A Global Comparison of National Biodiesel Production Potentials

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This study presents a consistent, national-level evaluation of potential biodiesel volumes and prices, replicated across 226 countries, territories, and protectorates. Utilizing all commercially exported lipid feedstocks from existing agricultural lands, we compare the upper-limit potential for expanded biodiesel production in terms of absolute biodiesel volumes, profitable potential from biodiesel exports, and potential from expanded vegetable oil production through agricultural yield increases. Country findings are compared across a variety of economic, energy, and environmental metrics. Our results show an upper-limit worldwide volume potential of 51 billion liters from 119 countries; 47 billion of which could be produced profitably at today's import prices. Also significant production gains are possible through increasing agricultural yields: a 12-fold increase over existing potential, primarily hinging on better management of tropical oilseed varietals.

1. Introduction

Petroleum is the largest single source of energy consumed by the world's population, exceeding coal, natural gas, nuclear, hydro, and renewables (*1*). Global demand for petroleum is predicted to increase 40% by 2025 (*2*). Concerns about oil supply and energy security have motivated many countries to consider alternatives to imported petroleum. Liquid biofuels, renewable fuels derived from biomass, are arguably one of the best options to lead the transition away from petroleum fuels in the near-term and have made a recent resurgence in response to rising oil prices. However, biofuels present resource and environmental challenges depending on where, how, and from which feedstocks they are developed. The U.S., with its rapid development of corn-ethanol, has demonstrated that countries with dwindling (or no) petroleum reserves will not always act in the best interests of global food markets (*3*). Our study attempts to calculate an upper-limit on biodiesel production and to help identify countries best positioned for development in an effort to anticipate changes to commodity markets.

Biodiesel is the biofuel of focus in our study due the diesel engine's wide range of applications, the diesel-cycle's inherent combustion efficiency advantage over otto-cycle engines (powered by gasoline), and diesel fuel's dominant position in the refined petroleum products market, accounting for 27.0% of worldwide refined petroleum consumption vs. 25.6% for motor gasoline (*1*). Even in countries where gasoline is the primary liquid fuel, diesel vehicles are used for the vast majority of commercial freight, construction, and infrastructure maintenance, giving them a unique importance across a wide range of economic sectors. Additionally, because biodiesel can be refined under normal atmospheric temperature and pressure, it can be produced economically across a variety of places and scales; from urban to rural, small to commercial. The ease of manufacture also contributes to biodiesel's high net energy balance, for example, soybean-biodiesel produces a 93% energy gain vs. 25% for corn-ethanol (*4*).

Biodiesel, formally known as either methyl-ester or ethyl-ester, is derived from naturally occurring vegetable oils or animal fats that have been chemically modified (esterified) to run in a diesel engine. Biodiesel's advantages compared to petroleum diesel include its renewable nature, superior emissions properties, support for domestic agriculture, compatibility with existing engines, and distribution infrastructure, and ease of manufacture (*5*). Although biodiesel has experienced episodes of popularity throughout the 20th century, the most recent biodiesel revival began in Europe in the early 1990s, spurred by mandatory alternative fuel use legislation and a liquid fuel market dominated by diesel fuel (66% of on-road, liquid fuel demand). As of 2004, Europe's biodiesel production has grown to over 2.0 billion liters, compared with U.S. production of only 100 million liters per year (*6*). Together, the European Union and the U.S. jointly account for over 95% of the global biodiesel demand. In addition, Canada, Australia, South Africa, Japan, China, India, Brazil, Thailand, Malaysia, and Indonesia all have small commercial biodiesel programs and many more in the research phase.

Although the technical details of biodiesel have been thoroughly studied (*7–9*), there has been less focus on what constitutes a strategic deployment. Our review, including both peer-reviewed and "gray" literature from state, federal, and international groups, identified thirteen publications estimating the volume and value of biodiesel that can be produced from domestic feedstocks, listed in Supporting Information Table S.1 (*10–22*). These studies differ from one another in terms of study type, geographical scope, feedstocks, and level of detail. Additional location-specific studies presumably exist, but were not widely circulated enough to be identified in our review. Whether due to the focus on specific feedstocks or the different methods used in calculating volume potential, these individual analyses do not lend themselves to comparisons with each other.

Our study presents a consistent, national-level evaluation of potential biodiesel volumes and prices, replicated across all countries in the world. This work is intended as a first-order comparison of countries based on national agricultural, economic, and fuel-use characteristics. Considering 226 countries, territories, and protectorates, and all major lipid feedstocks, we compare the potential for expanded biodiesel production from existing agricultural lands and animal fats.

2. Analysis Method

We have constructed a database spanning all countries and all lipid feedstocks, and a variety of economic, energy, and environmental metrics. Data are drawn from publicly available, online sources, so the conclusions may be independently updated as newer, more complete data sets become available. Unless otherwise noted, all of the sources below were converted to metric units and United States dollars (US$).

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Assessing the total volume of lipids that can be utilized for biodiesel remains difficult as there are over 350 species of oilseed plants, many of which are unique to specific locations and climates (*23*). Similarly, the fats from any animal species can be used as a feedstock. To ensure robust and comparable data, we limited our feedstocks to large-volume, commodity oilseed crops and fats tracked by the Food and Agriculture Organization (FAO) of the United Nations Statistics Division (FAOSTAT). All biodiesel volumes and prices are based on *processed* oils and fats export statistics from FAOSTAT (*24*). This study presumes nonexported lipids are required for domestic uses, including food demands, whereas exported lipids are free of encumbrances, if only from a national perspective. We also calculated biodiesel volumes resulting from crushing and processing primary oilseed crop exports; however, these estimates were left out of the final assessment for not significantly affecting the overall volumes.

2.1. Volume Calculations. We calculated the total biodiesel volume potential for each feedstock *i* and country *j*, BV_{ij}, using the following equation:

$$BV_{ij} = (EO_{ij} + EF_{ij}) \times LD \times RR \qquad (E1)$$

Exported, commercially traded, processed plant oils, EO_{ij}, and animal fats, EF_{ij}, are taken as the raw feedstocks, reported by FAOSTAT in mass (http://faostat.fao.org/site/567/default.aspx). The densities of vegetable oils are very similar, so an average lipid density of 0.92 kg/liter, LD, was used to convert the FAOSTAT reported mass to volume (*25*). This approach introduces an error of no more than 1% for vegetable oils, the maximum density difference between sunflower oil (the lightest oil) and linseed oils (the heaviest), and 3% for animal fats. RR reflects the conversion efficiency of processed vegetable oil to refined biodiesel. On average, using current refining equipment setup in a continuous flow process, RR = 0.98. (*26*). Converting these lipids into biodiesel would require investment in refining infrastructure, as lipid-processing capabilities are already in place.

2.2. Price Calculations. The FAOSTAT database also tracks commodity export values making it possible to determine the corresponding price per liter of biodiesels made from each individual feedstock and assess competitiveness with petroleum diesel. FAOSTAT export values include existing profits from growing, processing, and exporting. Biodiesel export values, BEV_{ij}, were calculated using the following equation:

$$BEV_{ij} = LEV_{ij} + RC - GV \qquad (E2)$$

The lipid export values for each country and each crop, LEV_{ij}, were first increased by average, commercial-scale production costs of $0.12 per liter, RC. These values were then decreased by the sale of the main by-product of refining, glycerol. In a typical continuous-flow process, glycerol, $C_3H_8O_3$, is produced at a rate of approximately 0.08 kg per liter of biodiesel refined (*27*). Factoring in the drop in value with increased biodiesel production, we apply a long-term value estimate for technical-grade glycerol of $0.04 per liter of biodiesel produced, GV (*28*). Lipid export values from FAOSTAT are considered free on board (FOB), an arrangement where the buyer pays for shipping and insurance. All resulting biodiesel export values are also assumed to be FOB, thus we do not include shipping costs.

While it may be technically possible for countries to convert these lipid feedstocks into biodiesel, we recognize that any large-scale reallocation of resources to would affect global export prices and potential profitability (*3*). Agricultural prices can already fluctuate significantly on a year-to-year basis due to changes in demand, climate, pests or other factors. For example, soybean price data from 1978 to 2003 (*29*), shows that U.S. soybean producers have been paid as much as $7.83/bushel (1983) to as little as $4.38/bushel (2002). However, despite year-to-year price oscillations of up to 34% (1983–1984), long-term price trends have varied much less with a trendline fit to 1978–2003 price data showing a 4% decrease. The USDA estimates that, if 2007–2016 soybean-biodiesel volume targets were to increase by 40%, soybean prices would be expected to increase by 3.9% (*30*).

To determine those countries currently positioned to profit most from biodiesel exports, we compare biodiesel production costs, BEV_{ij} calculated above, with a baseline price for imported biodiesel, IP. As noted, the European Union is the largest market for biodiesel, even with over 90% of worldwide biodiesel production, they cannot meet demand due to favorable subsidies and aggressive renewable fuel targets. The import price (IP) used in this study for biodiesel that meets EU quality standard EN14214 is €73.00 per 100 L, or $0.88 per liter, excluding VAT (exchange rate from March 21, 2006) (*31*). Because the FAOSTAT export prices include profits from lipid production, BP_{ij} is defined as each country's new profit resulting from biodiesel processing:

$$BP_{ij} = IP - BEV_{ij} \qquad (E3)$$

Thus, total national revenue would equal existing lipid revenues plus $BP_{ij.}$

Although this price is a convenient baseline, the import price of biodiesel can change quickly depending on such factors as current domestic biodiesel production levels, petroleum diesel prices, agricultural yields, and legislation. In addition to the baseline import price, we evaluate the sensitivity to reasonable historical minimum, historical maximum, and projected maximum prices. Because significant historical biodiesel pricing does not exist, we based our import price sensitivity analysis off fluctuations in petroleum diesel prices, which correlate well with current biodiesel prices. These diesel prices were normalized to the $0.88 per liter biodiesel price on January 13, 2006, 45% higher than petroleum diesel on that date. Our price sensitivity analysis employs a low biodiesel import price estimate of $0.26 per liter (March 1, 1999), a high import price estimate of $1.02 per liter (August 7, 2006), and a future maximum import price of $1.42 per liter. These prices are based on 10 years of historical diesel price data (*32*), and future extrapolations of price trends over a 10 year horizon.

Based on these volume and profitability estimates, we identify countries that have the best combination of high volumes and low production costs. We rank the countries with total annual production exceeding one million liters of potential, the volume throughput of an efficient large-scale, continuous flow biodiesel reactor, from lowest to highest cost (in $/liter). While refining costs generally scale linearly with volume for each processor type, continuous-flow reactors have lower overall costs of production than batch-reactors due to their higher overall efficiency and throughput (*26*). By limiting volumes to this threshold amount required for cost-effective, continuous-flow processing, comparisons between countries will be consistent and more accurate by focusing on differences in feedstocks, the most influential component in biodiesel cost.

2.3. Investment Environment. Factors such as perception of graft, safety, and foreign debt can be important gauges of the confidence and willingness of the investment community. Six indicators are used to identify which countries may be most favorable to large-scale infrastructure investments, whether domestic or foreign, and to offer a crude estimate of the investment climate.

(1) The *Corruption Perceptions Index* (CPI) annually ranks over 150 countries by their perceived levels of corruption, as

determined by expert assessments and opinion surveys, provided by Transparency International (*33*).

(2) Normalized *foreign direct investment* (FDI) is tracked by the United Nations Conference on Trade and Development (UNCTAD) for 199 countries, territories, and protectorates (*34*).

(3) *Debt status* estimates are classified by the World Bank for all member countries and other nations with populations of more than 30000 (208 total) (*35*).

(4) *Lack of travel safety*, actual or perceived, can be a limiting factor in business development. The U.S. Bureau of Consular Affairs' (CA) current travel warnings web site was used to identify countries which have excessive crime, areas of instability, or military activity which could impede infrastructure development (*36*).

(5) The United Nations Development Programme (UNDP) calculates the *Human Development Index* (HDI) as part of the Human Development Report, and it covers 177 countries. The HDI is a summary composite index that measures a country's average achievements in three basic aspects of human development: longevity, knowledge, and standard of living (*37*).

(6) *Gross Domestic Product (GDP) per capita* is factored into the HDI, but it is also used independently as a measure of average well-being and in later calculations on economic impacts of biodiesel production (*37*).

2.4. Impacts of Biofuel Operations. We calculate impacts of biodiesel production on unemployment and GDP per capita on a per liter basis to determine which countries are best suited to realize estimated biodiesel volume potentials, assuming all production occurs domestically.

Due to the extensive, region-specific data required by more sophisticated input-output (I-O) analysis models, we instead prioritized three calculations—change in GDP per capita, jobs created, and change in national unemployment—which could be performed consistently for all countries. All economic impacts calculated by this study are listed as a percentage so that relative impacts may be compared across countries of varying populations.

Estimates for the number of jobs created per liter of biodiesel produced were taken from an Iowa State University economic study of existing ethanol plants (*38*). That study estimated 220 newly created jobs for a 50 million gallon ethanol plant with 75% local ownership, which if extrapolated to biodiesel at an equal rate, results in a job-creation coefficient of 1.16 jobs per million liters of annual production. This figure is assumed to be conservative for countries that use more labor intensive processes. When combined with population statistics from the United Nations Development Programme (UNDP) and national unemployment figures from the U.S. Central Intelligence Agency (CIA), the job-creation coefficient is used to calculate the percentage impact on unemployment from jobs created through biodiesel production.

To compare environmental impacts among countries, we calculate the estimated CO_2 emissions reductions associated with moving from petroleum diesel, a sequestered carbon source, to agricultural biodiesel, a renewable carbon source/sink. However, biodiesel is not 100% carbon-neutral, as current production methods still depend on petroleum for fertilizers and delivery vehicles, and on coal-fired electricity in refining operations. For this study, we employ the Hill et al. (2006) estimate, which calculates CO_2 emissions from soybean-biodiesel to be 41% less than the comparable emissions from petroleum diesel (*4*). Actual CO_2 emissions reductions for each country will vary depending on the harvesting, transportation, and processing requirements of the crop used.

2.5. Study and Data Limitations. This study only considers existing lipid feedstocks on land already under cultivation. While the choices of lipid feedstocks available to a country are theoretically only limited by local growing conditions, in practice, crop selection depends on a combination of many factors including primary and alternate-use values, coproduct values, disease or drought resistance, fertilizer requirements, and historic market fluctuations. Crop selection is important for biodiesel production as cold-flow related properties such as viscosity, pour-point, and cloud-point can vary depending on the oilseed feedstock and can introduce incompatibilities with fuel specifications. Biodiesel made from tropical oils typically require thinning agents if they are to be exported to temperate climate countries. The costs of these additives are not included in this study, however, as the exact costs would vary depending on the exact feedstock used and where the biodiesel would ultimately be combusted. Further, the one-time capital costs of vegetable oil processing and biodiesel refining infrastructure were not included in this assessment. Determining the added cost per liter would depend on many country-specific factors including the discount rate, the profitability of the resulting fuel and the overall time frames of the investments.

Because we draw from a diverse array of data sources, not all countries have complete data sets. Countries were eliminated from the study if biodiesel volume potential could not be fully calculated. However, countries were still included if indicators or impacts were incomplete, and noted as such. An additional limitation of using data from such comprehensive, global sources was that, in many cases, the primary data is not tracked annually. In all cases, data from the most recent, complete years were used, all of which were between 2000 and 2006.

Although simple economic and environmental impacts are considered in our study, many of the more complex and far-reaching consequences are not. Vegetable oil currently used in biodiesel production only accounts for approximately 2% (2.2 billion liters) of global vegetable oil production, with the remainder going primarily to food supply (*6, 39*). While small today, as the biodiesel industry grows, the market effects on vegetable oils and their by-products could significantly impact global food supplies and the sustainability of agriculture practices if current trends continue.

3. Results

The opportunities for expanded biodiesel production on national scales are examined in three ways: as raw volume potential, as profitable potential from biodiesel exports, and in an upper bound estimate scenario with increased agricultural yields.

3.1. Absolute Biodiesel Volume and Feedstock Potential. Figure 1 shows global biodiesel potential, color-coded by absolute production volume from existing lipid exports. The aggregate volume potential is 51 billion liters annually spread over 119 countries. The top five, Malaysia, Indonesia, Argentina, the United States, and Brazil, collectively account for over 80% of the total. These countries are among the top palm and soybean growers, the two most prevalent oilseed crops in the world (*40*). The "top 10" producers from Figure 1 are presented in greater detail in Table 1, ranked by overall volume potential. Among these countries, the average feedstock dependence is 28% for soybean oil, 22% for palm oil, 20% for animal fats, 11% for coconut oil, and 5% each for rapeseed, sunflower and olive oils.

However, in part due to relying on different feedstocks, not all of the countries in Table 1 are equally suited to large-scale biodiesel production, as witnessed by the production cost per liter in Figure 2. Biodiesel production costs vary considerably, ranging from $0.29 per liter to over $9.00 per liter. Complicating the results, our study reveals what we term *processing-stopover countries*; countries which import raw oilseed crops or unprocessed oils, only to process them

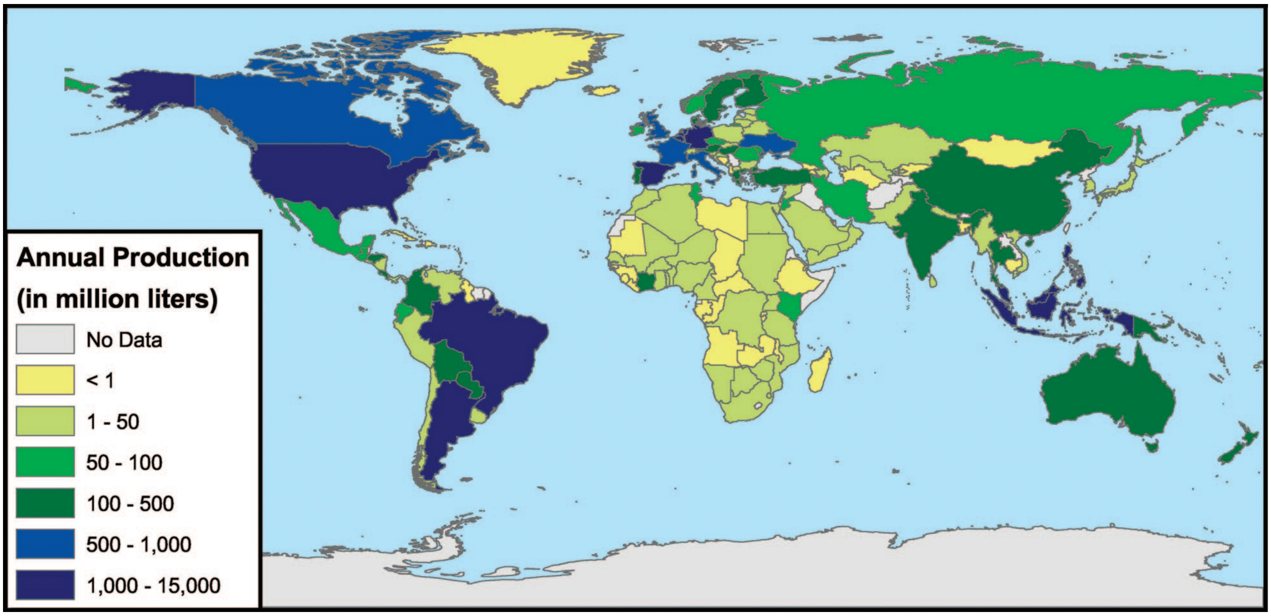

FIGURE 1. Global biodiesel potential from existing lipid exports.

TABLE 1. Top 10 Countries in Terms of Absolute Biodiesel Potential

rank	country	volume potential (L)	production ($/L)[a]
1	Malaysia	14540000000	$0.53
2	Indonesia	7595000000	$0.49
3	Argentina	5255000000	$0.62
4	USA	3212000000	$0.70
5	Brazil	2567000000	$0.62
6	Netherlands	2496000000	$0.75
7	Germany	2024000000	$0.79
8	Philippines	1234000000	$0.53
9	Belgium	1213000000	$0.78
10	Spain	1073000000	$1.71

[a] Average production cost per liter is calculated from all available lipid feedstock prices, increased by a $0.12 refining cost and decreased by $0.04 for the sale of by-products.

domestically for later export. The Netherlands is an example of one such country and was identified by the drastic difference in the feedstock distribution of exported processed oils and the distribution of domestic oilseed crops. Identifying *all* of these countries, however, requires country-specific data not included in our comparative database.

3.2. Investing in Biodiesel for Export. To get a more accurate assessment of which biodiesel resources are likely to be developed due to their profitability, we examine biodiesel potential from exports and calculate national trade balance gains from exporting refined biodiesel in lieu of vegetable oil. As noted above, we use the EU import price of $0.88 per liter, so we only include feedstocks that can be refined with a total production cost of less than the EU import price. The worldwide profit potential from biodiesel exports consists of 47.2 billion total liters from 109 countries, only 10 countries and approximately 4 billion liters less than the raw potential assessment above.

Our price sensitivity analysis showed few changes when applying the high import price estimate of $1.02 per liter or the future maximum import price estimate of $1.42 per liter. In these price scenarios, potential exports increase slightly to 48.8 billion liters from 112 countries and 50.0 billion liters from 117 countries, respectively, suggesting that the majority of lipid feedstocks can be profitably refined into biodiesel at today's prices. However, when applying the low import price estimate of $0.26 per liter, potential exports drop 99.7% to 134 million liters, all produced from animal fat feedstocks and spread over only 10 countries. This severe drop in profitability is not unexpected, as most biodiesel production is still subsidized and is only recently becoming profitable. While petroleum prices are expected to remain high in the near-term, any large-scale expansion of the biodiesel industry must be cognizant of the potential losses and stranded infrastructure which might result from either falling petroleum diesel prices, increasing lipid feedstock prices, or some combination of the two.

While all 109 countries can produce biodiesel profitably at the baseline import price of $0.88 per liter, some are better positioned to reach their production potential. Due to better agricultural management practices, more favorable growing conditions, and/or higher yielding feedstocks, many of the most profitable countries are those classified as "developed." However, as these countries already receive the largest share of attention—both in terms of scientific publications and industry development—the remainder of our results focus on countries likely to pursue biofuels for economic development. Considering only "developing" or "less developed" countries, Table 2 lists the "top 10" nations with the best combination of high potential volume and low production cost, ranked by total profit. All of the countries in Table 2 have production costs of $0.56 per liter or less, giving them all profit margins in excess of 50% compared to EU import prices. Volumes from tropical oils and animal fat feedstocks dominate, consisting of 71 and 26%, respectively, with each country utilizing one of the two for the majority of their potential biodiesel export.

Indonesia, Papua New Guinea, and the Philippines stand out from the group due to their high perception of corruption, low human development rating, and low GDP per capita. Thailand and Columbia, while not as low, also have poor scores in corruption perception, human development, and GDP per capita compared to the rest of the countries on the list. Indonesia, Columbia, and the Philippines all appear on the CIA's current travel warnings list, which can indicate increased safety concerns and decreased attractiveness of foreign investment. Narrowing the list further based on perceived corruption, human development, and CIA travel warnings, we identify Malaysia, Thailand, Columbia, Uru-

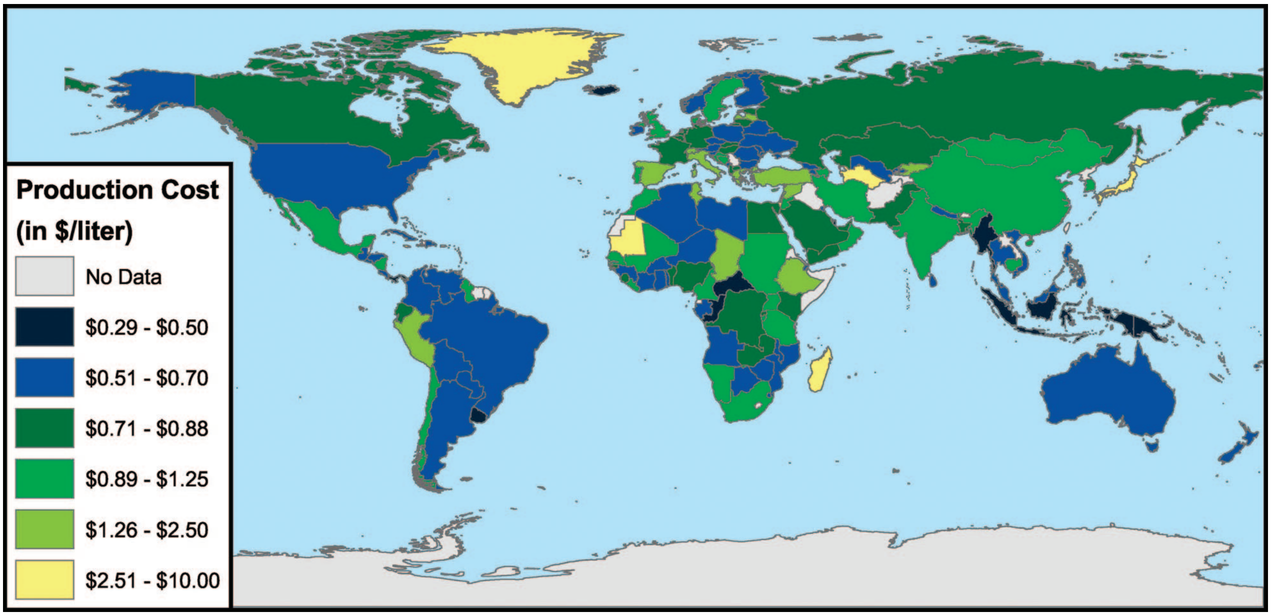

FIGURE 2. Biodiesel production cost per liter from existing lipid exports.

TABLE 2. Top 10 Developing Countries with the Highest Profit Potential from Biodiesel Exports: Bold Signifies the Country Is in the Top Third of All Countries, Italic in the Middle Third, and the Remainder in the Bottom Third

rank	country	biodiesel potential (L	total export profits ($)	HDI rank	GDP/ cap	Corr rank	FDI rank	WB debt	travel warning
1	Malaysia	14510000000	$5065000000	**66%**	*65%*	**75%**	**82%**	mod.	no
2	Indonesia	7593000000	$2967000000	*38%*	*34%*	13%	**68%**	sev.	yes
3	Philippines	1233000000	$432700000	*53%*	*41%*	26%	**70%**	mod.	yes
4	Papua New Guinea	383100000	$158500000	23%	31%	18%	*48%*	mod.	yes
5	Thailand	341700000	$109900000	*59%*	*61%*	*62%*	**82%**	less	no
6	Colombia	154600000	$52220000	*61%*	*55%*	*65%*	**76%**	mod.	yes
7	Honduras	123800000	$40290000	*34%*	32%	32%	*49%*	mod.	no
8	Nepal	49040000	$17910000	23%	14%	26%	12%	less	yes
9	Uruguay	40090000	$17390000	**74%**	*63%*	**80%**	*45%*	sev.	no
10	Ghana	40420000	$17300000	22%	27%	*59%*	*44%*	less	no

TABLE 3. Top 5 Developing Countries with Profitable Biodiesel Export Potential

rank	country	volume potential (L	total export profits ($)	rise in GDP/cap.	unemployment rate Δ[a]	jobs created	tons CO_2 reduced
1	Malaysia	14510000000	$5065000000	2.34971%	−2.062%	16827	2854300
2	Thailand	341700000	$109900000	0.02274%	−0.0445%	396	67200
3	Columbia	154600000	$52220000	0.01900%	−0.0037%	179	30400
4	Uruguay	40090000	$17390000	0.06200%	−0.0114%	47	7900
5	Ghana	40420000	$17300000	0.03834%	−0.0012%	47	7200

[a] This figure reflects a potential percentage change in the current unemployment rate, not the new rate of unemployment.

guay, and Ghana as "Top 5" list of developing countries likely to attract biodiesel investment.

The economic and environmental impacts of development projects in these countries are shown in Table 3. Malaysia stands out by the comparatively large feedstock volume that can be profitably refined into biodiesel and exported. Malaysia currently has a very low official unemployment rate at only 3.6%. By building-out biodiesel refining capacity, the country could potentially reduce that figure by more than 2%, down to 3.5% overall. The proportional rises in GDP per capita, number of jobs created, and amount of CO_2 reduced all dwarf the gains by the remaining countries (even including developed countries, not shown). If Malaysia were to join a CO_2 cap-and-trade regime at the current value of $20.44 per ton of CO_2 on the European Climate Exchange, their potential biodiesel exports could be worth over $58 million in credits alone (*41*).

While the gains look small comparatively, other countries can also benefit economically by developing their biodiesel refining and export infrastructure. By pursuing biodiesel exports, Thailand and Columbia could both contribute tens of millions of dollars to their GDPs while generating hundreds of jobs. Ghana has a unique position of having low debt, low perception of corruption, and high foreign investment, but low human development ranking and low GDP per capita so investment could have a high impact on economic well being.

Cumulatively, the biodiesel export potential identified by our study represents a 21-fold increase over current production. Not all of this potential could be realized, since even with animal fats removed, the necessary feedstocks make up almost one third of all vegetable oil demand. Converting all of these volumes to biodiesel would surely affect food supplies and increase feedstock prices. This study represents a first-order approach to identifying upper-limits of biodiesel production potential from existing commodity exports. To fully understand how development might impact market prices of specific feedstocks, individual countries are encouraged to perform detailed national and global economic analyses.

3.3. Preliminary Results from Increased Agricultural Yields. To help address the issue of a growing biodiesel industry increasingly competing with food resources, our study also conducted a preliminary analysis of increasing vegetable oil production through yield improvements. For this "well-managed yields" growth strategy—the expected production from a modernized farm with high-quality management—we considered only currently cultivated oilseed lands, as defined by the FAOSTAT database, and omitted animal fats. It is important to note that we define *well-managed yields* to be different from *best-case yields*, which are very regionally dependent and are typically reported from individual farms or even specific plots. For instance, instead of using the highly touted 6000 L/hectare best-case yield for palm oil, we chose a more realistic and widely achievable yield of 3800 L/hectare (*42*). We also recognize that yields naturally trend upwards over time due to technological and efficiency measures; albeit not nearly at the rate and scale we assume for this scenario.

To calculate vegetable oil volumes from agricultural intensification, PEO_{ij}, the following equation was used:

$$PEO_{ij} = [(AC_{ij} \times OY_j) \times PR] - CD_{ij} \qquad (E4)$$

Total crop-areas under cultivation from FAOSTAT, AC_{ij} (*24, 42*) are multiplied by the well-managed oil yields-per-hectare for each crop, OY_j. These calculations result in raw vegetable oil volumes on an individual crop and country basis. Oil volumes are reduced by a processing ratio (PR) of 0.9622 to account for processing into food-grade vegetable oil, a form suitable for food-exports and for refining into biodiesel (*26*). These results for increasing agricultural yields are aggregate totals for each crop, which would include domestic demand, so we subtract off crop-specific domestic demand, CD_{ij}.

To estimate CD_{ij}, we multiply FAOSTAT figures for aggregate domestic demand, AD_j, by the known ratio of a specific crop's production, CP_{ij}, to a country's total oilseed production, AP_j (*24*).

$$CD_{ij} = [AD_j \times (CP_{ij}/AP_j)] \times LD \qquad (E5)$$

Lipid density, LD, is used to convert CD_{ij} into liters. By retaining data at the crop level, it is possible to separate out volumes and prices to later determine which, if any, can be profitably refined into biodiesel. The methodology for converting vegetable oil to biodiesel remains unchanged from our previous section.

Using these well-managed agricultural yields, we estimate that total potential biodiesel volumes could reach 605 billion liters per year, distributed over 106 countries. This 12-fold increase is spread over many crops, but is mainly attributed to tropical oilseeds—namely palm and coconut—whose current yields are much below their well-managed yields. Even after a conservative increase in annual vegetable oil demand for food purposes of 188 billion liters by 2015, 417 billion liters of biodiesel could be produced with the remainder. Malaysia and Indonesia stand out above the rest, making up almost 75% of the potential volumes from increased yields. It is important to note that these two countries are also currently at risk of furthering deforestation by growing palm production through the current practice of clear-cutting. Agricultural intensification associated with boosting yields can introduce additional problems including pressure on fresh water supplies from irrigation, nitrogen fertilizer run-off, and soil degradation (*43*). However, if appropriately implemented, yield increases could help alleviate pressure on deforestation, growing the economy without destroying irreplaceable natural resources. While current farming practices are unlikely to change quickly, this untapped potential from increasing oil yields per hectare is promising news for proponents of sustainable palm production: the expected doubling of export volumes by 2020 may be attainable using land already under cultivation (*44*).

4. Discussion

This study, while by no means exhaustive, serves to highlight the untapped opportunities present in many developing countries, helping to address some of the most prominent perceived barriers to large-scale biodiesel development. We believe the individual country results and comparative rankings could be of use to national governments, as well as international organizations involved in energy planning and decision-making. Similarly, the CO_2 reduction estimates are important to examine globally as countries participating in trading markets can often invest in nonmember countries to count the emissions reductions toward their own targets.

We caution that biodiesel must be developed in a responsible and sustainable manner. Advanced production technologies are being pursued; including the use of crop selection optimization, the growing of dedicated energy crops such as jatropha on marginal lands, and eventually the use of algae-based oils which do not compete for fresh water or farm land (*45, 46*). However, until these more efficient modes of production become commercialized, the ad hoc nature of current biodiesel growth will eventually impact global food supplies and long-term sustainability of agriculture production. Nevertheless, with the possibility of large gains in crop yields alone, it may be possible to significantly increase biodiesel production in the near term without requiring additional land or sacrificing food supply.

For complete results and tables for all countries, please visit the Center for Sustainability and the Global Environment's (SAGE) Web site: http://www.sage.wisc.edu/energy/.

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Supporting Information Available

A review of publications that assess biodiesel potential, a table of variables used in the study, U.S. soybean production and pricing (1978–2003), European petroleum diesel pricing (1997–2006), a table of well-managed vegetable oil yields, and complete country lists of absolute biodiesel potential, profitable potential, and profitable potential from increased yields. This material is available free of charge via the Internet at http://pubs.acs.org.

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