Resetting global expectations from agricultural biofuels

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Abstract
Aggressive renewable energy policies have helped the biofuels industry grow at a rate few could have predicted. However, while discourse on the energy balance and environmental impacts of agricultural biofuel feedstocks are common, the potential they hold for additional production has received considerably less attention. Here we present a new biofuel yield analysis based on the best available global agricultural census data. These new data give us the first opportunity to consider geographically-specific patterns of biofuel feedstock production in different regions, across global, continental, national and sub-national scales. Compared to earlier biofuel yield tables, our global results show overestimates of biofuel yields by \( \sim 100\% \) or more for many crops. To encourage the use of regionally-specific data for future biofuel studies, we calculated complete results for 20 feedstock crops for 238 countries, states, territories and protectorates.

Keywords: agricultural biofuels, crop-based biofuels, biofuel yields, productivity

1. Introduction
Aggressive renewable energy policies have helped the biofuels industry grow at a rate few could have predicted. Surplus agricultural feedstocks in the US and Europe have quickly been exhausted, contributing to commodity prices increases of biofuel crops such as corn, soybean and rapeseed. And while biofuel’s role in the recent price increase of other agricultural commodities—such as rice and wheat—has been largely refuted, there is still forward-looking concern that the continued development of biofuels will place additional pressure on food supplies during a period of tremendous demand growth from developing countries [1, 2]. Many point to the vast potential of next-generation biofuels, such as cellulosic-ethanol and algae-biodiesel, however, agricultural-based biofuels are the only alternatives to liquid fossil fuels being produced profitably and in large volumes today [3, 4].

This has led to many developing countries—from Malaysia to Malawi—increasing their biofuel production for both export and domestic use [5–7]. While discourse on the energy balance and environmental impacts of agricultural biofuel feedstocks are common [8–10], the potential they hold for additional production has received considerably less attention. Using newly-developed, spatially-explicit global agricultural datasets (Monfreda et al. 2008), hereafter referred to as the M3 cropland datasets, we challenge widely-held assumptions about the global production of biofuels from agricultural feedstocks, and show it may be significantly less than previously thought [11]. Furthermore, based on the huge variability in global yields for agricultural biofuel crops, our results demonstrate the need to incorporate regionally-specific crop data in future studies.

The biofuel production potential from different feedstock crops are most commonly compared by their fuel yield per unit area. Media articles, journals, and policy reports are rife with examples of biofuel yield tables demonstrating, for example, the productivity per hectare of maize-ethanol is roughly half that of sugarcane [12–15]. Similarly, it is often reported that rapeseed (canola) will yield nearly twice the biodiesel as soybean per hectare [16–18]. Yield tables have become prolific due to their simplicity in conveying the otherwise complex relationships between the starch, sugar, or oil content of different crops and how they translate to potential fuel...
volumes—something most people tasked with communicating biofuels to ever diverse audiences can appreciate. However, the frequency at which these yield figures are quoted and re-quoted have led to an air of certainty in the data that was never originally intended. It is often unclear how agricultural yield values were first derived, how representative they are of different regions of the world, and how appropriate current yield estimates are for comparing different crops.

Crop handbooks, manuals, and, increasingly, online databases are some of the primary sources of consolidated information about agricultural crops and their potential application in energy production [19–23]. While these collections are often in an encyclopedic format, they are not intended to be replete. Biofuel yield estimates are collected from numerous disparate sources, often with little control for the geographic location, climate, soil type or agricultural management regime of the crop in question. Some of the yield estimates are from experimental agricultural stations (with exceptionally high yields), while others are from region-specific agricultural censuses, estimating the average yield of some countries. Yield tables that draw from these sources must often choose a single value (from either a single country, or even a single farm) to represent that crop globally. Building on these existing estimates to date, we provide improved, spatially-scalable methods of selecting more representative values. Table 1 lists the yield values from two commonly referenced crop tables and that form the basis for our comparison [16, 18].

Crop yields are influenced by several factors including mean climate and variability, soil conditions, and inputs and management, but are also impacted by social, political, and economic influences [24, 25]. Because research has already documented how historical yield increases have resulted from improved technology and advanced hybrids, better agronomic management practices, and increased inputs [25–32], we know that inconsistencies in adoption of these improvements from one region to the next, coupled with variability in climate and soil conditions, has created a large yield gap for many crops at the global scale. Mean climate and weather-variability impact yields by controlling diurnal temperature ranges, growing season length, the delivery of timely precipitation, and the frequency of extreme conditions such as droughts and floods [33]. Soil properties such as soil depth and water holding capacity, organic matter, bulk density, and pH—many of which are impacted by previous and current land use practices—ultimately influence crop yield potential [33]. Inputs such as irrigation, fertilizers, and pesticides, and management factors such as planting and harvest date, machinery usage, and efficiency of farming operations also contribute largely to global yield variability. As a result, estimating global biofuel feedstock production from these singular yield values—especially ones chosen arbitrarily—is problematic at best.

2. Materials and methods

The M3 cropland datasets combine the best available agricultural statistics from around the world—gathered across ~22,000 different census reporting units at the county, state, and country level—with a recent map of global croplands [34] to produce the most detailed global maps of crop area and only global maps of crop yield available [11]. The datasets depict crop areas and yields circa the year 2000 on a 5 min × 5 min (~10 km × 10 km) latitude–longitude grid, and are the first attempt to comprehensively depict the spatial patterns of yield and crop area for all 175 crops reported in the FAOSTAT database. For example, M3 maps of wheat area coverage and yield are shown in figures 1(a) and (b), respectively.

The crop area and yield statistics were drawn from a variety of agricultural surveys, censuses, and statistical databases, and vetted and standardized to ensure data quality and compatibility. Over 80% of the total area for all crops derives from sub-national sources obtained from ~2300 state-level and ~19700 county-level political units from 150 countries. The global cropland dataset used to provide a template to distribute these crop area and yield statistics is itself a fusion of national and sub-national cropland area statistics with two satellite-derived land cover classifications (Boston University’s MODIS-derived land cover product and the GLC2000 dataset).

The datasets for ten ethanol crops (barley, cassava, maize, potato, rice, sorghum, sugarbeet, sugarcane, sweet potato, and wheat) and ten biodiesel crops (castor, coconut, cotton, mustard, oil palm, peanut, rapeseed, sesame, soybean, sunflower) were converted from metric-tonnes-per-hectare to liters-per-hectare and analyzed across 238 countries, territories and protectorates.
Biodiesel-per-hectare yields for each crop $i$ and country $j$, $BY_{ij}$, were calculated using the following formula:

$$BY_{ij} = \left[ CY_{ij} \times OC_{i}/OD_{i} \right] \times PR \times RR.$$  (1)

Current agricultural yields, $CY_{ij}$, are recorded in tonnes-per-hectare, provided as by the M3 cropland database [11]. To determine what fraction of the mass of each crop is vegetable oil, the yields were first multiplied by the per cent oil content as recorded by the FAO for each crop $i$, $OC_{i}$ [35]. Vegetable oil masses were then divided by the oil densities corresponding to each crop, $OD_{i}$ [36, 37], to arrive at liters of raw vegetable oil per hectare. Raw vegetable oil volumes were 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 [38]. Finally, food-grade vegetable oils were multiplied by the refining
ratio, RR; a term that reflects the conversion efficiency of processed vegetable oil to refined biodiesel. On average, using current refining equipment setup in a continuous-flow process, $RR = 0.98$ [38]. Table 2(a) lists the simplified conversion factors to translate from tons of biomass to liters of biodiesel.

We calculated ethanol-per-hectare yields for each crop $i$ and country $j$, $EY_{ij}$, using the following equation:

$$EY_{ij} = CY_{ij} \times RF_j.$$  

(2)

As with the biodiesel example above, ethanol yield calculations began with the current agricultural yields in tonnes-per-hectare, $CY_{ij}$ [11]. These mass values were converted to liters using refining factors for each crop, $RF_j$ [39, 40]. Unlike biodiesel, which has similar processing and refining steps once the oil is separated, ethanol processing is more crop-specific. All the refining factors used in this study, listed in table 2(b), include the conversions from extracting, fermenting and distilling the sugars present in the various crops.

Litter-per-hectare fuel yield and area cultivated were analyzed globally for each of the 20 crops in study to provide yield quartiles and distributions. Additionally, quartiles and distributions were calculated individually for every country-crop combination allowing for more detailed region-specific studies in the future. All yield quartile values and distributions were first weighted by crop area so that smaller, unrepresentative plots would not artificially skew the results in one direction or another. To accomplish this, data was sorted by yield from lowest to highest, and then area was aggregated until the point at which each quartile ($0\%, 25\%, 50\%, 75\%, 100\%$) of the total cultivated area was reached. The yield values corresponding with these points were selected for each crop, giving the area-weighted quartiles used to construct the statistical box-and-whisker plots.

Potential error in our analyses may arise due to variation in the source quality of agricultural statistics used to create the M3 cropland datasets, as well as potential errors in satellite data input to the crop distributions and/or limitations of the statistical merging of these data inputs. The majority of these errors, however, would affect the spatial distribution of yields and area coverage, which would later be minimized when we aggregate statistics using political boundaries.

Additional sources of potential error could come from the factors used in ethanol and biodiesel mass-to-liter conversions. Ethanol conversions were estimates from Nigam and Agrawal (2004) and a USDA study titled *The Economic Feasibility of Ethanol Production from Sugar in the United States*, however, additional conversion estimates were identified from five other sources [41–45]. Across the various sources, seven of the ten ethanol crops had differing estimates for mass-to-liter conversions. These conflicting estimates deviated from those used in our analyses by 3%–16%, with an average of 10%. Biodiesel yields are also expected to vary, as FAO oil content percentages are based on global averages and processing and refining ratios assume large-scale, continuous-flow processes that may not be used by all countries.

Finally, we recognize that any agro-industrial sponsored biofuel feedstock projects would likely result in higher than average yields in many countries—if done on a large enough scale. However, these operations would face many of the same obstacles as domestic efforts to improve yields, including: inefficiencies in (or lack of) transportation infrastructure, distribution of soil inputs and hybrid crops, lack of mechanization and irrigation, knowledge-transfer of management practices, as well as cultural and political barriers. Access to capital could help alleviate many of these issues, but challenges remain and it would be risky to count on achieving large yield increases quickly.

### 3. Results

Compared to earlier biofuel yield tables, our detailed agricultural analysis (figures 2(a) and (b)) shows a strikingly different picture of global biofuel yields [16–18]. For most crops, previous reports have overestimated yields by $\sim 100\%$ or more. Barley, cassava, castor, maize, rapeseed, and sunflower all show that previous global biofuel yields were overestimated by at least 100%, with wheat–ethanol and groundnut–biodiesel estimates having been overestimated by $\sim 150\%$ or more. Our analysis shows that existing, commonly-accepted biofuel yield estimates become highly unrealistic as agricultural biofuels productions expands across the world. Even if we take an ‘optimistic’ view of global yield data, it is difficult to imagine how these yields could be achieved at a large scale in the near future. Comparing previously-reported biofuel

### Table 2. Biomass to biofuel conversion factors. (Note: these tables represent the expected volume of biofuel, in liters, which should be extractable from a metric ton of biomass for each of the 20 crops in this study.)

| (a) Crop to biodiesel conversions | Biodiesel conversions (l/ton) |
|----------------------------------|-------------------------------|
| Castor                           | 393                           |
| Coconut                          | 130                           |
| Cotton                           | 103                           |
| Groundnut                        | 309                           |
| Mustard                          | 370                           |
| Oil palm                         | 223                           |
| Rapeseed                         | 392                           |
| Sesame                           | 440                           |
| Tobacco                          | 183                           |
| Sunflower                        | 418                           |

| (b) Crop to ethanol conversions  | Ethanol conversions (l/ton) |
|----------------------------------|-------------------------------|
| Barley                           | 243                           |
| Cassava                          | 180                           |
| Maize                            | 410                           |
| Potato                           | 110                           |
| Rice                             | 430                           |
| Sorghum                          | 402                           |
| Sugarbeet                        | 103                           |
| Sugarcane                        | 81                            |
| Sweet Potato                     | 125                           |
| Wheat                            | 389                           |
Figure 2. Revised estimates of global biofuel crop yields. (a) Global ethanol yields, (b) global biodiesel yields. (Box plots represent the variation of yields for common biofuel crops. Here we show results averaged for the entire globe (gray), developed countries (green) and developing countries (blue). The horizontal black bars represent median yields, and the boxes are bound vertically by 25th percentile yields on the bottom and 75th percentile yields on the top. The whiskers (in light gray) represent the absolute minimum and maximum yield values recorded in the M3 cropland datasets. The red and orange bars offer comparisons to two previous examples of biofuel feedstock yield estimates, reported by Worldwatch Institute [18] and Brown [16] respectively. Please note, the M3 results for sorghum are compared to Brown’s estimate for sweet sorghum, which is a different variety with higher sugar content than is normally grown and traded commercially.)
As more and more biofuel production begins to be produced outside the few dominant countries of today—primarily the US, Brazil, and EU member countries—regionally-specific yield results will be needed in future policy, economic, and environmental analyses of biofuel growth. To encourage this, we also calculated complete results for 238 countries, states, territories and protectorates for use in more focused national and regional studies. Using these supplemental statistical analyses, publicly available at http://www.sage.wisc.edu/energy, future studies will be able to more accurately assess the potential and impacts of biofuels production from agricultural feedstocks. In aggregate, there are twenty summary tables (10 for ethanol crops, 10 for biodiesel crops) and over 3000 country box plots and histograms, such as those discussed above for sweet potato from the DRC (figure 3(a)) and rapeseed from Canada (figure 3(b)).
4. Discussion

Our results point to the continued existence of significant and geographically disparate agricultural yield gaps for most biofuel crops. This study demonstrates that using a single yield estimate (often taken from a unique location, or an agricultural field trial, and then applied to large regions—or worse globally) can be misleading, and often overestimates the actual yield of agricultural feedstocks by $\sim 100–150\%$. These gaps in productivity generally follow economic stratifications, but they are equally influenced by biophysical, political and cultural factors. Even when limiting yield values to the prime growing regions for common biofuel crops, existing biofuel yield tables have tended to choose values on the optimistic end of the range. For instance, even if one were to assume that the 4750 l/hectare oil palm-biodiesel yield from Brown were only intended to reflect Malaysian production potential, that value is still in the top 90th percentile of oil palm-agriculture in that country [16]. A more detailed, geographically-specific analysis of (actual and potential) yields is needed.

This paper is by no means the first to suggest the existence of such yield gaps [46-49]. Agro-businesses, academics and researchers have made great efforts to translate the post-WWII productivity gains of the ‘green revolution’ in developed countries to regions such as Central America, South Asia, and Sub-Saharan Africa—some more successfully than others [49-51]. However, existing assessments of yield variation have largely been data limited, and as such focus on particular data-rich crops or specific regions [52-54]. The spatially-explicit nature of the new M3 cropland datasets will allow for quantification of potentially closable gaps in agricultural production across the world and for all crops reported by the FAO.

Cassman [46], perhaps, defines yield potential most elegantly as, ‘the yield obtained when an adapted cultivar is grown with the minimal possible stress that can be achieved with best management practices.’ However, in addition to the myriad of agriculture-related factors influencing yield—from climate and soil conditions to management and mechanization—external political, economic and cultural factors often determine the ultimate success or failure of closing production gaps. Herculean efforts have been made in the past to close yield gaps in developing countries, only to be impeded by the lack of well-functioning transportation infrastructure, distribution of inputs, and access to capital and markets [55-57]. The biofuels revolution has lead to host of projects started under the guise of agricultural or rural development [58, 59]. The impact of important geographic variations in yield may be particularly acute when considering country-specific labor costs, land availability, agricultural management regimes, climate, and other factors. A better spatial understanding of yield potential can help optimize future development efforts and lower financial risk by coordinating with realistic infrastructure projects such as roads and ports, and choosing crops and regions that hold the most biophysical potential for the least investment.

Understanding where, how and for which crops yields can be improved globally will affect all aspects of agricultural production. However, this will be of particular importance to the biofuels industry, which has come under increasing pressure to slow the conversion of new agricultural lands for biofuels production. There is mounting research suggesting that the carbon benefits of biofuels will be eliminated, or worse reversed, if intact, carbon-rich ecosystems are converted to biofuel agriculture [60-62]. However, while a renewed focus on increasing production on existing agricultural lands may help slow this expansion, intensification can have equally devastating environmental effects as extensification depending on how it is implemented. Intense row-crop and plantation agriculture has been linked to eutrophication of rivers, lakes, and coastal areas [63, 64], depletion of soil nutrients and organic matter thereby decreasing soil quality [65, 66], and increased size and frequency of ocean hypoxic zones [67, 68]. Any efforts to increase crop productivity must do so as sustainably as possible—utilizing innovative agricultural initiatives such as more precise application of fertilizer inputs and irrigation through precision agriculture practices, improving nitrogen use efficiency [69, 70], and improved long-term tillage practices to reduce agrochemical runoff and organic matter losses—lest biofuel’s realized benefits become further diminished.

The intention of this study is to reset the global expectations surrounding agricultural biofuels to a more realistic starting point, not to provide the final word on the debate. We expect existing trends in the production and consumption of agricultural crops to continue, including: annual increases in yields, the expansion of agricultural frontiers into natural ecosystems, and growth in consumption due to rising affluence in developing countries [9, 32]. In fact, the recent increase in commodity prices will likely encourage renewed focus on research and development, spurring productivity gains beyond the typical $\sim 2\%$ averaged annual gains. And while the advent of next-generation biofuels may one day render the discussion of agricultural-based biofuels moot, it will take years for the technology to become widely distributed in developing countries—further increasing the importance of this study for near-term growth in the biofuels industry.

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Corrigendum

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The developing country comparison bars in figure 3 on page 6 of the original article have been revised as follows.

Figure 1. Revised versions of figure 3, left plots.