change in its rental rate. The more dominant a given use in total land revenue, the smaller its own-price elasticity of acreage supply. The lower bound on this supply elasticity is zero (the case of a unitary rental share – whereby all land is already devoted to that activity). Therefore, the actual supply elasticity is dependent on the relative importance of a given sector in the overall market for land and is therefore endogenous.

We implement a nested CET structure of land supply whereby the land owner first decides on the allocation of land among three land cover types, i.e. forest, cropland and grazing land, based on relative returns to land. The land owner then decides on the allocation of land between various crops, again based on relative returns in crop sectors. To set the CET parameter among three land cover types and among crops, we follow the recommendations in Ahmed, Hertel and Lubowski (2008). In our analysis, there are two policy simulation periods: historical 2001-2006 and policy 2006 - 2015. We set the CET parameter among three land cover types to -0.11 in historical simulation; and, for the policy simulation, we set the parameter to -0.2. In policy simulation the absolute magnitude of the parameter is higher to reflect the additional adjustment time.

Link to the Global Timber Model: Estimating the Change in Forest Carbon

One of the most challenging aspects of assessing the GHG emissions consequences of land use and land use change – particularly in an economy-wide context – is presented by the forestry sector. Any decision regarding forestry production is a forward looking decision. Unlike crops and, to some extent, livestock, growing a tree takes a very long period of time, and optimal decisions regarding the timing of forestry harvesting and management are best modeled in a forward looking framework.

To improve the representation of the forestry sector in a static model, we link our CGE model with the dynamic forward looking Global Timber Model (GTM) described in Sohngen and Mendelsohn (2007). Since GTM will have something different to say about the forestry sector in general, and land rents in particular, one could consider iterating between the models until they (hopefully) converge. However, since the main shock is in the non-forest sector, and since GTM is forward looking and hence fundamentally different from static GTAP, it seems that there is little to be gained from this. For this reason, we employ a "soft-link" between our CGE and GTM, wherein the GTAP model is used to generate the once-for-all-time, biofuel policy shock, while the GTM is used to compute the change in forest carbon stocks over time by species and age class within regions and AEZs, taking into account intertemporal, optimizing behavior.

Even though we do not iterate between the two models, it will be important to have a compatible treatment of land markets in the two models in order to facilitate accurate communication of results from GTAP to GTM. For this, the structure of the land market of the GTM has also been modified to conform with that in the CGE model so that the same Agro-Ecological Zones are referenced, both models uses the notion of a Constant Elasticity of

Transformation (CET) function which transforms land from one use (agriculture) to another (forestry), and the same CET parameters are used to model land supply. Thus, the two models are consistent in their representation of land markets.

Our approach for linking the two models draws on the paper by Horridge and Zhai (2006), written for the trade/poverty analysis. We can think in two dimensions (P, Q) space, viewing the iso-elastic supply function as follows:

$$Q = [B / P]^{\sigma} \tag{1}$$

where σ < 0 is the elasticity of transformation between uses, *B* is a shifter reflecting the impact of returns to competing land uses on supply, and *P* and *Q*, are the price (rental) and quantity of land within a given AEZ that is supplied to forestry. Since both models utilize this same CET function, we may proceed as follows. First, set the value of σ to be the same in both models, then take the solution values for *P* and *Q* from GTAP and use them to compute the implied shift in this land supply function in GTM. In this way, we preserve the fundamental structure of GTM, while ensuring maximum consistency between the two models.

Solving (1) for the vertical shift in supply of land to forestry in a given AEZ, we obtain:

$$B = PQ^{1/\sigma} \tag{2}$$

Since we often like to communicate results in a unit-free manner (i.e., in percentage change terms), it is useful to linearize (1) and manipulate that to see how this works in terms of percentage changes in price and quantity. Here, lower case denotes the percentage change in an upper case variable. So, totally differentiating (1) we get the following form of acreage supply response:

$$q = -\sigma[p - b] \tag{3}$$

So it is clear that the own-price elasticity of supply in this simplified formulation is just the negative of the CET parameter. And rearranging, we get the required shock to the shifter:

$$b = p + (q / \sigma) \qquad (4)$$

If the elasticity of supply is infinite, then the vertical shift is just determined by the change in the rental price of land in forestry from GTAP. Otherwise, this is modified by the scaled quantity change (recall that the CET parameter is negative, so if quantity rises, this will amount to a reduction in *b*). Since (3) is just a linear approximation to the true shift, we can write the true percentage change required in B as follows:

$$b = 100(\alpha - 1) \qquad (5)$$

where α is given by:

$$\alpha = [1 + (0.01p)][1 + (0.01q)]^{1/\sigma} \qquad (6)$$

In summary, first, the CGE model is solved for a new equilibrium in the context of projected growth in liquid biofuels, from which we obtain a vertical shift in the land supply schedule for forestry, in each of the AEZs in each of the model regions, as well as changes in average land rents across uses (crops, livestock and forestry). The latter reflects changes in overall condition in land markets. The shifts and the changes in average across uses land rents are taken as exogenous inputs to the GTM, which is subsequently solved intertemporally in order to develop projections of the new path of forest carbon in light of the growth in biofuels. The deviations of these carbon stocks from baseline give an estimate of regional and global net forest-based carbon emissions attributable to the additional growth in biofuels consumption.

Scenarios

Biofuels Growth in the US: US biofuels development dates back to the Energy Policy Act of

1978 and have been largely driven by an interest in energy security, as well as the presence of a strong farm lobby. Ethanol production received a boost from the 1990 Clean Air Act which required vendors of gasoline to have a minimum oxygen percentage in their product. Adding oxygen enables the fuel to burn cleaner, so a cleaner environment became another important justification for ethanol subsidies. With the ban of its major competitor (MTBE) due to groundwater contamination, there was a strong demand for ethanol use as a source of added oxygen. As a result, ethanol prices peaked at $3.58/gallon in June, 2006, shortly after the MTBE ban was complete. Since that time, the price of ethanol has been falling, as the demand for ethanol as an additive has become satiated, and ethanol is increasingly being priced for its energy content – which is only about 70% of that provided by an equivalent volume of gasoline. By the end of 2006, the US was consuming nearly 5 billion gallons of ethanol. The Energy Policy Act of 2007 stipulates that ethanol consumption should rise to 15 billion gallons by 2015 – implying roughly a tripling of 2006 production. Given current investments in ethanol plants, this target should be achieved well in advance of that date.

Biofuels Growth in the EU: The overall level of biofuels in the European Union is established in terms of share of biofuels on liquid fuels market. According to European Union Biofuels Directive, the share should achieve 10% by 2020 (European Commission (2007)). We follow Hertel *et al*. (2008) to set 6.25% share of biofuels in liquid fuels in 2015.

We begin with version 6 of the GTAP data base representing global economy in 2001 and update it to 2006. It is important to understand how we update the data base and what exogenous variables are shocked. To update the data base, we choose approach outlined in Hertel *et al*. (2008). Instead of shocking all the exogenous variables in the economy, we shock only those that are important in determining structure of biofuel economy. Under this approach, the information requirements for both historical 2001-2006 and policy 2006-2015 experiments is greatly reduced. In historical simulation, we focus only on those elements of the history (presented in Table 1) that are critical in shaping structure of biofuel economy from 2001 to 2006: rise in petroleum prices, the replacement of MTBE by ethanol as gasoline additive, and the subsidies to the ethanol and biodiesel industries in the US and EU. In US, we also target 0.0021 share of sugarcane ethanol in total liquid fuel consumption to reflect importance of Brazilian exports of ethanol to US.[1] Because we do not model other exogenous variables (population, labor, trade policies, technological change and/or income growth) we update 2001 data base to 2006 in terms of *shares* of renewable fuels in total liquid fuel consumption. Thus in our historical simulation we do not target quantity of biofuels in 2006, but shares. Specifically, we target 0.0182 share of biofuels in total liquid fuels for transport in US and 0.0123 share of biofuels in total liquid fuels for transport in EU. We target these shares by changing elasticity of substitution between gasoline and biofuels within household demand for liquid fuels (see Birur *et al.* (2008) for detailed description of the approach to historical simulation). And because our model includes BYPs, the resulted elasticities are slightly smaller than those reported in Birur *et al.* (2008) and consistent with elasticities used in Taheripur *et al.* (2008).

Starting from the updated data base representing 2006 biofuel economy, we run two policy simulations: US only biofuel growth and US plus EU biofuels growth. In these experiments we model policy, again, in terms of changes in *share* of renewable fuels in total liquid fuel consumption. We specify the 2015 target as a renewable fuel share of projected 2015 total liquid transportation fuel consumption, which is projected to rise from 0.0182 to 0.0509 in US and from 0.0123 to 0.0625 in EU over this period (Hertel *et al.*, 2008). This change in the

[1] The size of the shock to share of ethanol from sugarcane in total liquid fuel consumption in US is likely to be revised in the future versions of the paper as better data become available.

composition of the US and EU energy consumption profile forms the basis for our experiments and subsequently will be referred to as the “US+EU biofuels growth”. In US, we implement the growth in biofuels through budget-neutral subsidy on consumption of 1) domestically produced corn ethanol and biodiesel, and 2) imported ethanol from sugarcane. The cost of subsidy is offset by consumption tax on fuel mix that includes all components of liquid transportation fuel, domestic and imported: refined fuels, ethanol derived from corn, ethanol derived from sugarcane and biodiesel. As a result, consumer price of petroleum products increases in US, which leads to reduction in US consumption and reduction in global price of petroleum products. The later induces increase in consumption of petroleum products in the rest of the world. In EU, the policy is budget neutral as well with consumption subsidy on imported and domestic biodiesel and ethanol from corn.

It is important to note that we are estimating the potential GHG effects of an increase in total biofuel volumes from 2006 levels. The Energy Policy Act of 2007 has a stated goal of 15 billion gallons in 2015. Most of this goal is likely to be obtained simply through baseline forces, in particular, higher oil prices. As a result, the Energy Policy Act itself will only be called upon to produce an incremental increase.

Results

Table 3a reports the output changes (percentage increase or decrease) in the biofuel and land using sectors for the US biofuels growth scenario. In the US, production of corn ethanol (ethanol1) and biodiesel rise by more than 170%, while demand for ethanol from sugarcane is satisfied by imports from Brazil, where production is rising by 57%. Grain production rises in all regions, except Brazil, and by more than 9% in US in order to meet the increased demand for biofuel feedstocks. Similarly, to satisfy demand for biodiesel feedstock, oilseeds production rises in all regions, except Brazil and also US which specialized in sugarcane and corn, respectively. In Brazil sugarcane within our “other crops” grouping rise by more than 6% to satisfy increased US demand for sugarcane ethanol (ethanol2). The largest percentage reductions in US output come from paddy rice, wheat and other crops, followed by forestry and then beef and dairy industries. Output in livestock and forestry sectors also falls in some regions due to competition for land between crops for biofuels and other agricultural use. Table 3b reports the output changes in the biofuel and land using sectors for the US+EU biofuel growth scenario. In addition to expanded biofuel production in US, now EU production of biodiesel and corn ethanol rises by more than 400%. When US and EU policy are modeled together, oilseeds production rises in all regions of the world, including US and Brazil whereas under the US only scenario production of oilseeds falls.[2] Comparing to Table 3a, we see more decline in paddy rice and livestock sectors output in EU, Brazil, Canada and US.

Table 4a shows the global revenue share weighted changes in land use predicted by the CGE model, for all regions under the US biofuel growth scenario. Grains production rises worldwide in order to meet the increased demand for biofuels in the US (Table 3a). This rise in demand boosts the average return to cropland and, as a result, additional land is drawn into crops from forestry and grazing. These increases in crop land cover come from pastureland and commercial forest land. Note that, we are currently not modeling the potential for agricultural expansion into natural forests, nor are we considering the potential for idle lands to enter production. Not surprisingly, the percentage declines in forest and pasture land cover are largest in those regions where the rise in crop land is highest. And, in general, there is a larger

[2] The finding that addition of the EU biofuel program turns production of oilseeds in US from declining to rising is similar to result reported in Hertel *et al.* (2008).

proportional reduction in pastureland. Introduction of EU biofuel growth along with US growth has a huge effect on land use worldwide (Table 4b). Within crop sector, land in oil seeds expands in all regions at expense of paddy rice and, in some regions, wheat, and outside crops at expense of livestock and forest sectors. The exceptions are Rest of Europe, Former Soviet Union and most of regions in Asia where forestry expands to meet demand for forestry products, and expands even more when EU biofuel policy is brought into picture.

As noted, these changes in land cover arise due to differential changes in land rents. Changes in average land rents (across AEZs), by region and land cover type are reported in Tables 5a and 5b. Due to the imperfect mobility of land across uses, there are sizable discrepancies in the land rent changes across crops, forestry and pastureland. Due to the relatively inelastic supply of crop land, the associated rents rise sharply in most countries around the world. This rise draws land out of forestry and grazing, thereby bidding up those land rents as well.

In order to deduce the impact of the resulting changes in forest land area on GHG emissions, we turn to the Global Timber Model. While the global CGE model used up to this point includes a forestry sector, it does not differentiate forests by type of trees, management intensity, or vintage. Furthermore, as a comparative static model, it does not capture the long run investment nature of forestry management decisions, and thereby is not well-suited to looking at the long-run impact on forest carbon stocks (Sohngen *et al*., 2008). Since the two models use the same land supply function and the same definitions of AEZs, communication of the CGE results to the timber model is quite straightforward. Given the predicted by the CGE model changes in the quantity and rental rate on forest lands, by AEZ and region, as well as average land rental rate changes in AEZ, we compute the shift in forest land supply function implied by the biofuels growth. In Global Timber Model, this induces changes in forest stocks as well as optimal management regimes, which, in turn, lead to changes in carbon stocks.

Changes in carbon stock are reported in Tables 6a and 6b for the US biofuel growth and US+EU biofuel growth scenarios, respectively. We have calculated the annual equivalent amount (AEA) of the 50 year stream of carbon changes resulting from implementation of the model, assuming a discount rate of 5%. It is important to note that these changes in carbon reflect only above the ground changes and changes in forest product stocks. Changes in soil carbon due to conversion of forest land into agricultural use are not taken into account in the results. Changes in carbon stock in aboveground biomass include trees that are harvested and some of the future effects of the harvests today (due to the 50 year time period captured). For carbon stored in harvested trees, we assume that 30% of the carbon is immediately emitted.

With exception of Russia and Oceania, forest area generally declines under the US biofuel scenario resulting in global forests reduction of 2.56 million hectares per year on average (Table 6a). Almost half of this average annual loss is in Brazil (1.018 million ha). As a result, carbon emissions from land use change in forestry rise. Globally, US biofuel policy leads to additional average annual equivalent of 5.85 MMTCE emissions per year due to changes in land use in forestry (annualized using a discount rate of 5%). Fairly large additional carbon emissions from forests occur in EU, Brazil and US, due to increased deforestation in those regions. Forest area expands in Russia providing additional sequestration of 1.25 MMTCE annually.

US and EU biofuel growth lead to an 8.3 million hectare decline in global forest area on average annually and to an additional 13.45 MMTCE/year global emissions from forests. Largest emissions, as well as deforestation rates, are predicted in EU, Brazil, US and Canada. It is important to note, however, that we have not modeled changes at the inaccessible margin. To the extent that new forests are accessed to enhance crop production, emissions could increase.

Globally, US biofuels growth leads to 0.27% annual decline in forest area relative to baseline. US plus EU growth leads to 0.88% annual decline in global forests. Consequences for US are 1.12 and 2.06 annual % decline in forest area relative to baseline for US only and US+EU biofuel growth, respectively. Is this a rapid decline? Table A2 in the Appendix reports forest land area in 1000 acres in US from 1630 to 2002 as well as annual percent change (source: Smith *et al*., 2003). The annual rate of change between 1987 and 2002 (not reported) is 0.1%. Assuming this tendency will continue in the baseline, -1.12% change from baseline due to US biofuels growth will reverse the recent trend.

We can convert the forest carbon emissions to emissions per gallon of biofuel produced. In order to get to the actual amount of biofuel produced, we need to do some side-calculations for initial and ending biofuel production. The calculations are presented in Tables 7a and 7b for US only and US+EU scenarios, respectively. Comparison of quantity of ethanol projected to be used for transportation in 2015 reported in Table 2 is different from the simulated quantity of ethanol to be used for transportation in 2015 reported in Tables 7a and 7b. This is because we have specified the target in terms of a renewable fuel share, not an absolute level. In US biofuel scenario, 12.02 billions of gallons of renewable fuels used for transport (Table 7a) result in 5.85 MMTC of carbon emissions from changes in aboveground forest carbon stocks (Table 6a), or 6g of carbon per 1000 Btu (0.49 kg of carbon per gallon). For the US and EU biofuels scenario, carbon emissions from changes in aboveground forest carbon stocks are 7 g of carbon per 1000 Btu (0.71 kg of carbon per gallon). For comparison, gasoline emits 19 g of carbon per 1000 Btu (2.4 kg of carbon per gallon). However, before drawing conclusions regarding the environmental impacts of biofuels, we need to consider all other emissions related to biofuel production (conversion of unmanaged forests and other types of land cover, soil carbon, emissions from producing biofuel crops and biofuel itself etc.) and effect of changes in prices of other sources of energy due to the growth in biofuels.

Conclusion

There are many potential sources of GHG emissions stemming from land use. However, land use change is a significant individual source (IPCC, 2007). This paper provides a new perspective on the potential forest carbon sequestration implications of additional biofuels. We have developed an economic model that endogenously accounts for input and output market interactions and feedbacks, and sequestration implications of the resulting changes to the global economy. The model includes biofuels co-products that reduce the demand for grain for livestock feed and captures changes in realized yields that reflect input substitution and price changes. With this framework, we find a complex set of global reactions to a simulated increase in share of renewable fuels in total liquid fuels for transport in US and EU. We find increases in cropland for grains, oil seeds and sugarcane with decreases in grazing lands, forest lands, and other croplands.

Through the link with Global Timber Model, we find that growth in US biofuels leads to additional 5.85 MMTCE emissions per year from changes in aboveground forest carbon stocks. When considered together, US and EU biofuels growth adds 13.45 MMTCE annually. Globally, forests are a net source of carbon, to the tune of somewhere between 700 and 2000 MMTC per year. However, the losses are largely driven by deforestation in tropical countries. The US , Russia, Europe, and maybe Canada have been sinks. The US sink is around 200-220

MMTC per year. In this context the effects are miniscule. But in terms of the policy, they need to be counted in the net and compared with the other lifecycle estimates of carbon change resulting from the policy.

From the experiment with CGE model and subsequent link with GTM, we conclude that if we change 2006 world economy from one with 0.0183 to 0.0509 share of renewable fuels in total transportation fuels in US, these renewable fuels carbon emissions are on average 6g/1000Btu (0.49kg of carbon emissions per gallon) for the next 50 years when taking into account only changes in aboveground forest carbon and ignoring all other emissions. When we consider US and EU biofuel growth together, we find 7g of carbon emissions per 1000Btu (0.71 kg of carbon emissions per gallon) of renewable fuel. Our estimates do not capture changes in soil carbon and GHG emissions related to changes in crop and livestock production, and in the economy as a whole, and we are not yet modeling the potential for increased deforestation of natural forests.

In the future, we will be exploring interactions between biofuels and climate policies by assessing the effects of the biofuels growth on regional and global GHG emissions mitigation potential. To investigate the GHG emissions from land-use change consequences of biofuels growth, we draw on the framework of Golub *et al*. (2008) who analyze the role of global land-use in determining potential GHG mitigation by land-based activities in agriculture and forestry. These authors augment the GTAP model with a new non-CO2 emissions data base (Rose and Lee, 2008), linked to underlying economic activity. They also include new engineering GHG mitigation costs estimates (USEPA, 2006), as well as an explicit model of forestry intensification and extensification to capture changes in forest carbon stocks. For full GHG accounting, we include CO_2 emissions from fossil fuel combustion (Lee, 2007) linked to underlying economic activity. This permits us to provide a comprehensive analysis of the consequences of expanded biofuels production for GHG emissions.

An important question is whether biofuels growth could facilitate or constrain mitigation opportunities? For instance, Golub *et al.* (2008) estimate substantial GHG mitigation potential in non-US forests. Furthermore, those authors find that a carbon tax could lead to input substitution away from land and fertilizer. Both results run counter to the changes in land-use estimated by Hertel *et al.* (2008). Understanding interactions between potential biofuels and climate policies is important. There are regional comparative advantages in biofuels production (as well as food crops and timber production). There are also regional comparative advantages in land-based GHG mitigation. By modeling biofuels and climate policies simultaneously, we can assess the implications for land-use, production, and global competitiveness. This extension will include calibration of the model to the mitigation costs for non-CO2 GHGs from USEPA (2006) and for forest carbon sequestration from Sohngen and Mendelsohn (2007). It will then evaluate the CGE GHG mitigation responses to a range of carbon equivalent taxes with and without biofuels growth. We can then investigate the interactions between the policies at the global, regional and sectoral levels.

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Table 1. Description of 2001-2006 Historical Simulation

	Change 2001-2006	
	US	EU
Average crude oil price	136	
Increase in ethanol additive demand (incorporated by imposing negative shock to the factor augmenting technical change)	-49	–
Ad valorem equivalent of subsidy (US) or tax credit (EU)		
Ethanol	-10.9	50.77
Biodiesel	-7	81.18
Change in share of ethanol from sugarcane	0.0021	

Source: Birur, Hertel and Tyner (2008)

Table 2. Historical and Projected Shares of Biofuels in Liquid Fuels for Transport in US and EU

	2001		2006		2015	
	Quad Btu	Share	Quad Btu	Share	Quad Btu	Share
US						
Ethanol	0.1485	0.00572	0.471	0.0171	1.341	0.0453
Biodiesel	0.0011	0.00004	0.032	0.0012	0.167	0.0056
Gasoline	25.81	0.99424	27.067	0.9818	28.122	0.9491
Total	25.96	1	27.57	1	29.630	1
Share of biofuels in total liquid fuels for transport		0.0058		**0.0182**		**0.0509**
EU						
Ethanol	0	0	0.035	0.0019	0.183	0.0099
Biodiesel	0.037	0.0020	0.189	0.0104	0.973	0.0526
Gasoline	18.163	0.9980	17.976	0.9877	17.344	0.9375
Total	18.20	1	18.20	1	18.50	1
Share of biofuels in total liquid fuels for transport		0.0020		**0.0123**		**0.0625**

Source: Hertel, Tyner and Birur (2008).

Table 3a. Change in Output in Biofuel and Agriculture Sectors due to US Biofuel Growth, %

Sector	Oceania	China	Japan	East Asia	South East Asia	India	Rest of South Asia	Canada	US	Central and Caribbean Americas	Brazil	South and Other Americas	EU25	Rest of Europe	Russia	Rest of CIS and CEE	Sub-Saharan Africa	North Africa and Middle East
Ethanol1	-0.82	-0.76	-0.51	-1.09	-0.73	-0.99	-1.20	7.46	178.09	-1.30	-0.35	-1.24	-1.59	-0.34	-0.66	-0.10	-1.63	-1.12
Ethanol2	-0.87	-0.20	-0.12	0.02	-1.04	-0.29	-0.96	1.52	-12.78	-3.42	57.48	-2.86	2.03	-0.46	-0.23	-0.32	-0.75	-1.13
Biodiesel	-2.31	-1.37	-1.62	-3.73	-3.78	-3.13	-3.17	-2.13	177.47	-3.54	-1.54	-3.49	-2.50	-2.30	-2.47	-1.09	-2.40	-2.74
Paddy Rice	0.32	0.01	0.07	0.01	-0.06	0.05	0.06	-1.33	-2.22	0.61	-2.81	0.99	1.03	1.10	0.41	0.03	-0.17	-0.29
Wheat	-0.20	0.19	0.84	0.36	-0.09	0.12	0.24	0.25	-3.07	0.26	-7.27	-0.01	0.10	0.19	0.26	0.13	0.92	0.89
Other Grains	1.51	0.54	2.42	1.45	0.19	0.04	0.08	0.88	9.61	1.12	-3.12	0.86	0.42	0.57	0.27	0.22	0.08	1.07
Vegetables, Fruits and Nuts	0.12	0.03	0.04	0.05	0.03	0.08	0.04	0.60	-1.34	0.22	-3.79	0.09	0.02	-0.05	-0.06	-0.01	0.16	-0.10
Oilseeds	1.88	0.87	0.95	1.18	0.57	0.14	0.21	3.14	-1.15	1.41	-4.35	1.51	0.98	2.25	1.31	0.78	0.96	0.92
Other Crops	0.71	0.77	0.44	0.67	0.74	0.23	0.33	0.53	-1.79	0.41	6.02	0.90	0.74	0.87	0.43	0.53	1.09	2.03
Beef	0.35	0.00	-0.19	-0.01	-0.02	0.09	0.07	0.16	-0.53	0.12	-2.94	-0.01	0.30	0.15	-0.13	0.11	-0.19	0.09
Dairy	-0.01	-0.02	-0.05	0.02	0.03	0.08	0.05	-0.07	-0.32	-0.09	-0.32	0.00	0.01	0.05	-0.17	0.10	-0.20	0.03

Table 3b. Change in Output in Biofuel and Agriculture Sectors due to US and EU Biofuel Growth, %

Sector	Oceania	China	Japan	East Asia	South East Asia	India	Rest of South Asia	Canada	US	Central and Caribbean Americas	Brazil	South and Other Americas	EU25	Rest of Europe	Russia	Rest of CIS and CEE	Sub-Saharan Africa	North Africa and Middle East
Ethanol1	-1.46	-1.52	-0.78	-2.28	-1.49	-2.10	-2.48	4.62	178.58	-2.70	-0.38	-2.92	443.59	-0.74	-1.41	-0.36	-2.94	-2.38
Ethanol2	-1.24	-0.32	-0.17	0.05	-1.60	-0.47	-1.35	2.52	-13.70	-5.85	56.67	-4.11	1.29	-0.63	-0.34	-0.78	-1.10	-1.64
Biodiesel	-3.60	-3.19	-4.54	-8.55	164.83	-6.02	-7.44	-4.09	177.96	-8.18	-3.37	-7.37	454.71	-7.25	-6.47	-2.02	-5.26	-5.67
Paddy Rice	0.48	-0.02	0.16	-0.01	-0.23	0.26	0.22	-6.35	-3.07	0.75	-4.41	1.22	-6.22	2.46	0.33	-0.23	-1.53	-0.67
Wheat	0.47	0.74	4.12	1.39	1.34	0.82	1.08	2.27	-1.93	2.20	-9.03	-0.07	-9.39	1.51	1.70	1.21	3.55	3.62
Other Grains	2.37	1.02	3.99	2.62	0.26	0.04	0.08	1.66	11.07	1.40	-4.16	1.29	-4.36	0.78	0.69	0.57	0.03	2.26
Vegetables, Fruits and Nuts	1.22	0.11	0.15	0.15	0.19	0.42	0.22	1.44	-1.10	1.58	-3.80	1.15	-6.40	1.66	-0.08	0.49	2.81	0.23
Oilseeds	15.87	6.09	5.04	5.23	4.00	1.21	2.02	17.76	8.08	8.22	15.08	10.67	56.15	15.15	17.30	12.27	10.23	6.61
Other Crops	2.04	3.06	1.55	2.66	3.01	1.09	1.73	-0.32	-1.75	1.85	4.25	2.33	-6.80	4.48	1.14	2.06	4.72	7.21
Beef	1.34	-0.03	0.00	0.03	-0.13	0.37	0.20	-0.85	-0.54	0.18	-3.55	-0.25	-1.28	0.31	-0.33	0.31	-0.32	0.17
Dairy	0.46	-0.15	-0.07	0.09	0.41	-0.04	-0.06	-0.19	-0.49	-0.22	-0.04	-0.17	-1.01	0.17	-0.40	0.20	-0.30	0.09

Table 4a. Revenue Share Weighted Changes in Land Use due to US Biofuel Growth, (%)

	Oceania	China	Japan	East Asia	South East Asia	India	Rest of South Asia	Canada	US	Central and Caribbean Americas	Brazil	South and Other Americas	EU25	Rest of Europe	Russia	Rest of CIS and CEE	Sub-Saharan Africa	North Africa and Middle East
Land cover change																		
Forest	-0.07	0.00	-0.09	0.06	0.02	-0.01	0.00	-0.37	-1.25	-0.26	-2.16	-0.15	-0.40	-0.06	0.15	-0.03	-0.22	-0.11
Cropland	0.15	0.01	0.05	0.00	0.00	0.00	0.01	0.57	0.34	0.11	1.02	0.16	0.18	0.26	-0.02	0.05	0.36	0.05
Cattle, sheep, goat, horses	-0.14	-0.09	-0.34	-0.13	-0.12	-0.01	-0.04	-0.67	-1.39	-0.26	-3.11	-0.34	-0.44	-0.22	-0.28	-0.21	-0.42	-0.15
Milk Animals	-0.31	-0.10	-0.27	-0.11	-0.08	-0.02	-0.05	-0.79	-1.28	-0.38	-1.80	-0.33	-0.57	-0.26	-0.29	-0.23	-0.42	-0.18
Cropland change																		
Paddy Rice	0.09	-0.09	-0.06	-0.11	-0.22	-0.08	-0.05	-1.87	-2.97	0.23	-3.54	0.55	0.89	0.89	0.21	-0.09	-0.31	-0.34
Wheat	-0.42	0.13	0.65	0.22	-0.22	0.02	0.10	-0.02	-3.58	-0.03	-7.47	-0.28	-0.11	-0.03	0.14	0.04	0.76	0.80
Other Grain	1.11	0.42	2.11	1.14	-0.01	-0.07	-0.06	0.54	7.29	0.65	-3.73	0.48	0.19	0.26	0.12	0.15	-0.08	0.93
Vegetables, fruits and nuts	-0.09	-0.08	-0.09	-0.07	-0.16	-0.04	-0.09	0.27	-2.12	-0.14	-4.32	-0.23	-0.22	-0.31	-0.17	-0.16	-0.01	-0.18
Oil Seeds	1.44	0.69	0.74	0.81	0.31	0.01	0.06	2.76	-2.06	0.95	-4.74	1.08	0.69	1.92	1.03	0.64	0.73	0.82
Other Crops	0.41	0.57	0.28	0.40	0.36	0.07	0.15	0.06	-2.69	0.01	4.27	0.45	0.48	0.61	0.27	0.45	0.90	1.89

Table 4b. Revenue Share Weighted Changes in Land Use due to US and EU Biofuel Growth, (%)

	Oceania	China	Japan	East Asia	South East Asia	India	Rest of South Asia	Canada	US	Central and Caribbean Americas	Brazil	South and Other Americas	EU25	Rest of Europe	Russia	Rest of CIS and CEE	Sub-Saharan Africa	North Africa and Middle East
Land cover change																		
Forest	-0.37	0.28	-0.25	0.50	0.26	0.00	-0.10	-2.01	-2.02	-0.92	-4.09	-0.13	-7.49	0.61	0.82	0.06	-1.10	-0.66
Cropland	0.70	-0.01	0.15	-0.01	-0.03	0.06	0.07	2.67	0.58	0.39	1.90	0.69	2.37	1.37	-0.11	0.35	1.76	0.36
Cattle, sheep, goat, horses	-0.83	-0.49	-0.94	-0.34	-0.56	-0.08	-0.29	-3.57	-2.64	-1.10	-6.21	-1.62	-9.09	-1.72	-1.58	-1.93	-2.47	-1.26
Milk Animals	-1.25	-0.56	-0.98	-0.30	-0.18	-0.34	-0.45	-3.25	-2.62	-1.32	-4.48	-1.59	-8.94	-1.76	-1.60	-2.01	-2.45	-1.32
Cropland change																		
Paddy Rice	-0.54	-0.47	-0.34	-0.44	-0.98	-0.42	-0.33	-8.08	-4.72	-0.43	-6.43	-0.28	-7.46	1.47	-0.76	-1.16	-2.39	-1.13
Wheat	-0.69	0.44	3.33	0.90	0.28	0.29	0.41	1.02	-3.51	0.96	-9.95	-1.27	-11.52	0.08	0.87	0.56	2.61	3.11
Other Grain	0.98	0.61	3.23	1.93	-0.54	-0.50	-0.54	0.34	7.50	0.11	-5.93	-0.10	-6.91	-0.78	-0.30	0.03	-0.94	1.59
Vegetables, fruits and nuts	0.14	-0.39	-0.35	-0.27	-0.68	-0.22	-0.47	0.12	-2.87	0.11	-5.57	-0.38	-9.21	-0.22	-0.95	-0.78	1.52	-0.40
Oil Seeds	12.90	4.95	4.13	3.64	2.52	0.45	1.05	15.75	4.86	6.11	12.14	8.19	47.31	12.91	13.92	10.70	8.39	5.84
Other Crops	0.76	2.21	0.96	1.64	1.39	0.27	0.78	-2.04	-3.85	0.35	1.14	0.59	-9.23	2.94	0.15	1.54	3.55	6.52

Table 5a. Changes in Land Rents due to US Biofuel Growth, (%)

	Oceania	China	Japan	East Asia	South East Asia	India	Rest of South Asia	Canada	US	Central and Caribbean Americas	Brazil	South and Other Americas	EU25	Rest of Europe	Russia	Rest of CIS and CEE	Sub-Saharan Africa	North Africa and Middle East
										Land rents change								
Forest	2.81	1.09	2.06	1.28	1.51	0.94	1.01	5.34	7.83	2.21	9.43	2.86	2.94	2.67	3.06	2.88	1.47	0.76
Cropland	4.80	1.14	2.82	0.95	1.38	1.02	1.04	10.79	18.16	4.17	29.22	4.66	6.75	4.37	1.22	3.23	4.84	1.77
Cattle, sheep, goat, horses	2.50	0.53	0.72	0.10	0.79	0.87	0.79	4.18	5.19	2.15	3.47	1.71	3.39	1.78	0.10	1.71	0.89	0.45
Milk Animals	1.49	0.47	1.07	0.33	0.97	0.84	0.72	3.56	5.78	1.57	10.66	1.76	2.72	1.56	0.05	1.64	0.83	0.31

Table 5b. Changes in Land Rents due to US and EU Biofuel Growth, (%)

	Oceania	China	Japan	East Asia	South East Asia	India	Rest of South Asia	Canada	US	Central and Caribbean Americas	Brazil	South and Other Americas	EU25	Rest of Europe	Russia	Rest of CIS and CEE	Sub-Saharan Africa	North Africa and Middle East
										Land rents change								
Forest	15.03	7.49	8.60	6.18	8.27	4.85	4.60	21.22	20.72	8.57	30.07	18.03	44.67	26.18	23.38	26.71	16.29	9.85
Cropland	25.51	5.58	10.83	3.30	6.51	5.30	5.66	56.57	39.59	16.18	82.08	23.89	178.02	31.26	12.35	28.21	36.75	16.79
Cattle, sheep, goat, horses	11.85	2.73	4.62	1.21	3.73	3.61	3.46	14.81	13.18	7.57	18.39	8.33	48.59	11.57	5.34	12.57	10.86	5.85
Milk Animals	8.97	2.38	4.42	1.62	5.69	2.27	2.60	16.71	13.30	6.45	29.74	8.62	50.61	11.33	5.24	12.09	10.80	5.74

Table 6a. Emissions from Changes in Forest Land Area due to US Biofuel Growth, MMTCE/yr

	US	China	Brazil	Canada	Russia	EU 25	Rest of Europe	South Asia	Central and Caribbean Americas	South and Other Americas	Sub-Saharan Africa	South East Asia	Oceania	Japan	North Africa and Middle East	East Asia	Global
Annual Emissions (AEA, 50 yrs)	1.7	0.37	1.72	-1.2	-1.25	2.99	0.9	-0.01	0.02	0.23	0.09	0.03	-0.02	0	0	0.28	5.85
Forest area																	
Baseline area (million ha)	77.522	97.904	80.638	107.92	133.12	121.736	28.938	39.674	10.26	47.798	58.152	63.39	34.552	17.53	12.002	9.344	940.48
Biofuels policy area (million ha)	76.654	97.888	79.62	107.606	133.3	121.44	28.936	39.668	10.226	47.704	58.032	63.362	34.618	17.52	12.002	9.344	937.92
Area Change (million ha)	-0.868	-0.016	-1.018	-0.314	0.18	-0.296	-0.002	-0.006	-0.034	-0.094	-0.12	-0.028	0.066	-0.01	0	0	-2.56
% change from baseline	-1.12	-0.02	-1.26	-0.29	0.14	-0.24	-0.01	-0.02	-0.33	-0.20	-0.21	-0.04	0.19	-0.06	0.00	0.00	-0.27

Note: Annual equivalent amount (AEA) over 50 years at r=0.05. Positive numbers indicate additional emissions as a result of the policy, while negative numbers indicate sequestration. Baseline land area and policy land area are simple average over 50 years.

Table 6b. Emissions from Changes in Forest Land Area due to US and EU Biofuel Growth, MMTCE/yr

	US	China	Brazil	Canada	Russia	EU 25	Rest of Europe	South Asia	Central and Caribbean Americas	South and Other Americas	Sub-Saharan Africa	South East Asia	Oceania	Japan	North Africa and Middle East	East Asia	Global
Annual Emissions (AEA, 50 yrs)	1.82	0.15	2.76	1.92	-1.19	6.41	0.31	0.01	0.06	0.41	0.49	0.11	-0.08	0.02	0	0.25	13.45
Forest area																	
Baseline area (million ha)	77.522	97.904	80.638	107.92	133.12	121.736	28.938	39.674	10.26	47.798	58.152	63.39	34.552	17.53	12.002	9.344	940.48
Biofuels policy area (million ha)	75.922	98.022	78.93	106.492	133.796	118.254	28.968	39.646	10.14	47.494	57.52	63.288	34.882	17.502	11.994	9.346	932.196
Area Change (million ha)	-1.6	0.118	-1.708	-1.428	0.676	-3.482	0.03	-0.028	-0.12	-0.304	-0.632	-0.102	0.33	-0.028	-0.008	0.002	-8.284
% change from baseline	-2.06	0.12	-2.12	-1.32	0.51	-2.86	0.10	-0.07	-1.17	-0.64	-1.09	-0.16	0.96	-0.16	-0.07	0.02	-0.88

Note: Annual equivalent amount (AEA) over 50 years at r=0.05. Positive numbers indicate additional emissions as a result of the policy, while negative numbers indicate sequestration. Baseline land area and policy land area are simple average over 50 years.

Table 7a. Emissions from Changes in Forest Land Area due to US Biofuels Growth, per Gallon of Biofuel for Transport

	2015 (CGE simulation result)			Emissions, MMTC (GTM simulation result)	Biofuel emissions, g of C per 1000 Btu	Gasoline emissions, g of C per 1000 Btu	Average liquid fuel for transport emissions, g of C per 1000 Btu
	Quad btu	Share	Billions of gallons				
1	2	3	4	5	6	7	8
				US biofuels			
Ethanol	1.0043	0.0503	11.92				
Biodiesel	0.0131	0.0007	0.10				
Gasoline	18.9680	0.9491	151.66				
Total liquid fuels for transport	19.9854	1	163.68				
Total biofuels	1.0174	0.0509	12.02	5.85	6	19	18.34

Table 7b. Emissions from Changes in Forest Land Area due to US and EU Biofuels Growth, per Gallon of Biofuel for Transport

	2015 (CGE simulation result)			Emissions, MMTC (GTM simulation result)	Biofuel emissions, g of C per 1000 Btu	Gasoline emissions, g of C per 1000 Btu	Average liquid fuel for transport emissions, g of C per 1000 Btu
	Quad btu	Share	Billions of gallons				
1	2	3	4	5	6	7	8
				US and EU biofuels			
				US			
Ethanol	1.0061	0.0503	11.94				
Biodiesel	0.0131	0.0007	0.10				
Gasoline	19.0015	0.9491	151.93				
Total liquid fuels for transport	20.0207	1	163.97				
Total biofuels	1.0192	0.0509	12.04				
				EU			
Ethanol	0.0160	0.0011	0.19				
Biodiesel	0.8674	0.0613	6.75				
Gasoline	13.2568	0.9375	105.99				
Total liquid fuels for transport	14.1402	1	112.93				
Total biofuels	0.8834	0.0509	6.94				
Total biofuels in US and EU			18.98	13.45	7	19	18.18

Appendix

Table A1. Production Sectors and Regions of the CGE Model

Sectors		Regions	
Sectors	1 Paddy rice	Regions	Oceania
	2 Wheat		China
	3 Other grain		Japan
	4 Vegetables, fruit, nuts		East Asia
	5 Oilseeds		South East Asia
	6 Other Crops		India
	7 Cattle, sheep, goat, horses		Rest of South Asia
	8 Raw milk		Canada
	9 Non-ruminant livestock		United States
	10 Forest		Central and Caribbean Americas
	11 Ethanol from corn (produce ethanol 1 and DDGS)		Brazil South and other Americas
	12 Ethanol from sugarcane (produce ethanol2 and BDBP)		European Union-25 countries Other Europe
	13 Biodiesel		Russia
	14 Coal		Other CEE and CIS countries
	15 Oil		Sub-Saharan Africa
	16 Gas		North Africa and Middle East
	17 Petroleum and coal products		
	18 Electricity		
	19 Gas distribution		
	20 Beef, mutton, horse meat		
	21 Dairy products		
	22 Other meat products		
	23 Processed rice		
	24 Other food processing		
	25 Wood processing		
	26 Chemical, rubber, plastic prods		
	27 Energy intensive manufacture		
	28 Wholesale and Retail Trade		
	29 Private Services		
	30 Ground Transport		
	31 Other Transport		
	32 Textiles, Apparel, Footwear		
	33 Other manufacture		
	34 Housing and Govt Services		

Table A2. Forest land area in the United States

Year	US	
	1000 acres	Annual % change
1630	1,045,435	-0.115
1907	759,140	0.003
1938	759,814	-0.032
1953	756,167	0.076
1963	761,936	-0.174
1977	743,633	-0.079
1987	737,750	0.124
1997	746,958	0.053
2002	748,923	

Source: Smith *et al.* (2003)