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What Is the Social Value of Second-Generation Biofuels?

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Abstract

What is second-generation biofuel technology worth to global society? A dynamic, computable partial equilibrium model (called FABLE) is used to assess changes in global land use for crops, livestock, biofuels, forestry, and environmental services, as well as greenhouse gas emissions, with and without second-generation biofuels technology. The difference in the discounted stream of global valuations of land-based goods and services gives the value of second-generation technology to society. Under baseline conditions, this to amounts to $64.2 billion at today's population or an increase of roughly 0.3 percent in the valuation of the world's land resources. This gain arises despite the fact that, in the baseline scenario, the technology does not become commercially viable until 2035. Alternative scenarios considered include: diminished crop yield growth owing to adverse climate impacts, flat energy prices, low economic growth, and high population growth, as well as greenhouse gas regulation. The most important factor driving second-generation valuation is greenhouse gas regulation, which more than doubles the social value of this technology. Flat energy prices essentially eliminate the value of second-generation technology to society, and high population growth reduces its value because of the heightened competition for land for food production.

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Introduction

Commercial scale implementation of second-generation (2G) biofuels has long been 'just over the horizon – perhaps a decade away'. However, with recent innovations, and higher oil prices, 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 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 which 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 in press). By running the model twice – once with 2G technology available, and once without, 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 GHG regulation, which, when present, doubles the value of this technology. 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%. The flat energy price scenario, reflecting an abundance of fossil fuels supply, relative to demand, nearly eliminates the value of 2G technology to society. On the other hand, slower economic and population growth rates boost the value of 2G technologies due to the diminished competition for land with food, forest and environmental services production.

1. Methods

1.1 Overview of the FABLE Model

The FABLE model brings together recent strands of the agronomic, economic, and biophysical literature into a single, intertemporally consistent, analytical framework, at global scale. The model is a perfect foresight, discrete time, dynamic, finite horizon partial equilibrium model of global land use. Income, population, wages, oil prices, total factor productivity, and other variable input prices are assumed to be exogenous. The model seeks to determine the optimal allocation of scarce land across competing uses and across time. As such, it reflects incentives faced by forward-looking, profit-maximizing investors, as well as their responses to alternative states of the world, including climate change, population and economic growth, GHG emissions polices and energy prices.

Figure 1 summarizes the structure of FABLE (Steinbuks and Hertel 2013; Steinbuks and Hertel in press). The model includes ten sectors producing intermediate and final goods and services, including: agrochemicals, crops, feedstuffs, livestock products, other processed food, biofuels, energy, forestry, timber processing, and ecosystem services. There are two natural resources in the model: land and fossil fuels (the latter encompassing oil and natural gas). The supply price of fossil fuels follows an exogenous path. The supply of land is fixed and faces competing uses that are determined endogenously by the model. We distinguish between five types of land: 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. Institutionally protected lands require resources to be maintained and include natural parks, biodiversity reserves and other types of protected forests. These lands are best used to produce ecosystem services for society and, once protected, we assume they can no longer be converted to commercial use. Commercial lands, on the other hand, are available for use in either the agriculture or forestry sectors. Agricultural lands may be used as pasture for livestock, cropland to grow food crops or second-generation biofuel feedstocks.

The biofuels sector converts agricultural products into liquid fuels, which substitute for petroleum products. We consider two types of liquid biofuels: first-generation biofuels (e.g., corn-based ethanol), which substitute imperfectly for petroleum in final demand, and second-generation biofuels (e.g., cellulosic biomass-to-liquid diesel obtained through fast pyrolysis), which offer a ‘drop-in’ fuel alternative. The energy sector combines petroleum products with first- and second-generation biofuels, and the resulting mix is further combusted to satisfy the demand for energy services. The agrochemical sector converts fossil fuels into fertilizers that are used to boost yields in the agricultural sector. The farm sector combines cropland and fertilizers to produce agricultural output that can be used to produce food or biofuels. The food-processing sector converts agricultural output into food products that are used to meet global food demand. The forestry sector produces an intermediate product, which is further used in timber processing. The timber-processing sector converts output from the forestry sector into a final timber product, which satisfies commercial demands for lumber and other wood products. The ecosystem services sector combines different types of land to produce terrestrial ecosystem services. The production of non-land based goods and services is exogenous and drives the overall rate of income growth in the global economy.

The societal objective function being maximized in FABLE places value on processed food, energy services, timber products, and ecosystem services. The specific functional form for the utility function is based on implicitly directive additive preferences, AIDADS (Rimmer and Powell 1996). Our choice of the utility function based on AIDADS preferences is motivated by its important advantages over many other functional forms underpinning standard models of consumer demand. For example, the AIDADS model is flexible in its treatment of income effects, allowing for greater expenditures on land based “luxury” goods, such as ecosystem services, as the global economy grows. Under pre-specified conditions, it is also globally well-behaved, which is critical for our long run simulations.

GHG emissions in the model result from a number of sources: (a) combustion of petroleum products, (b) the conversion of unmanaged and managed forests to agricultural land (deforestation), (c) non-CO2 emissions from use of fertilizers in agricultural production as well as from livestock, and (d) net GHG sequestration through forest sinks (which includes the GHG emissions from harvesting forests). We calculate GHG emissions using exogenous conversion factors corresponding to each of these (endogenous) sources. In the baseline, there is no climate regulation, which is introduced in a separate experiment as a time-varying constraint (Figure 2). Exogenous drivers of global land use include: population growth, oil prices, climate change, and technological progress, which captures yield improvements in agriculture and forestry, and more efficient use of services from the food and timber processing, energy, and recreation sectors.

By solving the model first without, and then with 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 intertemporal welfare function to discount this stream of benefits to the present, thereby obtaining a single value 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.

FABLE model equations, variables, and parameter values are provided in the model's technical documentation (Steinbuks and Hertel 2012; Steinbuks and Hertel in press).

1.2 Model Performance and Evaluation

There is no guarantee that FABLE, as a global optimization model, will produce a path of land use which 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 biofuels in the model baseline. The baseline assumes the following: petroleum prices rise over the 21st century according to DOE-EIA reference forecasts, 2G technology is available, climate impacts are moderate, economic and population growth follow their most likely paths, and there is no climate regulation (Fig. 2). In the near term, under this baseline, area dedicated to food crops increases by 7 percent compared to 2004, reaching its maximum of 1.4 billion hectares in 2035 and thereafter declines due to slowing population growth (Fig. 3a). Area dedicated to livestock feed expands by 750 Mha by 2100 as a result of the intensification of rapidly growing livestock production (Fig. 3c), whereas pasture land declines by 230 Mha. Managed and unmanaged forest areas decline, resulting in significant GHG emissions (Fig. 3c). Rising real incomes drive a growing demand for ecosystem services over the 21st century (Fig. 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, driven by emissions from the rapidly growing livestock sector. Under the baseline oil price scenario, 2G biofuels become a significant share of global fuel consumption in 2100 (Fig. 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 observed FAO's food crop production total in the initial year, 2004, it comes close. Observed production was 6.5 Giga-tons (GT) – a figure which rose to 7 GT by 2013. 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 biofuel production in 2012 than was actually observed. This is due to the fact that we do not reflect the presence of government mandates. Absent a GHG emissions constraint in our baseline run, higher biofuels output 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 seek to leave biofuel production unconstrained and thereby assess the value to society of the optimal path of future production. If the model does not bring 2G biofuels into production, then this technology will have no added value to society. On the other hand, if it brings in 2G production at some future date, then we can assess the value of this technology – as well as 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 values (Lambin et al. 2013; Dietrich et al. 2014), making such validation exercises 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 would expect these two variables to move together. However, in practice there is a large, and poorly understood, gap between these two observations, with cropland cover typically generated via remote sensing and cropland harvested area obtained from census data and national estimates. Managed forests are little changed – both in observations and in the model output.

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 Inter-comparison Project (AgMIP) has recently published the 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 (including assumptions about the evolution of 2G biofuel technologies). 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 (Havlik et al. 2011) model results. Our baseline decline in pasture land is consistent with the predictions of 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 to US land cover change. However, the patterns in our global results for ecosystem services demand are consistent with the outputs from their analyses. Based on these comparisons we can conclude that our model is appropriate for use in the valuation of second-generation biofuels technology at global scale – the focus of our present work.

A final, important dimension of model validation 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) 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 reference year 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 the 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. We use this as a target in 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 valuation to society.

1.3 Characterizing Improvements in 2G Biofuels Technology

Valuation of 2G biofuels within FABLE depends critically on the expected cost of production which may be influenced by future R&D as well as 'learning by doing'. We draw on recent literature (T. R. Brown and Brown 2013b; T. R. Brown and Brown 2013a), replicating the Brown et al. (2013) analysis of fast pyrolysis (Petter and Tyner 2014) for the N^{th} 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 percent 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. This is particularly the case in light of the substantial technical gains recently achieved in shale oil and gas technology. 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 US DOE Annual Energy Outlook includes a low crude oil price case 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 percent 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 percent of total cost, feedstock 33 percent, hydrogen 20 percent, and other operating costs 13 percent. 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 lower capital costs by 20%, which reduces total costs by about 7%. This would drop the breakeven from $110 to $102.50. These gains are solely due to increased experience with the 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, currently are 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, or similar crops. 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 US 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 percent 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 these costs, but with limited success. And so getting future cost reductions in hydrogen will likely be more difficult than for cellulosic feedstocks and capital. If we assume a modest 5 percent reduction in hydrogen cost, which currently comprises about one-fifth of total costs, then that would reduce the breakeven cost 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 percent drop from 2013 levels. Thus, 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 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 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, capital costs higher than expected, hydrogen costs higher than projected, or higher feedstock costs.

2. Results

Baseline Results: Introducing 2G biofuels technology sharply alters global land use, GHG emissions, the path of land-based consumption and also biofuels' market share over the course of the next century (Fig. 4). 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.

Under our baseline scenario, in the absence of subsidies or mandates, and without further technological improvements, 2G biofuels do not enter into commercial production until 2035 (Fig 4d). At that point, cellulosic feedstock area expands, forcing other land uses to contract (Fig 4a). Increased competition for land resources translates into reduced consumption of food, timber and ecosystem services from land (Fig. 4b), 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 2080 (Fig. 4d). The presence of 2G biofuels *increases* GHG emissions up to 2047 due to increased deforestation – an anticipatory outcome which begins prior to the arrival of commercially viable 2G biofuels. However, by 2100, the flow of annual emissions from land-based activities is 1,300 MtCO2e/yr. below the baseline (Fig. 4d) 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 \$US at 2004 prices and population levels (Table 3, baseline technology and drivers, as well as Fig.5, grey circle in the first bar). Under this baseline scenario, nearly all of the societal benefits are generated by reduced petroleum costs (Fig. 5, blue segment). However, heightened competition for land affects land rents and thereby boosts the cost of producing other land-based services, including crops, livestock and forestry products and ecosystem services. This reduces consumption levels (Fig. 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 left at the end of the model's planning horizon. This diminishes the value of society's 'bequests' for future generations which also diminishes the total value of 2G technology to society (Fig. 5, light blue component).

Impacts of Alternative States of the World: The valuation of current 2G technology is highly dependent on the 'state of the world' throughout the 21st century (see columns 2 – 6 in Table 3). 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), but do not alter the yields of cellulosic feedstocks which are likely robust to temperature rises (R. A. 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, total welfare is little affected (Climate Impacts column in Table 3: $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 (Fig. 3c) including: carbon fluxes from land conversion, nitrous oxide emissions from fertilizer applications, and methane emissions from livestock and rice production. There are also important opportunities for GHG mitigation, including forest carbon sequestration, avoided deforestation and the replacement of gasoline with 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: 60% reduction in baseline GHG emissions. This corresponds to the contributions necessary to achieve GHG concentration stabilization between 445-490 ppm (Solomon et al. 2008). After the target is introduced in 2025, it rapidly becomes more stringent, reaching the maximum stringency by 2050.

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: climate regulation/green component). Overall, current 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 $139.30 at 2004 population levels.

We also value 2G biofuels in the context of flat oil prices over the course of the 21st century. The emergence and application of new technologies for extracting shale oil and gas raises the specter of energy abundance and a reversal of the recent trend of rising oil prices. In this case, 2G biofuel technology has almost no economic value to society (Table 3, column 4).

Finally, we consider how global rates of economic and population growth interact with the valuation of 2G biofuel technology. These results are reported in columns 5 and 6 of Table 3. 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 biofuel technology faces less competition and therefore becomes somewhat more valuable than under the baseline rate of economic growth (\$10.14 vs. \$10.03/capita). And 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 valuable to society, dropping to \$8.54/capita in the case of rapid population growth.

Impacts of Alternative 2G Technologies: Considerable investments are currently being undertaken to improve 2G technology (Haq 2013). As noted above, we estimate that total cost reductions of 18% could be potentially achieved (Table 2). This is our 'optimistic' technology scenario shown in the third row of each block of Table 3. As a consequence, 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 percent 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 costs 18% higher than baseline, the social valuation of 2G technology is about just \$7.49/capita or \$47.9 billion at 2004 population.

3. 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 societal benefits. Indeed, in a world of flat oil prices, 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. Clearly, in any future except the worst cases evaluated here, policies to invest in research to improve the biofuel technologies would have a high payoff. The magnitude of this policy payoff is significantly increased if policy makers get serious about controlling GHG emissions.

Our findings also highlight the fact that estimates of the 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 access to improved technology could deliver significant benefits to society – particularly in the context of a world in which climate mitigation is a high priority.

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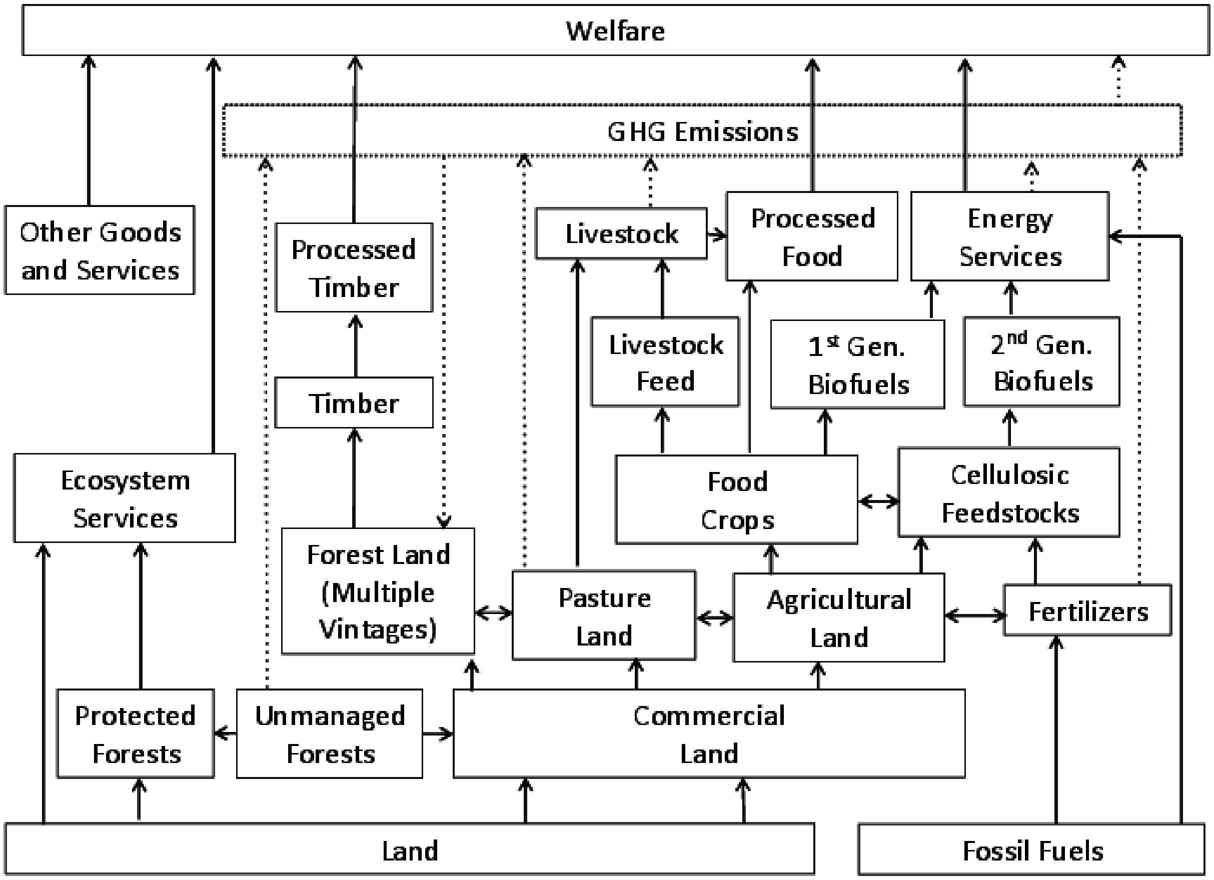


Figure 1. Structure the FABLE model. This figure depicts key flows of goods and services from the two natural resources in the model: land and fossil fuels, to households (welfare).

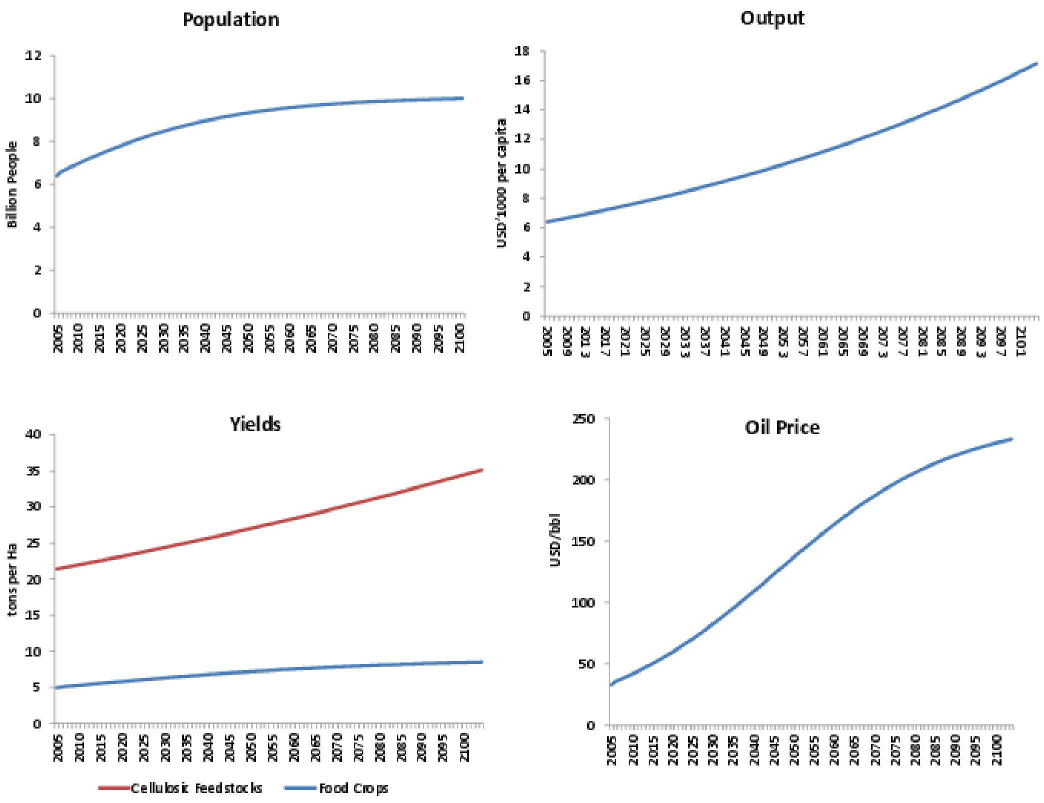


Figure 2. Projections for key exogenous variables in the FABLE baseline. Population is based on UN projections, aggregate per capita output follows global GDP projections, yield projections are specially constructed for this study, and oil prices are extrapolated based on DOE forecasts.

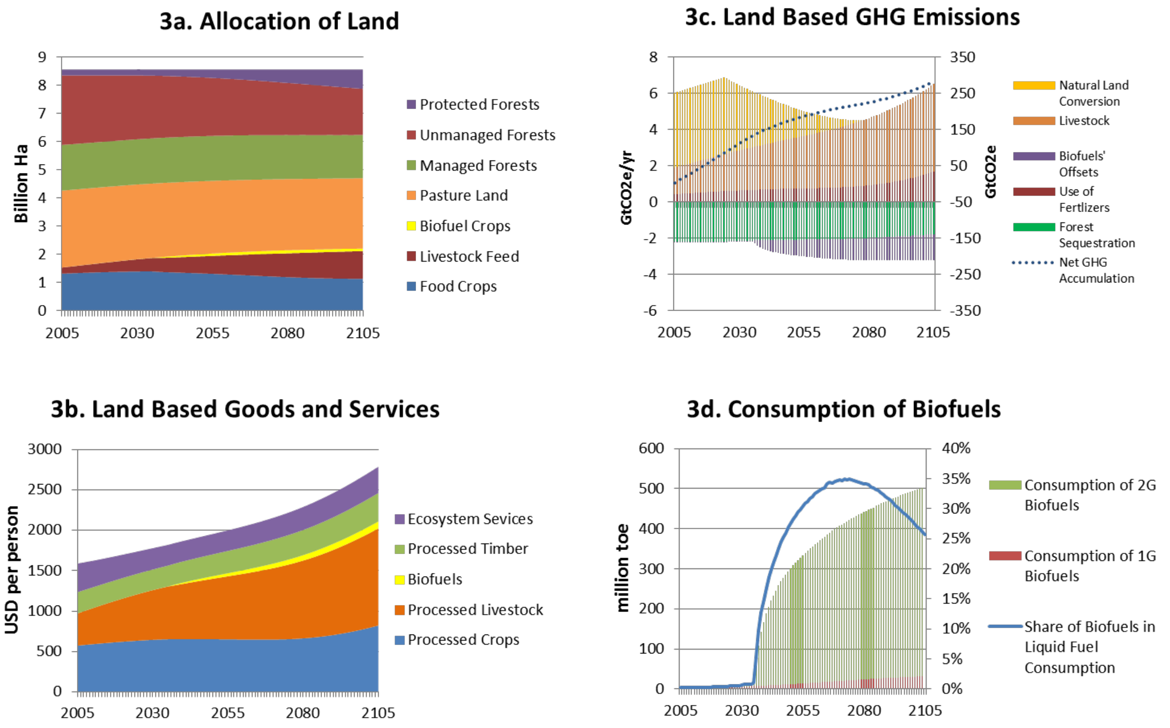
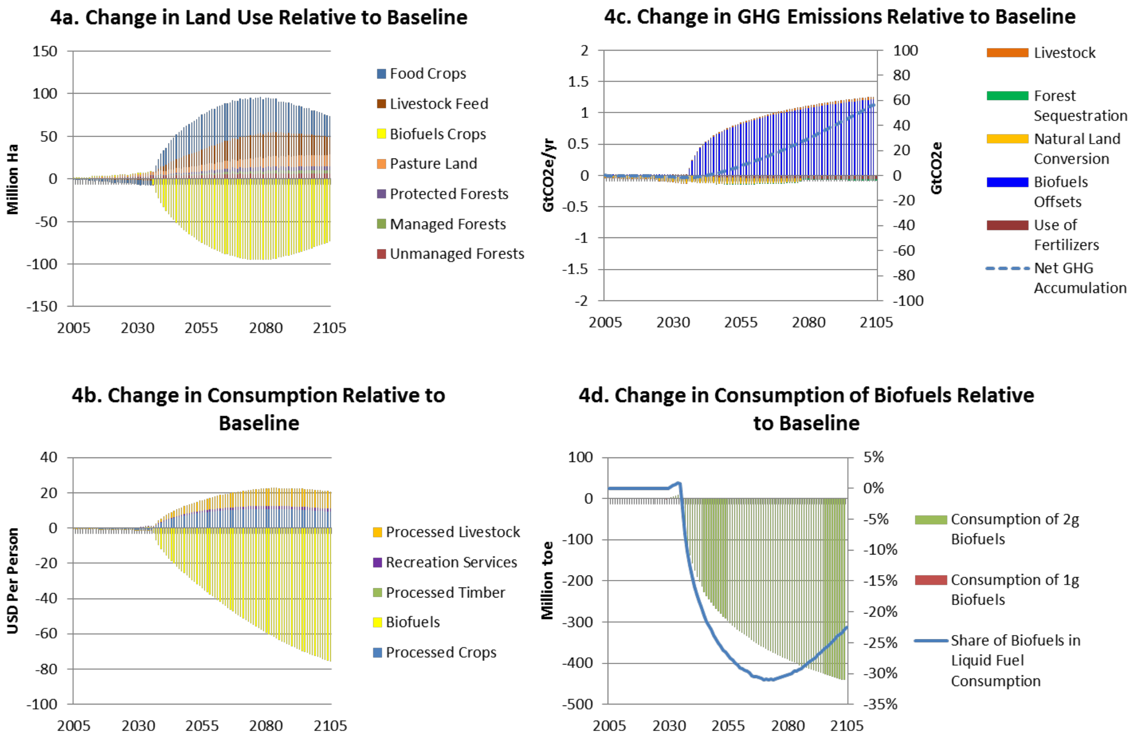


Figure 3. Optimal path for: (a) global land use, (b) associated services, (c) GHG emissions and (d) biofuels in the presence of 2G technology: 2005 – 2105. Results obtained by solving the FABLE model in light of the exogenous variable paths reported in Fig. S2.



4a. Change in Land Use Relative to Baseline

4c. Change in GHG Emissions Relative to Baseline

4b. Change in Consumption Relative to Baseline

4d. Change in Consumption of Biofuels Relative to Baseline

Figure 4. Deviation in optimal path for: (a) global land use, (b) associated services, (c) GHG emissions and (d) biofuels due to the absence of current 2G technology: 2005 – 2105. Results obtained by solving the FABLE model twice, once with the technology and once without.

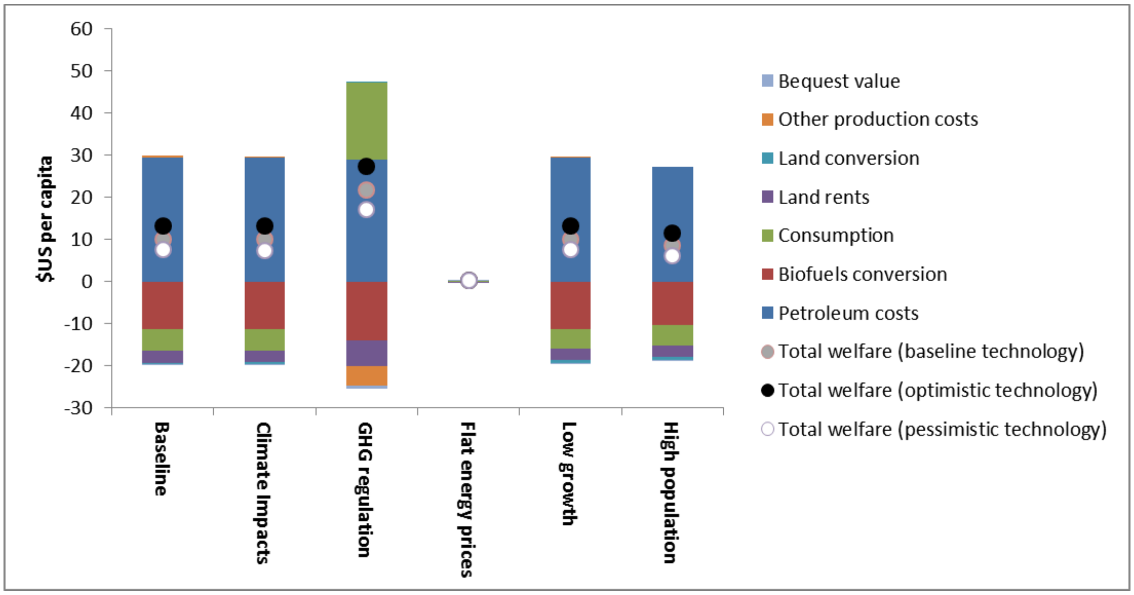


Figure 5. Valuation of 2G biofuel conversion technology in $/capita. Values on the y-axis correspond to the difference in global per capita welfare and were obtained by solving FABLE model twice: once with technology and once without. The difference is the value of current 2G technology (square markers) 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.

Table 1. Evaluation of FABLE's performance:
2004-2012

FABLE Endogenous Variables	Data Source	Actual Values		Predicted Values	
		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

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)

Table 3. 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: Once with 2G technology available and once without 2G technology.