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Submitted Article

What Is the Social Value of Second Generation Biofuels?

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Abstract *What are second-generation (2G) biofuel technologies worth to global society? A dynamic, economic model is used to assess the impact that introducing 2G biofuels technology has on crops, livestock, biofuels, forestry, and environmental services, as well as greenhouse gas emissions. Under baseline conditions, this amounts to $64 billion and is $84 billion under the optimistic technology case, suggesting that investing in 2G technology could be appropriate. Under greenhouse gas regulation, global valuation more than doubles to $139 and $174 billion, respectively. A flat energy price scenario eliminates the value of 2G technology to society.*

Key words: Global land use, biofuels, climate policy, climate impacts, energy prices.

JEL Codes: Q15, Q42, Q54.

Commercial-scale implementation of second generation (2G) biofuels has long been considered to be "just over the horizon—perhaps a decade away". However, with recent innovations, we appear to be on the verge of finally seeing commercial-scale implementations of cellulosic to liquid fuel conversion technologies (Committee on Economic and Environmental Impacts of Increasing Biofuels of the National Research Council 2011). Interest in 2G technology derives from many quarters. Environmentalists see this as a way of reducing our carbon footprint, as second generation biofuels offer the potential for fueling combustion engines with fewer GHG emissions (Havlík et al. 2011). Those interested in poverty and nutrition see this as a channel for lessening biofuels' impact on food prices (Naylor et al. 2007). But what is the overall value to society of developing and implementing these new technologies? And what factors determine this value? How sensitive is this valuation to uncertainty in climate impacts and policies, economic growth, energy prices and population growth? This paper seeks to answer these questions.

Valuation of global-scale implementation of 2G biofuel technology faces three challenges. Firstly, it is plagued by uncertainty, since the viability of 2G technology depends on policies relating to renewable fuels and climate mitigation, climate impacts, and oil prices (Rose et al. 2012). However, absent a global market for carbon emissions, private firms will not factor into their decisions the potential impacts of biofuels on greenhouse gas (GHG) emissions. Secondly, the effects of the associated changes in global land use are long-lived, making the distant future quite important. The third point made clear by these studies is that large scale implementation of 2G biofuels will have impacts well beyond those which play into an individual firm's decision making process, including agricultural and oil markets (Paltsev 2012), as well as the provision of non-market ecosystem services by natural lands.

In this paper we provide a systematic valuation of improved 2G biofuel technology in the context of large scale uncertainty and non-market externalities using the Forest, Agriculture, and Biofuels in a Land use model with Environmental services (FABLE) model; FABLE is a dynamic optimization model for the world's land resources that characterizes the optimal long run path for protected natural lands, managed forests, crop and livestock land use, energy extraction and biofuels over the period 2005–2105 (Steinbuks and Hertel 2014). By running the model twice—once without 2G technology, and once with it available, we can ascertain the global value to society of 2G biofuels. Furthermore, we can decompose the factors driving this valuation, including things such as land conversion costs, cropland rents, fertilizer costs and the bequest value of forests and natural lands at the end of the planning horizon. In our baseline case, in the absence of government mandates, current 2G technology becomes commercially viable in 2035, and its global discounted value to society is estimated to be $64.2 billion.

By altering the assumptions surrounding our baseline scenario, we are able to evaluate the sensitivity of 2G technology valuation to factors such as climate impacts on crop yields, oil prices, global economic and population growth rates, GHG regulation, and the rate at which society discounts future benefits. We find that the most important factor driving 2G valuation is the oil price path. With flat oil prices over the course of the coming century, the societal value of 2G biofuels is virtually eliminated. On the other hand, GHG regulation enhances the value of 2G biofuels. Indeed, when present, GHG regulation doubles the value of this technology to society. By placing a value on carbon emissions, aggressive climate policies result in earlier and more ambitious deployment of 2G technologies, boosting their valuation to $139.3 billion under the climate regulation scenario. This represents an enhancement of the present value of services from the world's land resources of about 0.6%. Slower economic and population growth rates also boost the value of 2G technologies due to the diminished competition for land with food, forest and environmental services production.

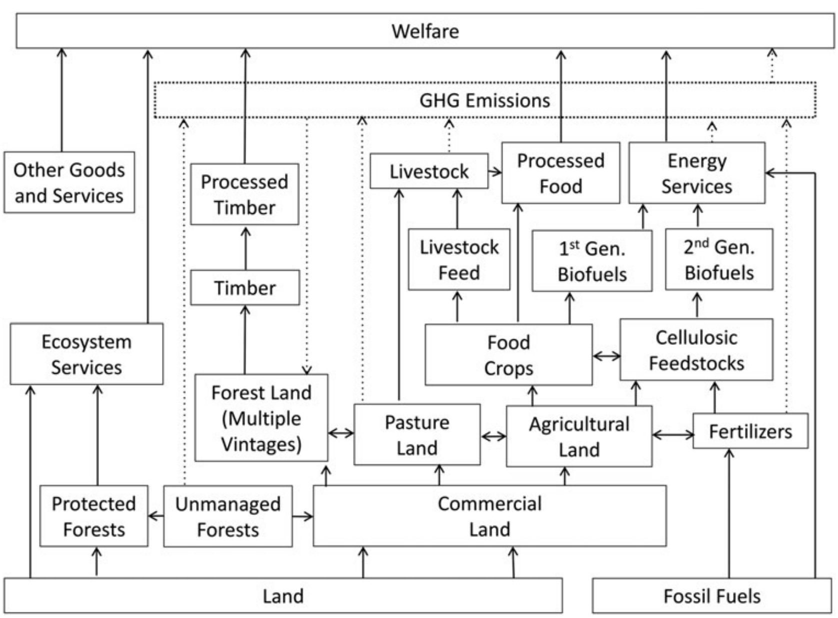
Methods

Overview of the FABLE Model

The FABLE model is a perfect foresight dynamic model of global land use that is solved in discrete time over a finite horizon. Income, population, wages, oil prices, total factor productivity, and other variable input prices are assumed to be exogenous. The model obtains the optimal allocation of scarce land over time and across competing uses. It thus reflects incentives faced by forward-looking, profit-maximizing investors, as well as their responses to alternative states of the world, including population and economic growth, GHG emissions polices, climate change, and energy prices.

Figure 1 provides an overview of FABLE (Steinbuks and Hertel 2014). The model includes ten sectors producing, respectively, agrochemicals, crops, feedstuffs, livestock products, other processed food, biofuels, energy, forestry, timber processing, and ecosystem services. Land and fossil fuels are treated as endowments (the latter encompassing oil and natural gas), with the cost of fossil fuel extraction following an exogenous path. The competing uses for land include: unmanaged forests, protected forests, commercial forests, pastures, cropland dedicated to food crops and cellulosic feedstocks. Unmanaged forests are natural lands in an undisturbed state. These lands can be accessed at some cost and thereupon converted to commercial land (deforested) or, alternatively, these lands may be protected. Deforested land has diminished the potential for providing ecosystem services, and this cannot be restored within the (single century) time frame of the analysis. Institutionally protected lands require resources to be maintained, but are highly productive in the provision of ecosystem services for society. Once they are protected, they can no longer be converted to commercial use within the time frame of this analysis. Commercial lands, on the other hand, are available for use in either the agriculture or forestry sectors. The managed forest land is differentiated by the age of the forest, adding to the computational complexity of this dynamic forward-looking analysis.

Figure 1 Structure the FABLE model



Note: This figure depicts key flows of goods and services from the two natural resources in the model, land and fossil fuels, to households (welfare).

This vintage structure is, however, essential to our analysis, since it allows us to capture differential growth rates of harvestable timber and carbon stocks across forest vintages. Agricultural lands may be used as pasture for livestock, cropland to grow food crops, or for the cultivation of feedstocks such as switchgrass, which are used in the production of second generation biofuel.

There are two biofuel sectors in the model. The first utilizes food crop feedstocks (e.g., corn) and produces a liquid fuel (e.g., ethanol), which substitutes imperfectly for petroleum in the production of energy services. Second-generation biofuels (e.g., cellulosic biomass-to-liquid diesel obtained through fast pyrolysis) are treated as a "drop-in fuel" that substitutes perfectly with petroleum-based products in the production of energy services. There is a fertilizer sector that converts fossil fuels into nitrogenous fertilizer that is applied in variable proportions to land in the cropping sector, thereby altering yields. In addition to providing a feedstock for first generation biofuels, food crops can be fed to livestock for use by non-ruminant livestock or as a substitute for grazing in the case of ruminants. Of course, the majority of food crops enter the food-processing sector which converts crop outputs into final food products which are sold to consumers. The forestry sector's timber output is converted into a marketable product by the timber-processing sector, which satisfies commercial demands for lumber and other wood products. The ecosystem services sector assembles a composite of terrestrial ecosystem services, the productivity of which varies by land use, with the highest productivity stemming from the protected lands and the lowest from the intensively cropped lands. All other goods and services are exogenous, and the productivity of this sector drives the overall rate of income growth in the global economy.

The objective function in FABLE places value on all of the land-based services, including timber, food, energy, and eco-system services. This function is defined as the sum of net aggregate societal surplus, the stream of which is discounted at a constant rate. In the terminal period, we attach a "bequest value" to the unmanaged forest and commercial forest areas that remain at that point in time. This is intended to reflect the interests of future generations. The societal surplus associated with each good or service consumed is computed by integrating over the marginal valuation of each product. From this surplus, we deduct land access costs as well as the cost of non-land-based inputs used in the production of these land-based services. For example, in the case of biofuels, these comprise the non-land biofuels costs and fossil fuel costs used in producing this product. For forestry, these are harvesting and planting costs, and so on. There are also costs of maintaining the protected lands that we conceptualize as natural park lands, and these must be deducted from the social surplus generated by the consumption of ecosystem services.

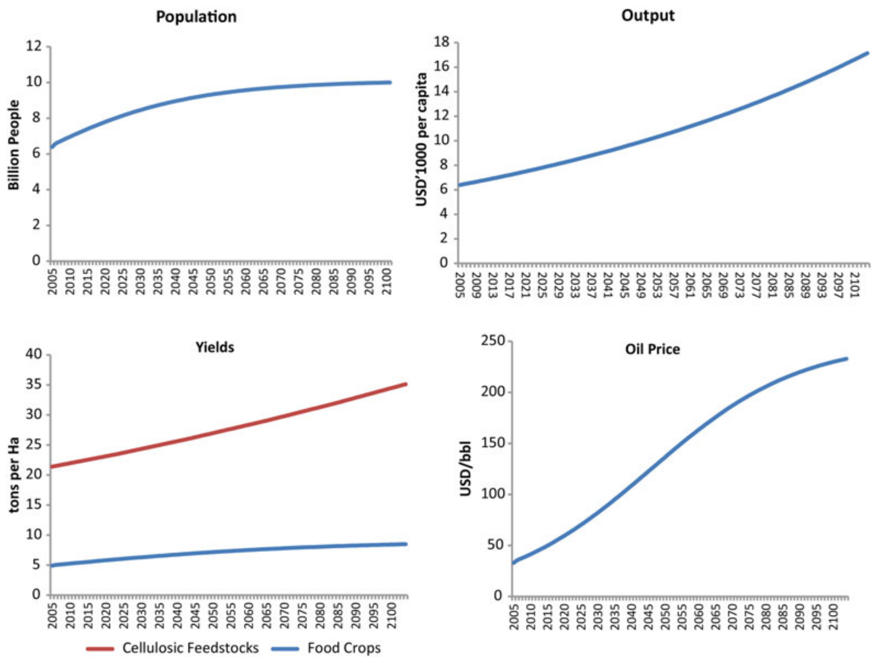
The aggregation of land-based services, as well as the consumption of other goods and services, is based on a global utility function. In choosing a specific functional form to encompass the valuation of land-based services, the extremely long time horizon poses a difficult challenge. While consumers in low income countries today have a fairly high marginal valuation of food (i.e., they devote a significant share of added income to food), this will change as they become wealthier. Towards the end of our time horizon, we expect that the global marginal budget share associated with crop consumption, for example, will approach zero. On the other hand, with the high per capita incomes expected in the 21st and 22nd centuries, we anticipate a much higher valuation of ecosystem services. There are not many demand systems that have the flexibility to represent the transition from the current state of consumption to the expected future state in 2100, for example. One such utility function is AIDADS (Rimmer and Powell 1996). Under pre-specified conditions, AIDADS is also globally well-behaved, which is critical for our long run simulations. In addition, earlier work has demonstrated that AIDADS outperforms other popular empirical models of consumer demand in out-of-sample predictions of international food demand (Cranfield et al. 2002). For these reasons, we choose AIDADS to represent global preferences. We rely on international cross-section estimates of the key parameters, following the approach outlined in Reimer and Hertel (2004). Parameters are provided in the online appendix to Steinbuks and Hertel (2014).

The FABLE model tracks land-based carbon fluxes that stem from a variety of sources, including: fossil fuel combustion (liquid fuels only); deforestation; non-CO_2 emissions stemming from fertilizer applications as well as livestock production, and; forest carbon sequestration as well as CO_2 releases in the wake of forest harvest. We assume that GHG emissions from the first three sources are a linear function of the combustion of fossil fuels and from the current use of commercial lands. Forest sequestration potential is a non-linear function of forest age. Young forest vintages grow quickly and sequester carbon at a rapid rate, while older vintages grow slowly and eventually cease to sequester carbon. Based on these assumptions, we calculate GHG emissions using exogenous conversion factors corresponding to each of these (endogenous) sources. In the baseline, there is no climate regulation. In a separate experiment this is introduced as a time-varying constraint (Steinbuks and Hertel 2014).

The dynamic development of FABLE is driven by exogenously specified drivers of supply and demand as shown in figure 2 and further discussed in Steinbuks and Hertel (2014). These drivers include population growth (based on UN projections) and global GDP projections (driving growth in the rest of the economy). Growth in yields of food crops, forestry, and cellulosic feedstocks for use in 2G biofuels have been specially constructed for this study, as have the rates of growth in efficiency of land-based services. Also exogenous are the cost of fuel extraction and hence oil prices, which are extrapolated based on DOE forecasts to 2040.

The model is solved for the period 2005–2204. However, the analysis presented here emphasizes the first century of results in order to limit the effect of terminal period conditions on our findings. By solving the model first without (the baseline), and then with (the counterfactual) second generation biofuel technology, then differencing the discounted welfare of each solution, we are able to obtain an estimate of the value to society of biofuel technology over the course of the next century. We use our inter-temporal welfare function to discount this stream of benefits to the present, thereby obtaining a single figure representing the value of this technology to society. By varying the characteristics of the 2G production process, we can assess the value of potential improvements in the efficiency of second generation biofuel technology. By altering the exogenous drivers of the baseline (population and GDP growth rates, oil prices, climate impacts, and mitigation policies), we can evaluate the impact of future uncertainty on this valuation of a given type of 2G biofuel technology.

Figure 2 Projections for key exogenous variables in the FABLE baseline



Notes: Population is based on UN projections, aggregate per capita output follows global GDP projections, yield projections are specially constructed for this study and differentiate between crops used for food and first generation biofuels, and cellulosic feedstocks for use in 2G biofuels. Oil prices in the baseline are extrapolated based on DOE forecasts.

Further details about the FABLE model are available in Steinbuks and Hertel (2014).[1]

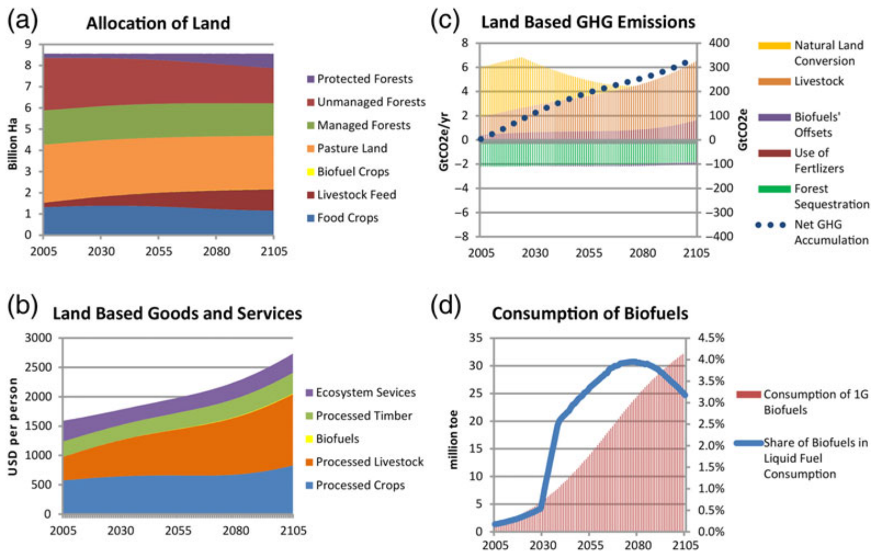
Model Performance and Evaluation

There is no guarantee that FABLE, as a global optimization model, will produce a path of land use that in any way resembles the observed patterns of land use, which are themselves driven by the decisions of hundreds of millions of individual landowners. Therefore, it is important to carefully evaluate the model's performance before using it to evaluate 2G biofuel technology.

Figure 3 depicts the optimal allocation of global land-use, land-based GHG emissions, per capita global consumption of goods and services that draw on land resources, and consumption of first generation biofuels in the model baseline. The baseline assumes the following (recall figure 2): petroleum prices rise over the 21st century according to DOE-EIA reference forecasts, 2G technology is not available, climate impacts are moderate, economic and population growth follow their most likely paths, and there is no climate regulation. In the near term, under this baseline, the area dedicated to food crops increases by 7% compared to 2004, reaching its maximum of 1.4 billion hectares in 2035, and thereafter declines due to

[1] *The complete set of model equations, variables, and parameter values are provided in the technical appendix to that paper, http://static-content.springer.com/esm/art%3A10.1007%2Fs10640-014-9848-y/MediaObjects/10640_2014_9848_MOESM1_ESM.pdf (accessed September 21, 2015).*

Figure 3 Optimal path for (a) global land use, (b) associated services, (c) GHG emissions and (d) biofuels *in the absence of 2G technology*, 2005–2105



slowing population growth (figure 3a). Area dedicated to livestock feed expands by 775 Mha by 2100 as a result of the intensification of rapidly growing livestock production (figure 3c), whereas pasture land declines by 215 Mha. Managed and unmanaged forest areas decline (figure 3a), resulting in significant GHG emissions (figure 3c). Rising real incomes drive a growing demand for ecosystem services over the 21st century (figure 3b). While increasing access costs of natural land, combined with declining demand for food crops, results in a decline in GHG emissions from deforestation by mid-century, net accumulation of GHG emissions increases throughout the century (figure 3c), driven by emissions from the rapidly growing livestock sector. In the absence of 2G biofuels technology, biofuels consumption remains insignificant, taking a mere 3.5% of global liquid fuel consumption in 2100 (figure 3d).

From the standpoint of model evaluation, we are fortunate that the model solution begins in 2004, as this gives us nearly a decade over which to evaluate its performance (2012 data for key variables are available at the time of this writing). A comparison of predicted and observed outputs of land-based products (in physical terms) is reported at the top of table 1. While this perfect foresight model (values for all periods are determined simultaneously) does not exactly reproduce the Food and Agricultural Organization of the United Nation's (FAO) observed food crop production total in the initial year, 2004, it does come close: observed production was 6.5 Giga-tons (GT)—a figure that rose to 7 GT by 2013 FAOSTAT (2015). FABLE starts with a value of 6.01 GT in 2004 and predicts a slightly higher value for crop production (7.1 GT) in 2012. The model also tracks livestock output, animal feed production, and aggregate fertilizer use reasonably well over this period, although the growth in animal feed is overly rapid. While observed timber products barely changed over the 2004–2012 period, the model predicts growth in this variable—driven by rising incomes. On the other hand, as a model seeking to maximize global welfare, FABLE predicts far less first

Table 1 Evaluation of FABLE's performance: 2004–2012

		Actual Values		Predicted Values	
***FABLE* Endogenous Variables**	**Data Source**	**2004**	**2012**	**2004**	**2012**
Physical Products					
Food Crops, Gton	FAOSTAT	6.50	6.98	6.01	7.14
Animal Feed, Gton	USDA FAS PSD	1.01	1.20	0.85	1.20
Livestock, Gton	FAOSTAT	0.95	1.13	0.84	1.08
Fertilizers, Gton	FAOSTAT	0.09	0.12	0.10	0.13
Biofuels, Gtoe	US EIA	0.026	0.076	0.0013	0.0023
Timber Products, Gton	FAOSTAT	1.85	1.83	1.65	1.8
Land Use					
Cropland Cover Area, GHa	FAOSTAT	1.53	1.56	1.53	1.62
Cropland Harvested Area, GHa	FAOSTAT	1.15	1.20	n/a	n/a
Pasture Land Area, GHa	GTAP LU Database / FAOSTAT	3.39	3.36	2.73	2.70
Commercial Forest Area, GHa	GTAP LU Database / FAO FRA	1.62	1.63	1.62	1.61
Unmanaged Natural Land Area, GHa	GTAP LU Database / FAO FRA	2.47	n/a	2.47	2.41
Protected Natural Land Area, GHa	Antoine et al. (2008, p.8, Table 3).	0.21	n/a	0.21	0.21
Total Forest Area, Gha	GTAP LU Database / FAO FRA	4.06	4.03	4.30	4.22

generation biofuel production in 2012 than was actually observed. This is due to the fact that we do not incorporate government mandates. Absent a GHG emissions constraint in our baseline run, higher biofuels output in this baseline simulation would simply serve to reduce welfare. Of course, if we introduced mandates and pre-specified biofuel production in 2012, we would hit this target precisely. However, our interest in this paper is not to assess the impact of mandates per se; rather, we leave biofuel production unconstrained, thereby assessing the value to society of the optimal path of future production. When we make 2G technology available, if the model does not bring this activity into production, then 2G technology will have no added value to society. On the other hand, if 2G technology enters the optimal solution at some future date, then we can assess its social value—as well as the value of prospective improvements in 2G conversion of biomass to energy.

The second block of table 1 reports observed and modeled land use over the 2004–2012 period. This is more difficult, as global land use data are updated less frequently and they are not broken down in the way that FABLE reports them. Furthermore, there are great uncertainties in these observations (Lambin et al. 2013; Dietrich et al. 2014), making validation quite challenging. The most notable feature of the land cover/land use changes observed over the 2004–2012 period is the rise in cropland cover and harvested crop area. Absent changes in multiple cropping intensity and crop failures, we expect these two variables to move together. However, in practice there is a large and poorly understood gap between land cover and harvested area.

Cropland cover is typically generated via remote sensing and cropland harvested area is obtained from census data and national estimates. Managed forests change little in our solution, as well as in the observed data.

In addition to comparing model outputs with observed values over this historical period, it is useful to compare results with those from other models of global land use. Fortunately, the Agricultural Modeling Intercomparison Project (AgMIP) has recently published projections of global land use in 2050 from 10 models (four partial- and six general-equilibrium models) of global agriculture. It should be noted that our model is fundamentally different from all of these other models in that it is fully dynamic, with current land conversion decisions depending not only on what happens this period, but also on expectations of what will happen in the future. Nonetheless, FABLE's projections for global crop land change from 2005 to 2050 fits comfortably in the range of estimates from these other models surveyed by Schmitz et. al. (2014). Our results are very close to the GCAM (Wise et. al. 2011) and GLOBIOM (Havlík et. al. 2011) model results. The baseline decline in pasture land is consistent with the predictions of the AIM (Fujimori et. al. 2012), GCAM, and EPPA (Paltsev et. al. 2005) models. None of these models includes demand for natural lands for recreational purposes—a point highlighted by Antoine, Gurgel, and Reilly (2008) who report results of U.S. land cover change. However, the pattern in our global results for ecosystem services demand are consistent with the outputs from the latter analysis. Based on these comparisons we conclude that our model is appropriate for long run analysis of the land use impacts of second generation biofuels technology at global scale—the focus of our present work.

A final, important dimension of model evaluation for this paper pertains to its valuation of current services provided by the world's land resources. Here, we do not have global observations with which to compare FABLE's estimates. Instead, we utilize the imputed land rents reported in the 2004 GTAP database (Narayanan et al. 2012) of globally aggregated agriculture and forestry activities. These are obtained by multiplying region- and sector-specific land shares in costs by GTAP estimates of sectoral costs. In the version 7 GTAP database, with a reference year of 2004, the global valuation of these commercial lands is \$347 billion. Assuming a 1.5% rate of social discount, and assuming that this stream of valuation applies over a FABLE horizon of the next 200 years, we obtain a net present value of \$22,029 billion. Dividing by the 2004 population of 6.4 billion people yields a per capita valuation of \$3,442/capita. We use this as a target for calibrating the value of services from the world's land resources under the FABLE model baseline. The remainder of this paper focuses on how future uncertainty in 2G biofuels technology as well as economic growth, climate impacts, energy prices, population growth, and GHG regulation alters this societal valuation of services provided from the world's land resources.

Characterizing Improvements in 2G Biofuels Technology

While there are several types of 2G technologies vying for attention presently, we focus here on *fast pyrolysis*, a process in which the biomass feedstock is rapidly heated and converted into bio-oil. This oil is further processed in the presence of a catalyst and hydrogenated to ultimately produce a range of "drop-in" hydrocarbons including gasoline, diesel, and jet fuel. Valuation of 2G biofuels within FABLE depends critically on the expected cost of production that may be influenced by future R&D as well as learning by doing. We draw on recent literature (Brown and Brown 2013a; Brown and Brown 2013b), replicating the Brown et al. (2013) analysis of fast pyrolysis (Petter and Tyner 2014) for the Nth plant, which is common in the engineering economic literature. Because we want to base our analysis on a 2013 starting point, we increase the capital cost in the Brown et al. analysis by 20% to approximate the cost of a plant built today. We then take the net present value of all costs and calculate the breakeven cost and cost breakdown for a plant to be built today.

Our estimate of the breakeven cost for this technology for a plant constructed today is equivalent to $110/barrel crude oil. However, the degree of uncertainty is very high and so firms considering the risk-profit tradeoff likely will require a higher expected net present value for a biofuels investment than for a conventional fossil fuel investment. For example, Petter and Tyner (2014) do a techno-economic analysis of a fast pyrolysis plant incorporating uncertainty in feedstock prices, conversion efficiency, hydrogen prices, and future crude oil prices. The future crude oil price was by far the greatest source of uncertainty. These authors' stochastic analysis with increasing fossil fuel prices yields a mean net present value (NPV) for the plant of $80 million. However, the NPV standard deviation is $76 million, highlighting the considerable uncertainty surrounding investor returns in this technology. This uncertainty is exacerbated by the recent improvements in shale oil and gas technology. As a consequence of these advances, North America is projected to be energy independent by 2030 (IEA 2012), and the increased supplies could put downward pressure on world crude oil prices. For example, the U.S. Department of Energy Annual Energy Outlook includes a low crude oil price scenario in which the oil price is flat at $75 through 2040 (U.S. Energy Information Administration 2013). So even if the biofuel technology is today within 10–20% of fossil fuel prices, that does not mean we will see substantial investment until the cost comes down more (MASBI 2013).

To get a better idea of the potential for cost reductions in thermochemical biofuel production, we first determine the cost breakdown for current technology (table 2; Petter and Tyner 2014). Capital is estimated to represent 34% of total cost, feedstock 33%, hydrogen 20%, and other operating costs 13%. Of these, capital and feedstock represent the best possibilities for cost reduction. If we assume that Brown's capital cost estimate is the cost achievable for the Nth plant (as opposed to the first few commercial scale facilities), then we can expect to lower capital costs by 20%, which reduces total costs by about 7%. This would drop the breakeven oil price from $110 to $102.50. These gains are solely due to increased experience with the

Table 2 Cost Breakdown for Fast Pyrolyis Biofuel Production

Cost component	Percent	Potential Cost Reduction
Capital cost	34	20
Feedstock	33	25
Hydrogen	20	5
Other operating costs	13	0
Total	100	16

Source: Petter and Tyner (2014).

facilities. But they will not be achieved if the industry remains at the pilot project level of production.

The other strong candidate for cost reduction resides in the feedstock costs which, like capital costs, are currently estimated to account for about one-third of total cost for fast pyrolysis biofuel production. All of the cost estimates today are done using equipment originally designed for hay or similar crops. With the development of a biofuel feedstock industry, we expect to see development of specialized, more efficient equipment for harvesting corn stover, switchgrass, and similar cellulosic feedstocks. In addition, our model baseline projects higher crop yields in the future, which in turn translates into higher yields for the corn stover by-product—a key cellulosic feedstock in the U.S. Corn Belt. Higher feedstock yield per hectare reduces feedstock cost per ton. If the combination of higher feedstock yield and more efficient feedstock harvest and storage resulted in a 25% reduction in feedstock cost, which is quite plausible, then that would reduce the breakeven crude oil price by a further 8%.

Hydrogen is a key ingredient in many refining and chemical processes, and research has been underway for years to reduce its associated costs, but with limited success. Thus, getting future cost reductions in hydrogen will likely be more difficult than for cellulosic feedstocks and capital. If we assume a modest 5% reduction in hydrogen costs, which currently comprise about one-fifth of total costs, then that would reduce the breakeven cost by another $1, or about 1%.

In our view, significant reductions in other operating costs are not likely. Labor is a large component of these other costs, and labor costs are expected to be driven by factors outside the biofuel sector. Leaving other costs unchanged, we believe that it is quite reasonable to project a cost reduction in biomass-based hydrocarbons from $110 today to $93/barrel crude oil equivalent, or a 16% drop from 2013 levels. In summary, the total expected decline in cost, under the improved technology scenario, is 16%, with half of that being capital cost and hydrogen, and the other half being associated with the cost of feedstock. We treat this cost reduction scenario as the optimistic technology case.

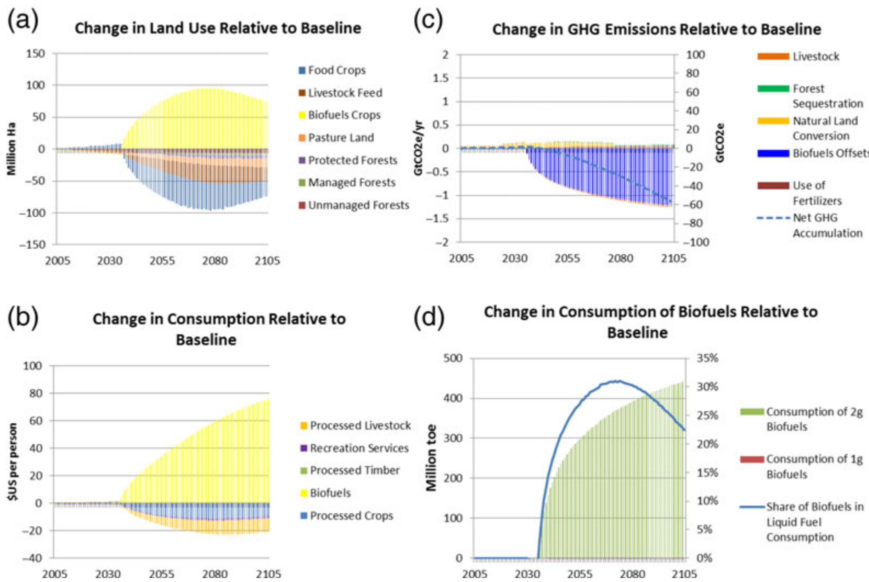
In addition to the cost reduction scenario, we also evaluate a more pessimistic case in which second generation biofuel costs are increased by the same amount (16%) as the decrease described above. This case is plausible due to the fact that realized costs in infant industries are often higher than engineering estimates. In the case of biofuels, this could be because of inability to achieve the projected biomass conversion rates and higher than expected capital, hydrogen, and feedstock costs.

Results

Baseline Results

Introducing 2G biofuels technology significantly alters the optimal paths for global land use, GHG emissions, the path of land-based consumption, and also biofuels' market share, over the course of the next century (figure 4 and table 3). When we modify the baseline by allowing 2G biofuels to enter the production mix, in the absence of subsidies or mandates, and without further technological improvements, 2G biofuels do not enter into commercial production until 2035 (figure 4d). At that point, cellulosic feedstock area expands, forcing other land uses to contract (figure 4a and table 3).

Figure 4 Deviation in optimal path for (a) global land use, (b) associated services, (c) GHG emissions, and (d) biofuels due to the presence of current 2G technology, 2005–2105



Note: Results obtained by solving the FABLE model twice, once without the technology and once with 2G biofuels present, and subtracting the first from the second set of results (see also table 3).

Table 3 Impact of 2G Biofuels Technology on Global Land Use and Land-based Services in 2100: Deviations from Baseline Scenario for Land use Consumption and GHG emissions

Sector	Land Use (MHa)	Consumption ($US per capita)	Net GHG emissions ($MtCO_2e$)
Food Crops	−27.5	−9.8	61
Biofuels	79.0	73.1	−1,198
Livestock	−36.5	−10.1	−43
Timber	−6.0	0.0	22
Ecosystem Services	−9.0	−1.6	0

Source: Authors calculations (see also figure 4).

Increased competition for land resources translates into reduced consumption of food, timber, and ecosystem services from land (figure 4b and table 3), while the introduction of 2G biofuels, as a cheaper drop-in alternative to petroleum products, boosts consumption of energy services, with biofuels accounting for nearly one-third of global liquid fuel consumption by 2100 (figure 4d and table 3). The presence of 2G biofuels increases GHG emissions up to 2047 due to increased deforestation—an anticipatory outcome that begins prior to the arrival of commercially viable 2G biofuels. This is a direct result of the forward-looking nature of our model, which captures the fact that land owners' long run investment decisions depend not only on current conditions, but also on expected future developments in technology, demands, and oil prices. This medium-term rise in GHG emissions notwithstanding, by 2100 the flow of annual emissions from land-based activities is 1,160 MtCO2e/yr below the baseline (table 3) indicating that, by this point in time, the displacement of fossil fuels by bio-based fuels reduces GHG emissions.

The global value of existing 2G technology is estimated to be \$10.03/capita, or \$64.2 billion in USD at 2004 prices and population levels (see table 4, baseline technology and drivers, as well as figure 5, grey circle in the first bar). Under this baseline scenario, nearly all of the gross societal benefits are generated by reduced petroleum costs (figure 5, blue segment). However, focusing solely on this change would be seriously misleading from the point of view of overall net societal benefits. Heightened competition for land in the presence of 2G biofuels affects land rents, thereby boosting the cost of producing other land-based services, including crops, livestock, forestry products, and other ecosystem services. This reduces consumption levels (figure 5, green component). It also encourages additional land conversion, which is itself costly. Finally, because the introduction of 2G technology encourages additional conversion of land for biofuel feedstocks, it reduces the amount of forests and natural lands remaining at the end of the model's planning horizon. This diminishes the value of society's "bequests" for future generations, which in turn also diminishes the total value of 2G technology to society (figure 5, light blue component).

Impact of Alternative States of the World

The valuation of current 2G technology is highly dependent on the "state of the world" prevailing throughout the 21st century (see columns 2–6 in table 4, as well as additional bars in figure 5). We explore these alternative states of the world by incorporating them into a modified baseline and also into the model simulation with 2G biofuels present. As with the baseline "state of the world", the difference between the valuation of global land resources in these two simulations gives a revised measure of the value of 2G biofuels to society. If there is little interaction between the modified state of the world and 2G biofuels, we expect little difference in this valuation, compared to our baseline valuation, with and without the technology. However, in those cases where the alternative state of the world does interact with 2G biofuels, both the total and the component parts of this social valuation will be different.

Stronger climate change impacts on agriculture could lead to a significant drag on productivity growth for the world's food crops (Lobell, Schlenker, and Costa-Roberts 2011; Rosenzweig et al. 2013). We implement the slower crop yield growth rates (Rosenzweig et al. 2013) in the first alternative to our baseline, but do not alter the yields of cellulosic feedstocks, which are likely robust to temperature rises (Brown et al. 2000). More cropland is required to meet global food demand, given lower food crop yields, which raises the cost of land for biofuels production and slightly diminishes the amount of biofuel produced. However, the difference in welfare due to the presence of 2G technology is little affected (see Climate Impacts column in table 4: \$9.98/capita vs. \$10.03/capita under baseline technology).

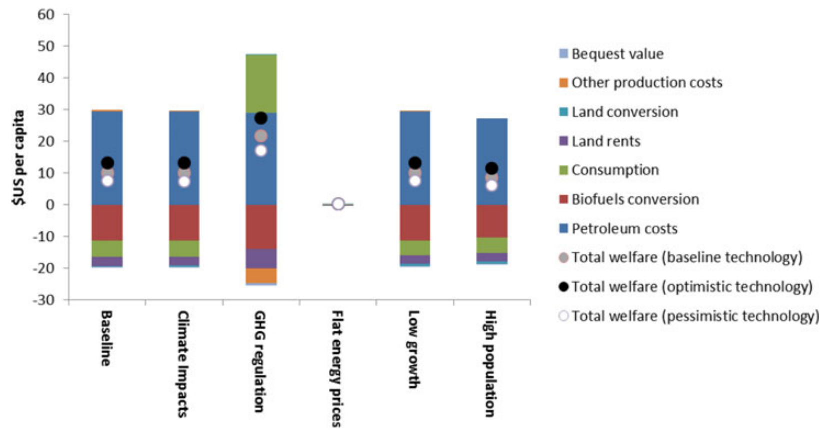
In contrast, there is strong interaction between climate regulation and 2G biofuels valuation. In our baseline there are substantial GHG emissions associated with land using activities (figure 3c), including carbon fluxes from land conversion, nitrous oxide emissions from fertilizer applications, and methane emissions from livestock and rice production. There are also

Table 4 Valuation of 2G Biofuel Technology under Alternative Future Scenarios ($bill. 2004)

	Alternative States of the World					
	1	**2**	**3**	**4**	**5**	**6**
Per capita basis ($) Technology	Model Baseline	Climate Impacts	GHG Regulation	Flat Energy Prices	Low Growth	High Population
Pessimistic	7.49	7.44	17.18	0.25	7.55	6.19
Baseline	**10.03**	**9.98**	**21.76**	**0.25**	**10.14**	**8.54**
Optimistic	13.14	13.08	27.23	0.25	13.28	11.45
Total Gains ($Billion) Technology	Model Baseline	Climate Impacts	GHG Regulation	Flat Energy Prices	Low Growth	High Population
Pessimistic	47.9	47.6	109.9	1.6	48.3	39.6
Baseline	**64.2**	**63.9**	**139.3**	**1.6**	**64.9**	**54.7**
Optimistic	84.1	83.7	174.2	1.6	85.0	73.3

Source: Authors calculations obtained by running FABLE twice. We subtract the baseline (no 2G) outcome from the case with 2G technology available. The optimistic scenario refers to the case wherein costs are 18% below baseline, while the pessimistic case assumes 2G costs end up 18% above baseline.

Figure 5 Valuation of 2G biofuel conversion technology in $/capita



Notes: Values on the y-axis correspond to the difference in global per capita welfare and were obtained by solving the FABLE model twice: once without the technology and once with it present. The difference obtained by subtracting the second set of results from the first is the value of current 2G technology (square markers) or improved 2G technology (circle markers) under four alternative sets of baseline assumptions. Colored components refer to the sources of welfare change under current technology.

important opportunities for GHG mitigation, including forest carbon sequestration, avoided deforestation, and the replacement of gasoline by 2G biofuels. When GHG emissions targets are introduced into the optimization problem, emissions mitigation takes on economic value, thereby shaping global land use decisions. In the climate regulation scenario, we introduce an aggressive target: a 60% reduction in baseline, land-based GHG emissions. After the target is introduced in 2025, it rapidly becomes more severe, reaching the maximum stringency by 2050. This 60% reduction, if matched by reductions in other GHGs not modeled here, corresponds to the contributions necessary to achieve GHG concentration stabilization between 445–490 ppm (Solomon et al. 2008).

This policy of land-based climate regulation has several important effects on the optimal path for global land use. Firstly, it increases the social value of forests, introducing a disincentive for their conversion to agricultural uses. This raises the cost of land in food and biofuel production. All of this contributes to higher costs for food, forest, and ecosystem goods and services—highlighting the tradeoff between GHG emissions and consumption. Into this environment of constrained land and consumption we introduce 2G biofuels, permitting some of the targeted GHG reduction to be achieved via substitution of cellulosic biofuels for petroleum products. With 2G technology present, this frees up room under the GHG constraint for additional land conversion, fertilizer use, etc., thereby boosting consumption of land-based goods and services (figure 5: GHG regulation/green component). As a consequence, 2G technology is worth more than twice as much to society under climate regulation than in its absence, raising the global gains to nearly $22/capita, with a total value of $139 billion at 2004 population levels.

We also evaluate the social benefits of 2G biofuels in the context of flat oil prices over the course of the 21st century. This alternative to the baseline scenario is motivated by the emergence and application of new technologies for extracting shale oil and gas, which raises the specter of energy abundance and a reversal of the recent trend of rising oil prices. Indeed, as we write this paper, oil prices have fallen to about \$60/bbl. In this case, 2G biofuel technology has almost no economic value to society (table 4, column 4).

Finally, we consider how global rates of economic and population growth interact with the valuation of 2G biofuel technology. The results from running these alternative scenarios first without, and then with 2G biofuels technology, are reported in columns 5 and 6 of table 4. Low rates of economic growth serve to diminish the rate at which land rents rise over time. With land relatively less scarce, the land-using 2G biofuels technology faces less competition and therefore becomes a bit more valuable than under the baseline rate of economic growth (\$10.14 vs. \$10.03/capita). The same principle applies in the case of high population growth—only this time working in the opposite direction. With population growing more rapidly than under the baseline scenario, there are more people to feed and house and land becomes scarcer. Therefore, the 2G technology, which requires land in order attain value, is less beneficial to society, with the net social benefits dropping to \$8.54/capita in the case of rapid population growth.

Considerable public investments are currently being undertaken to improve 2G technology (Haq 2013). As noted above, we estimate that total cost reductions of 18% could potentially be achieved in the context of commercialization and added investment in the sector (table 2). This is our "optimistic" technology scenario shown in the third row of each block of table 4 (see also the black dots in figure 5). When this technological future is present, the global land area allocated to second generation biofuels in 2100 rises by nearly 10 Mha, and liquid fuel penetration rises by an additional 5% by 2100. These technological enhancements contribute roughly 30% more (about \$20 billion at 2004 population) to the social valuation of 2G technology. On the other hand, if the technology pessimists are correct, and the 2G pilot technology does not scale up effectively, the global valuation of 2G technology could be less than projected. In our pessimistic case, with projected costs 18% higher than baseline, the social valuation of 2G technology is about just \$7.49/capita or \$47.9 billion at 2004 population (table 4 and figure 5).

Conclusions and Policy Implications

Private investors are currently reluctant to invest in second generation biofuel technology at a large scale due to the enormous uncertainty in future oil prices (Petter and Tyner 2014). We find that the same sensitivity to future oil prices exists when it comes to the evaluation of societal benefits from 2G biofuel technology. Indeed, in a world of flat oil prices, and in the absence of very significant cost reductions, there is no social benefit to further improvements in this technology. Furthermore, the magnitude of societal benefits depends critically on future climate regulation. In the context of aggressive climate regulation, improved technology boosts the global valuation of 2G biofuels to as much as \$174 billion in today's economy, assuming oil prices, population, and economic growth follow baseline projections. This represents roughly a 0.8% increase in the value of all land-based services provided to society globally. When these two alternative scenarios—low oil prices *and* climate regulation—are combined, the former dominates and 2G biofuels continues to have no social value. This derives from the fact that, when oil is cheap, rather than mitigating through the replacement of fossil fuels, the optimal strategy is to use the land for carbon sequestration instead of biofuel feedstock production.

If one believes in the future states of the world which give rise to significant societal benefits from 2G biofuels (rising oil prices, climate regulation and slowing economic and population growth rates), the question arises: how can this technology be encouraged? One means of developing 2G technology is getting biofuel plants built and learning through that process how to make further improvements in the technology. That is what happens in the development process of many new technologies. Petter and Tyner (2014) conclude that using a policy instrument such as a reverse auction could be an effective means of getting biofuel plants built and under operation, thereby accelerating the pace of technology development. In a reverse auction, firms bid for the right to produce and sell a stipulated quantity of product to an entity such as the government or military over a period of years. For example, the U.S. Navy could put out a reverse auction invitation requesting bid for 50 million gallons per year of jet fuel for 15 years. Firms would then bid for that contract, with the lowest qualified bidder winning (hence the name reverse auction). This approach entirely eliminates future crude oil price uncertainty because the bid price becomes the contract price. This policy approach is one way of stimulating development of the 2G biofuels industry by government. In essence, it transfers risk from the private to the public sector—a step which may be justified under those future states of the world in which the 2G technology is shown to have large societal benefits.

Such potential benefits notwithstanding, our findings highlight the fact that estimates of the net social benefits of 2G technology must go beyond displaced petroleum and conversion costs. Aggressive expansion of cellulosic biofuels will have broader impacts, including increased land rents and land conversion costs, reduced consumption of other land-based goods and services, and reductions in natural forests and protected lands left for future generations. Having considered these, we find that, should oil prices resume their upward trend later in the century, and if climate regulation becomes a policy priority, then access to improved technology could deliver significant benefits to society.

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