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The International Agricultural Prospects Model: Assessing Consumption and Production Futures Through 2050 (version 2.1)

[Supporting Material for "A Bounds Analysis of World Food Futures: Global Agriculture Through to 2050." *Australian Journal of Agricultural and Resource Economics* 2014 (forthcoming)]

by

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STAFF PAPER

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The world's agricultural sector is of concern to many people for a variety of reasons. Agriculture accounts for almost two thirds of the working population in low-income countries and is thus a source of livelihoods for many people (FAOSTAT 2012a). Chronic hunger persists, especially in many low-income countries, while at the same time obesity is on the rise, renewing concerns about the relative rates of growth in and changing composition of global food consumption and production (Alston and Pardey 2014). The relative rates of growth of these quantity aggregates affect the price, accessibility and health outcomes of food consumption. Agricultural production occurs on about 40 percent of the world's land area, and consumes large quantities of water, and so how and where agricultural production takes place, and the state of the natural inputs used in or affected by agriculture, are also subject to much scrutiny. For these and a host of other reasons, developing an informed sense of the production prospects of global agriculture has significant policy and practical value.

Pardey et al. (2014) provide new projections of agricultural consumption and production for the period 2010-2050, derived using version 2.1 of the International Agricultural Prospects (iAP) model.[1] In this paper we provide details of the iAP model used to derive those results. The iAP model uses a parsimonious and transparent approach to projecting agricultural futures. The modeling process begins by projecting aggregate agricultural consumption derived from the demand for biofuels, plant- and animal-sourced food calories, and cotton lint. We then assess if production can meet that projected consumption by way of a dynamic, spatially-explicit determination of the location of production subject to the available agricultural cropland, the suitability of that land to grow each particular crop, and the prospective changes in crop yields for each of the world's 16 principal crops (accounting for about 88 per cent of total crop area in 2010) in each country grouped into 17 regions. The robustness of our estimates is assessed by deriving plausible alternative projections in the underlying drivers of consumption and production, which we report in Pardey et al. (2014) as bounds to the variation in our projections stemming from the empirical uncertainties inherent in these underlying factors.

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[1] It is worth noting that we do not consider climate change in this version of the iAP model because credible spatially explicit estimates of the potential effects of climate change on agricultural production and productivity are not available. Not only is there substantial uncertainty in the potential changes in climate for any particular location, but since both farmers and technology respond to changing conditions, projecting the effects of climate on yields would be fraught with errors (see Appendix 1).

1. Prior Projections (Models)[2]

Up to their point of publication, McCalla and Revoredo (2001, p. 4) noted that "[o]ver the past 50 years there have been at least 30 quantitative projections of world food prospects (supply and demand balances)."[3] Perhaps the most often cited estimates of projected global agricultural consumption, production, and food security outcomes are those published periodically by the U.N. Food and Agricultural Organization (FAO). The first in this series was published in 1962 with the latest published in 2012 (Alexandratos and Bruinsma 2012). They report estimates for the two years, 2030 and 2050, updating two sets of prior projections; one by FAO (2006) for the same two years and the other by Bruinsma (2003) for the years 2015 and 2030. The revised 2012 estimates suggest that world agricultural output (as measured by the aggregate volume of production) is expected to increase by 60 percent from 2005/07 to 2050 (or 1.07 percent per year), down from the 70 percent projected increase (or 1.21 percent per year) over the same period reported by FAO (2006).

Building on a number of world food budgets prepared by the United States Department of Agriculture (USDA) dating back to the early 1960s, in 1993 the USDA launched a commodity and trade projections effort that has produced a regular series of 10-year forward projections (on an annual time step) for U.S. agricultural production and use, and global trade of crops and livestock in addition to aggregate U.S. agricultural sector indicators like prices, consumption, and income. These projections reflect a combination of modeled results and expert judgment, involving an extensive review by a suite of USDA agencies. The U.S.-centric scope of these projections, along with their relatively short projection horizon limits their contribution toward understanding longer-term trends in *global* food security, which admittedly is not their intended purpose.

IFPRI (1977) and Paulino (1986) represent the first published attempts by the International Food Policy Research Institute (IFPRI) to project global food trends. In the 1977 report, developing-country production and consumption trends were projected to 1990; and to 2000 in the subsequent 1986 report. Thereafter, IFPRI's projections work centered on evolving versions of a recursive-dynamic, global, partial equilibrium model dubbed IMPACT (International Model

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[2] This section is an extended version of the corresponding section in Pardey et al. (2014).

[3] See also the recent cross-model comparisons of Valin et al. (2014), von Lampe et al. (2014), and others in the same volume.

for Policy Analysis of Agricultural Commodities and Trade), developed under the continuing leadership of Mark Rosegrant (for model details see Rosegrant et al. 2012). The first published projections in this series were Rosegrant et al. (1995). The most recent, with projections through to 2050, was Rosegrant et al. (2013), where the baseline projection had world cereal production (including wheat, maize, rice, millet, sorghum and "other grains") growing from 2.12 billion tonnes in 2010 to 3.22 billion tonnes in 2050 (equivalent to growth of 1.04 percent per year).

The Food and Agricultural Policy Research Institute (FAPRI) has produced 10-year forward global agricultural outlooks from its inception in 1984. FAPRI projections are developed through the collaborative efforts of the Center for Agricultural and Rural Development (CARD) at Iowa State University and the Center for National Food and Agricultural Policy (CNFAP) at the University of Missouri-Columbia. Projections are based on a suite of non-spatial, partial-equilibrium, econometric models for dairy, ethanol, grains, livestock, oilseeds, and sugar. The latest FAPRI projections for the 2013 to 2022 period show grain production (including wheat, corn, barley and sorghum) increasing by 1.3 percent per year from 1.8 to 2.0 billion tonnes, oil seed production (including soybean, rapeseed, sunflower, palm oil, and peanut) increasing by 1.5 percent per year from 453 to 520 billion tonnes, and sugar production (including sugarbeet and sugarcane) increasing by 3.2 percent per year from 2.0 to 2.6 million tonnes (FAPRI 2012).

The AGLINK-COSIMO model (OECD 2007) jointly maintained by the OECD and FAO is another recursive-dynamic, partial equilibrium, supply-demand model of world agriculture used for projections purposes. This model underpins the annual OECD-FAO Agricultural Outlook publication that provides decade ahead (annual time step) consumption, production, stocks, trade and price prospects for 33 commodities, with the latest projection (OECD-FAO 2013) spanning the 2013-2022 period.

In addition to these partial equilibrium projections efforts there are a series of less regular projections based on several recursive-dynamic multi-sector, multi-region computable general equilibrium (CGE) models, including the ENVISAGE (ENVironmental Impact and Sustainability Applied General Equilibrium) (for details see Van der Mensbrugghe 2009) and the LINKAGE model (for details see Van der Mensbrugghe 2011) developed at the World Bank.

2. International Agricultural Prospects (iAP) Model

The partial and general equilibrium models used to project the future prospects of global consumption and production are structural in nature. They derive equilibrium outcomes in terms of prices and quantities by relying on detailed descriptions of consumer, producer, and government motivations and endowments of primary factors like land and labor cast within the context of explicit market institutions. A virtue of these models is their strong theoretical foundations, though operationally these foundations must inevitably be caricatured. Another strength is that their level of detail provides an opportunity to assess how exogenous perturbations to the system such as changes in government trade or tax policy or productivity shocks due to climate change are likely to affect economic activity. Thus, they serve as a useful tool for conducting comparative static analyses in large, complex economic systems. The disadvantage is that these models are data intensive requiring the specification of a large number of parameters such as own-price, cross-price, expenditure, and income elasticities that can vary across commodities, regions, and time. Often the information available for estimating or calibrating these parameters is limited, while model outcomes can be quite sensitive to the values ultimately employed (Valin et al. 2014; von Lampe et al. 2014).[4] This is a particularly salient challenge when using these types of models to assess the global prospects of agriculture—not least assessing those prospects for several decades into the future—because many pertinent elasticities will evolve overtime in ways that can be difficult to forecast.

The iAP model differs in that we opt for a more parsimonious approach. It is a reduced form approach to the extent that we econometrically identify the relationship between equilibrium food consumption and its key drivers for which plausible projections were to hand or within reach. It also has structural elements to the extent that spatial production relationships are described in the context of Ricardian and Heckscher-Ohlin notions of comparative advantage and then used with econometric estimates of crop yield growth to ascertain how global crop production can plausibly fulfill consumption prospects. A key advantage of our approach is its more modest data requirements and strong empirical foundations, including paying explicit

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[4] For example, Rosegrant et al. (2012, p. 10) report that the IFPRI IMPACT model is calibrated on demand elasticities taken from a 1998 compilation made available on-line by USDA. The latest version of this database is available at USDA, ERS (2013b). It was last updated in February 2006 and consists of an extensive and well documented compilation of own, cross price, expenditure, and income elasticity estimates for various commodities (or commodity aggregates) spanning various countries and various periods taken from a host of studies using a range of estimation methodologies. However, the compilation is neither comprehensive (vis-à-vis the commodity and country composition being projected) or necessarily properly calibrated for long-run projections purposes to the year 2050.

attention to the spatially sensitive aspects of agricultural production which aspatial market models ignore. A disadvantage is that equilibrium price relationships are implicit as are its theoretical links.

2.1 Model Overview

The model starts with a country-level econometric characterization of equilibrium food consumption in terms of plant- and animal-source food calories based on national population, per-capita income, and—explicitly for the first time to our knowledge in a global agricultural projections setting—elements of the age structure of the population. This characterization is used with population, income, and age structure projections to project plant- and animal- sourced calorie consumption through to 2050. Biofuel consumption in terms of biodiesel and ethanol was also projected through to 2050 taking into account projected changes in feedstock-to-fuel conversion ratios (arising from changes in conversion technologies), crop composition and non-crop sources of biofuel feedstocks, often ignored recycling of biofuels co-products into animal feed, and projected government biofuel policies. Biodiesel, ethanol, and plant- and animal-sourced food calories were then translated into the global crop production necessary to fulfill these consumption prospects.

With a view of the likely trajectory of global agricultural consumption in hand, we then assess the prospects that growth in agricultural production can meet projected consumption, as well as the land use and other implications of that production. To do this, we estimated crop-by-region yield growth models for 16 crop categories and 17 regions. Conditioned on these yield growth estimates, we dynamically, and in a spatially sensitive fashion, model the implied crop area responses required to meet the projected changes in consumption, allowing for constraints in the changing amount of usable (and variably "suitable") land per crop per region per year.[5] The projected land use patterns are adjusted according to crop suitability criteria based on IIASA's year-2000 global agro-ecological zones assessment (Fischer et al. 2000).

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[5] In this respect our approach has similarities to the Alexandratos and Bruinsma (2012, p. 7) wrote "Since at the world level (but not for individual countries or regions) consumption equals production…" and "…the projected increases [in production cum supply] are those required to match the projected demand as we think it might develop." One major difference is that we make a clear conceptual distinction between our reduced form approach to modeling equilibrium changes in the quantities consumed, and the feasibility of production meeting that projected consumption, versus other attempts to model shifts in supply and demand per se.

2.2 Global Crop Consumption Prospects

An overview of our procedure for projecting crop consumption using kilocalories consumed as food and biofuel prospects is summarized in Figure 1. In this section, we provide further details regarding these procedures.

[Figure 1: *Estimation of Crop Consumption*]

2.2.1 Food Prospects

Counting Calories

Calories provide a convenient and practical unit of account. In general, goods can be measured in quantity- or characteristics-space (Gorman 1980; Beatty 2007). In what follows, we focus on a fundamental characteristic, the ability to provide energy when eaten. This has the advantage of greatly reducing the dimensionality of the consumption projections exercise. Instead of considering interrelated consumption of potentially hundreds of commodities, we use a single additive characteristic of each commodity, its caloric content, as a metric of food consumption. A limitation of our approach is that we do not directly consider many other attributes of food that may drive consumption, such as taste, form, perishability, protein and micro-nutrient content. However, a stylized fact is that the primary dietary change that occurs as incomes rise and demographics shift is captured by the proportion of calories that derive from plant versus animal sources, which we do consider. [6]

Accounting for World Consumption of Calories

In the iAP model, we begin by estimating the likely quantity of calories consumed from plant and animal sources over the period 2010–2050. The consumption model builds on a simple Engel-style relationship between food quantities demanded and income. We take total calories as our measure of quantities and GDP per-capita as our measure of income. Figure 2, Panel a summarizes this relationship (in natural logarithms) for the period 1980-2009. Over the support of the data, the relationship is roughly linear (in logs), though at higher levels of GDP per-capita the slope declines, reflecting a declining income elasticity for calories.

[Figure 2: *Global Calorie Consumption, 1980-2009*]

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[6] Jureen (1956) also used calories to aggregate food items into two large groups, “animal foods” and “vegetable products” (i.e., cereals, potatoes, sugar, vegetable oils, fruits and vegetables, etc), for one of the earliest multi-country economic examinations of the changing demand for food.

Another important stylized fact is that the calories consumed from animal sources relative to plant sources increases as countries become wealthier (Figure 2, Panel b). To capture this effect, we produce separate estimates of total calories consumed from plant and animal sources. A final important feature of our approach is that while the midline projection of global population in 2050 is 9.6 billion people, there is likely to be a marked shift in the distribution of age over this period as well. Figure 3, Panel a illustrates the high, midline and low population scenarios (right-hand axis) as well as the shares of the global population under 20 years of age, between 21 and 60 years, and over 60 years (left-hand axis). Notably, while the share of the world's population between 21 and 60 varies only slightly over the period, the share of the population under 20 years old declines from 45 percent in 1980 to an estimated 28 percent in 2050. Further, the share of the global population over 60 years old increases from 8.6 percent to 21 percent over the same period. Thus, the world's population is aging—the share of population under 20 years old is falling, while the share over 60 years old is rising.

[Figure 3: *Global Demographics*]

China and India both have large populations—together they accounted for 37 percent of the world's population in 2010 (with slightly fewer people residing in India than in China). By 2050 their combined population share is projected to slip somewhat, to 32 percent, with the balance shifting a little away from China (15 percent of the 2050 world total) and towards India (17 percent). Over the same period, the share of people living in sub-Saharan Africa is expected to increase from about 12 percent to nearly 22 percent. While China and India will continue to dominate world population totals, the present and projected future age structure of those two populations differ dramatically (Figure 3, Panel b). In 2010, 40 percent of India's population was under 20 years of age (compared with 26 percent in China). By 2050, the 20 years or younger cohort in India will still account for 26 percent of their projected 1.62 billion people, but only 20 percent of China's 1.39 billion. In fact, China is rapidly aging and by 2050 will have a population pyramid very similar to that of Japan today, with 33 percent of its population projected to be older than 60 years (compared with 18.3 percent in India). To the extent that age has a measurable effect on the total amount and composition of calories consumed, these large demographic differences are worthy of attention.

Our consumption projections are based on the following equations:[7]

$$\ln\left(\text{kcal}_{it}\right) = \alpha + \beta_1 \ln\left(\text{pGDP}_{it}\right) + \sum_j \beta_j \ln\left(\text{pGDP}_{it}\right) \cdot d_{ji} + \sum_j \delta_j d_{ji} + \sum_k \gamma_k s_{kit} + \sum_l \eta_l r_{li} + \varepsilon_{it}$$

$$w_{it} = a + b_1 \ln\left(\text{pGDP}_{it}\right) + \sum_j b_j \ln\left(\text{pGDP}_{it}\right) \cdot d_{ji} + \sum_j \theta_j d_{ji} + \sum_k g_k s_{kit} + \sum_l \phi_l r_{li} + e_{it}$$

The first equation models the natural logarithm of total kilocalories consumed per person per day (from all sources) for country *i* at time *t* as a function of the natural log of per-capita GDP in 2005 PPP dollars (pGDP), which we allow to vary over the development spectrum by interacting it with indicator variables denoting income categories (high, upper-middle, lower-middle, low), designated d_{ji}. For each country and time period, we also include the share (s_{kit}) of the population between 0-20 years of age, and over 60 years of age (where *k* represents the age category). Finally, we include a series of indicator variables to capture the effect of time-invariant regional differences, denoted r_{li}.[8] The second equation models the share of total kilocalories derived from animal sources for country *i* at time *t* as a function of the same explanatory variables.

Data on per-capita calories per day from all plant and all animal sources by country over the period 1980-2009 are from the FAO Food Balance sheets (FAO 2012b).[9] Where possible, we worked at the lowest spatial unit of disaggregation; practically speaking this means we worked with successor states of the former USSR and Yugoslavia over the entire period. Data on population and the age distribution for the period 1980-2050 were obtained from the 2012

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[7] Several alternative families of models were estimated. Predictions from models estimated in logarithms were more stable and generated more plausible out-of-sample estimates compared with models measured in levels. More complicated dynamic structures were also tested, including linear and quadratic trends (global, region and country alternatives) as well as various lag structures. While these added some to the in-sample fit they also generated unstable dynamics in the out-of-sample predictions. This is driven by the fact that much of the net effects of the dynamics are implicitly incorporated into the projected per capita GDP and population projections.

[8] The regions used in the demand estimation differ from those used in the agricultural projections. Namely, the consumption estimates use the following country groupings: Asia & Pacific, Eastern Europe & Former Soviet Union, High Income, Latin America, Middle East & North Africa, and sub-Saharan Africa. A table mapping countries to regions is provided in Appendix 4.

[9] As Alexandratos and Bruinsma (2012) note, the FBS calorie data represent "national average apparent food consumption or availability (p. 24)" and not consumption as conventionally conceived. Like Alexandratos and Bruinsma (2012) and others, we treat these values as if they represent direct caloric consumption or disappearance. In practice, the differential between consumption and availability is also used in the food system (with a share of these calories deemed "wastage"), and thus it is appropriate to capture this usage within the model.

revision of the United Nations World Population Projections (UN 2013a, 2013b). The GDP data use World Bank and IMF sources, as reported by Fouré et al. (2012).

The resulting estimates were obtained via weighted ordinary least squares, using each country's population in a given year (or population projection, for predicted calories and animal-calorie shares) as the weights. Weighting improved in-sample prediction of world calorie demand relative to an unweighted version of the model.

Our model relies on the intuition provided by Figure 2, panel a, which plots the per-capita daily calorie consumption against per-capita GDP. The figure reveals a roughly linear relationship between the natural log of these variables. Results for the regressions are reported in Table 1, and the corresponding kilocalorie consumption projections are shown in Table 2. The results imply that a one percent increase in per-capita GDP yields a 0.13 percent increase in calories consumed from all sources in high-income countries. The estimated effect of a change in per-capita GDP on caloric consumption is estimated to be slightly smaller in low- and middle-income countries. Further, as average per-capita GDP rises, the estimated propensity to consume calories from animal products increases with income until a country reaches the upper-middle income bracket, then decreases slightly for high-income countries. Critically, the income effect on both caloric consumption and the relative propensity to consume animal-sourced calories is positive at all levels of income.

[Table 1: *Consumption Model Point Estimates*]
[Table 2: *Global Calorie Consumption Projections*]

Our estimates imply that the age distribution of a country's population has relatively small but statistically significant effects on both the total calories consumed and the share of those calories that derive from animal sources. The results indicate that countries with a relatively larger share of their population in the younger (under 20 years old) or older (over 60 years) age groups tend to consume fewer calories than average. Age distributions also affect the source of calories, with the share of calorie consumption deriving from animal sources increasing as the population becomes relatively older.

This specification yielded the best in-sample performance in terms of predicting global calorie consumption. As a further validation of this exercise, we omitted the last ten (2000 to 2009) years of data and used data from the earlier period to predict the out-of-sample calorie consumption and the animal calorie share. The current specification also yielded the best global calorie prediction among the class of models without time trends. The model relies on a very small number of parameters to explain roughly 80 percent of both the variation in (logged) total calorie consumption and the share of calories from animal products. This parsimony reduces unstable out-of-sample dynamics. However, a potential weakness is that the quality of our projections is a function of the quality of the underlying GDP and population forecasts.

One complication of a model specified in logarithms is that given point estimates of the independent variables, we need to predict total calories in levels rather than logarithms. Thus, there is a retransformation problem since simply exponentiating the fitted values results in an underestimation of the transformed variable in levels (due to Jensen's inequality). Thus, we use a heteroskedastic-robust version of the smearing estimator specified by Duan (1983).

Converting Calories to Crops

Although consumption is projected in terms of plant- and animal-sourced kilocalories, the iAP model considers consumption and production in terms of crop output, measured in metric tonnes. Plant- and animal-sourced kilocalorie consumption is converted to crop consumption by utilizing information in the FAO's Food Balance Sheets (FBS) (FAO 2102b). The first step in this conversion aggregates the global FBS data into the 16 crop categories used in the iAP model. In this process, rice is converted from milled equivalent (as reported in the FBS) to paddy equivalent using a constant conversion factor based on 1961-2007 data from FAO (2012b). Further, the FBS reports rapeseed and mustardseed as a single category, but the iAP model does not include mustardseed. The corresponding FAO (2012b) data for each year are therefore used to derive the percentage of this aggregation accounted for by rapeseed, and that percentage is applied to the FBS aggregate to remove mustardseed from the data. Our "Other Cereals" crop category is an aggregate of the following FBS categories: "Cereals, Other", rye and oats. Finally, melons are included in our vegetables category.

The FBS data provide estimates of the amount of each commodity that was used for food, seed, processing, animal feed and "other utilizations." Since "processing" includes commodities processed for human food consumption, we assume that the consumption of plant-sourced calories reflects both food and processing uses of crops, with the exception of soybeans where we assume that 80 percent of the soybean processing reflects demand for animal feed. Similarly, feed uses of crops are assumed to reflect the demand for animal-sourced calories. The seed and “other” crop uses delineated in the FBS are assumed to be associated with either plant- or animal-sourced calories, according to which they are historically most highly correlated.[10]

The amount (in metric tonnes) of each crop is delineated into the portion that reflects plant- or animal-sourced calorie consumption, and we sum the tonnage attributable to each of these components of consumption separately for each crop (excluding cotton, the consumption of which is estimated separately). Next, the average metric tonnage of food and feed of each crop per billion kilocalories of plant- and animal-sourced calorie consumption is derived and used as a conversion factor. We create a vector of such conversion factors, each element of which is the tonnage of crop consumption per billion kilocalories. This vector is then used to convert the annual total plant or animal calories consumed into the corresponding implied quantity of crop consumed. These conversion factors are applied to the corresponding annual calorie consumption estimates for 2010-2050 to project crop consumption.

To check the accuracy of this procedure and the underlying assumptions, we applied the derived conversion ratios to the total plant- and animal-sourced kilocalorie consumption from the 1961-2007 FBS. That these (quasi-)in-sample predictions represented the observed data well for most crops was verified by regressing the estimated values on the global production of each crop as reported by FAO (2012a). The regressions for nine crops, representing about 84 percent of global output by weight in 2007, had R^2 values over 0.90 and twelve crops (representing almost 97 percent of output) had R^2 values over 0.73. The procedure was less accurate for three crops (barley, millet and sorghum), which together accounted for less than 3.5 percent of global output in 2007.

Applying a constant factor to convert from kilocalories consumed to the implied quantity consumed for individual crops produces generally good results, but does not account for changes in the *relative* propensity to consume different commodities. That is, although the procedure performs well in-sample, changes in the crop composition used to meet a given calorie consumed would not be captured using this method. Indeed, the data reflect an increasing tendency toward consumption of fruits, vegetables and sugarcane, and away from other commodities. To account for this, we performed simple time-series regressions to project the share of total tonnage

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[10] Seed and other uses of wheat, rice, sugarcane, roots & tubers, pulses, vegetables and fruits were most correlated with demand for plant-derived calories. All other crop categories were most correlated with demand for animal-derived calories. This method exploits correlation between animal- or plant-sourced calorie demand and should not be interpreted as attributing demand for “other uses” and “seed” to kilocalorie demand.

consumed per billion plant-based kilocalories accounted for by these commodities. Plotting the trend in the commodity share accounted for by fruits reveals a structural break at around 1992, after which the fruit share appears to increase more-or-less linearly. Thus, we project the fruit share forward based on a linear time trend of that variable for 1993-2007. The post-1961 data were used in similar models to project the shares for sugarcane and vegetables (the latter using a logit model). These regressions fit generally well, with R^2 values ranging from 0.64 to 0.79. The projected shares for these three crops were then used to create an annual series of implied calorie-to-commodity conversion factors for 2010-2050, proportionally adjusting the conversion ratios of other crops such that the total tonnage consumed per billion plant-derived kilocalories was maintained.[11] The historical crop composition of animal feed was much more stable; therefore, we did not adjust the conversation factors for our projected animal-sourced kilocalories.

2.2.2 Biofuels Prospects

For this version of the iAP model, the biofuels assessment entails a) projecting the production of biofuels in light of prospective changes in technologies and policies that affect that estimate, b) converting the likely total biofuels production into the quantity of feedstock used to produce it, and c) estimating the amount of by-products (e.g., distillers dried grains with solubles, DDGS) that can be fed to animals, which substitutes for the respective input crop as an animal feed source. The model takes explicit account of six biofuels-producing crops (maize, wheat, sugarcane, rapeseed/canola, sunflower seed and soybeans).

Background

In 2010, 37.7 percent of the U.S. corn crop and the oil from 7.1 percent of the country’s soybean crop were used as feedstocks for biofuels production (USDA, ERS 2013a; AgMRC 2013).[12] That same year, 55 percent of Brazilian sugarcane production was distilled into ethanol and 67 percent of European Union (EU) rapeseed production was used to produce biodiesel (USDA, ERS 2013a; USDA, FAS 2012). During the past decade, the global production of biofuels rose more than five-fold (or more than 20 percent per year), from 18.3 billion liters in

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[11] Maize, rapeseed, soybeans, sunflower seed and rice were not adjusted and therefore total tonnage of agricultural output per billion plant-derived kilocalories increases over time as would be expected if overall consumption were shifting towards relatively less calorie dense foods such as fruits and vegetables.

[12] In 2001, the corresponding biofuels feedstock shares for the United States were much smaller: 7.2 percent for corn and 0.47 percent for soybeans.

2000 to 110.1 billion liters in 2011 (Figure 4, Panel a). The majority of biofuels production consists of ethanol derived from corn and sugar (mainly cane but also beets) and biodiesel made from soybean and vegetable oils such as canola, rapeseed, palm oil, and sunflower (Figure 4, Panel b).[13] The United States accounted for 56.4 percent of the world's biofuels production in 2011, followed by Brazil (25.4 percent) and Europe (14.5 percent) (EIA 2013).

[Figure 4: *Global Biofuels Production, 2000-2050*]

Methodological Details

Ethanol and biodiesel production are derived based on growth rates implied by OECD-FAO (2011) for 2010-2020 and from Alfstad (2008) for 2020-2030.[14] Biofuel production for 2030 through 2050 is derived by carrying forward trends implied by the Alfstad estimates for 2025-2030. Specifically, the projected annual rate of increase in biofuels production for 2031-2035 is projected to be one-third of Alfstad's (algebraic) rate of increase for the 2026-2030 period while the projected annual rate of increase for each subsequent five-year period was specified as one-half the annual growth rate of the previous period. In all cases, the minimum specified growth rate was 0.95 percent per-year, reflecting historic rates of change due to improvements in productivity over time.

Modifications to the above approach were made in three cases where the data did not conform to the typical situation. First, Alfstad projects annual U.S. grain ethanol production will decline from 2025-2030; the implied rate of decline for this period was used to project U.S. grain ethanol values through to 2050. Second, Alfstad projected a decline in Latin America's biodiesel production from 2025-2030. No rationale was provided for this projected decline, and we are of

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[13] Other agriculturally-related biofuels feedstocks include cassava and other assorted sources such as whey and beverage waste. According to Copper and Weber (2012, Figure 2), 462.1 million tons of agriculturally related products went into biofuels production in 2010. Sugarcane made up 63 percent of the total, grains accounted for 31 percent, and sugar molasses (from cane and beet) and sugarbeet 5.5 percent. Fresh cassava, whey, beverage waste and other feedstocks accounted for just 0.004 percent of the total.

[14] The OECD-FAO study provides a single set of estimates of the amount of biofuel produced by region of the world through to 2020. Alfstad (2008) reports first and second generation biofuels estimates for each region of the world for a baseline, high and low oil price scenarios through to 2030. First generation biofuels are ethanol produced from sugarcane, starch (corn, grain sorghum, cassava and wheat), and biodiesel made from vegetable oils (soybean, rapeseed, sunflower, palm), animal fats, and waste cooking oils. Second generation biofuels are those produced from cellulose, hemicelluloses and lignin. They include cellulosic ethanol—and so called drop-in fuels (i.e., a fuel substitute rather than a fuel additive to replace methyl tertiary-butyl ether (MTBE) as a means to increase the octane ratings of gasoline)—made from processes including pyrolysis, and gasification Fischer-Tropsch processes (Butler et al. 2011; French 2010; and National Research Council 2011).

the opinion that the declining trend is unlikely to continue in this region.[15] Thus, the annual rate of increase for 2021-2025 is used with the procedure described above to complete the biodiesel production projection for Latin America through to 2050. Finally, Alfstad did not provide biodiesel projections for 2025-2030 for two regions (the remainder-of-the-OECD and the remainder-of-the-world). For these regions, we apply the above procedures to the projected rate of increase for 2016-2020 to complete the projections for 2021-2050.

To convert from ethanol production to the amount of crop feedstock consumed in its production, we start with a vector of annual ethanol output shares by region and type of processing, including: conventional dry mill, dry mill with oil extraction, wet mill, and "new" dry mill. These processing shares were slowly adjusted from the current (2010) technology mix to reflect expert opinion on anticipated use by year. Each of these technologies has an associated (implied) ethanol and DDGS output per unit of crop (wheat, corn or sugarcane) input (e.g., Table 3). The "new" dry mill technology accounts for anticipated increases in productivity beginning in 2015 (due to implementation of the hot process) and, additionally, conversion of pericarp using cellulosic technologies beginning in 2022 (as ethanol productivity increases, DDGS output is decreased accordingly).

[Table 3: *Yield per Bushel of Corn, by Ethanol Production Technology*]

Ethanol productivity and feed by-products for each technology are estimated based on reported values for dry milling (RFA 2013). For example, RFA reports that, on average, 2.8 gallons of ethanol and 16.7 pounds of animal feed are produced per U.S. bushel of corn processed in a conventional dry mill. Based on consultation with knowledgeable experts along with an analysis of data from pilot plants, we assume that wet milling has a slightly lower yield (2.6 gallons per bushel) and that the hot ethanol process has a higher yield (3.02 gallons per bushel). Accounting for additional output from cellulosic conversion of pericarp, combining these new technologies will yield about 3.22 gallons per bushel.

In 2011, U.S. shares of grain ethanol production by technology were estimated to be about 70 percent conventional dry mill, 18 percent dry mill with oil extraction and 12 percent wet mill. These are slowly adjusted such that by 2050, 62 percent of grain ethanol output is expected to be produced using "new" dry mill technologies, largely supplanting conventional dry milling. We

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[15] To inform our opinion on regional and country biofuels policy and technology trends we canvassed a good deal of literature, the highlights of which we summarize in Appendixes 2 and 3 of this paper.

suppose that U.S. ethanol production will continue to use only corn as a feedstock. Thus, taken together, the U.S. technology shares and conversion ratios imply a national average amount of ethanol per bushel of corn, which changes over time as the technology mix is adjusted. We can therefore estimate the amount of corn feedstock required to meet a given annual amount of ethanol production in any given year.

Other regions use various combinations of corn, wheat and sugarcane to produce ethanol. For each region, the proportions deriving from each crop are assumed to remain constant at the values reported in the USDA's Global Agricultural Information (GAIN) reports (USDA-FAS various reports). For example, Europe uses both corn and wheat in its ethanol production. We apply different feedstock-conversion rates for corn and wheat (with lower conversion for wheat). Corn conversion is assumed to be the same conversion rate as in the United States (i.e., ranging from 50,000 to 53,571 gallons per million pounds of feedstock) while wheat uses a slightly lower constant conversion ratio.

For biodiesel, we start with the projected total production by year derived as reported above. These annual production values are converted to gallons of biodiesel deriving from each feedstock based on the GAIN reports (e.g., reporting the percentage of biodiesel production that derives from each feedstock in a given year). Next, the gallons-by-feedstock estimates are converted to crop equivalents. Since biodiesel production is essentially an oil-extraction process, there is little room for technological improvement in biodiesel output per unit of feedstock, and we therefore apply constant crop-to-biodiesel conversion ratios for all crops. Whenever biodiesel is produced, there is also some ethanol production (via glycerin) that is also taken into account (assuming countries do not waste this byproduct).

Figure 5 shows the annual trend in global biofuels production from 2003 to 2011, along with our projected output through to 2050 compared with various other estimates. Overall, global biofuels production is projected to increase by almost 169 percent (averaging 2.4 percent per year) from 2011 to 2050, and totaling 302.5 billion liters in the final year of our projections period. This overall growth in global biofuel production masks a projected slowdown in the growth of biofuels over the longer run: from growth of 4.4 percent per year from 2011 to 2025 to 3.3 percent per year for the 2025-2030 period (consistent with the slowdown evident in the OECD-FAO (2011) and Alfstad (2008) projections). We foresee a continuing decline in the rate of growth of global biofuels production thereafter through to 2050, in line with emerging perspectives on the projected consumption of oil as (mandated) fuel efficiencies continue to improve and natural gas increasingly substitutes for oil-based fuels.[16]

[Figure 5: *Global Biofuels Production, 2003-2050*]

United States production is projected to peak at 80.2 billion liters in 2030, dropping to 74.5 billion liters in 2050, such that the U.S. share of global production falls from 48.2 percent in 2011 to 24.6 percent in 2050. We project Latin America to be the biggest source of biofuels by 2050, with 83 percent of the production being ethanol sourced mainly from Brazilian sugarcane production. At 73.8 billion liters, total biofuels production in Europe in 2050 is close to the corresponding U.S. figure, but with 29.6 percent of that production being for biodiesel (compared with a projected 12.8 percent of the U.S. production going to biodiesel that year). The growth in overall biofuels production overstates the implied growth in the use of agricultural crops for biofuels to the extent that our estimates account for projected improvements in crop-to-biofuels conversion efficiencies and a move towards cellulosic feedstocks assuming pilot scale technologies that now appear cost-competitive are commercialized during the projections period (Dutta et al. 2011; Pezzullo 2013).[17]

2.2.3 Combining Food and Biofuel Prospects

The final step in deriving our global crop consumption prospects is to aggregate food and biofuel prospects. Since these food prospects implicitly include biofuels usage (as part of the FBS "processing" category), we do not add our biofuels use estimates to these values. Rather, we assume that the (unknown) 2010 biofuels usage included in the FBS data equals our 2010 biofuels use estimate for each crop. We then difference our 2011-2050 biofuels projections by subtracting the 2010 usage of each crop. This yields a projected series of net changes in biofuels-sourced usage for each crop, which are then added to our 2011-2050 food crop consumption prospects. Thus, if the projected biofuels use of a crop decreases below (or

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[16] Our projected annual rate of increase in global biofuel production is 2.64 percent per year for the period 2031-2035 (i.e., beginning of 2031 to the end of 2035), 1.32 percent per year for the period 2036-2040, and 0.95 percent per year for the period 2041-2050. Notably, a number of recent reports point to the pending prospects of "peak oil" in terms of "peak consumption," in contrast to the "peak production" scenarios that were prominent until quite recently. See for example, Economist (2013a and b), Hughes et al. (2011), Kleinman et al. (2013), and Morse et al. (2012).

[17] The most likely feedstocks for cellulosic ethanol are corn stover (perhaps harvested by specialized companies rather than farmers) and, especially wood, that hitherto supplied the now dwindling demand for paper production, at least in some (large) markets, including the United States (Ince 2009; Ince and Nepal 2012).

increases above) the estimated 2010 biofuels usage of that crop, our more explicit accounting of biofuels futures will decrease (or increase) the projected consumption of that crop accordingly.

2.3 Projecting Global Food Production

Given our estimates of the agricultural output required to satisfy global human food, animal feed and biofuel consumption, we now describe the procedures we used to assess the prospects of crop production meeting this projected growth in agricultural consumption. We do this by way of a dynamic, spatially-explicit determination of the amount and location of crop production among 17 regions worldwide, subject to the available agricultural cropland, the suitability of that land to grow each particular crop, and the prospective changes in crop yields for each of the 16 crop categories that we modeled.

2.3.1 Changes in Crop Yields

The process of projecting yields began by identifying a set of plausible crop yield models. Yield model selection was based on an econometric analysis of production, area, and yield data for 1961 to 2010. Country level data were acquired from (FAO 2012a) for 16 crop categories: barley, cereals, fruit (excluding melons), maize, millet, pulses, rapeseed, rice (paddy), roots & tubers, seed cotton, sorghum, soybeans, sugarcane, sunflower seed, vegetables & melons, and wheat. These data were first aggregated to 16 production regions (see Appendix 4), namely Argentina, Australia, Brazil, Canada, China, European Union (EU12), India, Japan, Mexico, Rest of Africa & the Middle East (R_Af_ME), Rest of Asia (R_Asia), Rest of Latin America (R_LA), Rest of the World (ROW), South Africa (S_Africa), the United States (USA) and the Former Soviet Union (R_FSU plus Russia).

Plots of yield trends suggested that methods used by FAO to partition crop production between Russia and the Rest of the Former Soviet Union countries prior to the collapse of the Soviet Union were inconsistent—yield trends for many crops shifted implausibly in 1992. Therefore, the data for Russia and the Rest of the Former Soviet Union were further aggregated for subsequent analysis, which resulted in more plausible yield trends. Similarly suspicious single year shifts were also noted in the yield trends for China barley in 2001, Argentina fruit in 1980, Rest of Latin America fruit in 1985, and Rest of World fruit in 1985. Peculiar precipitous multi-year increases in Brazil seed cotton between 1998 and 2001, and declines in European Union seed cotton between 2005 and 2008 were also noted when they produced implausible econometric results for the range of specifications that were explored (a plausible explanation for the precipitous decline in European Union seed cotton yields beginning in 2005 is the elimination of cotton subsidies in 2004).

After preliminary exploratory and econometric analysis looking at a variety of model specifications (e.g., log versus level models, growth rates versus yields, and various yield lag structures), a set of eight nested yield models were estimated for each crop category. The dependent variable for these models was the region- and year-specific natural log of yield. Explanatory variables for the most general specification of the model included region specific intercepts, a one-period lagged area share of the crop (relative to the total area of all crops in the region), a one-period lagged total area of all crops in the region, and a one-period lagged yield.[18] The area share captured the observed comparative advantage of the crop in a region; the total area captured the scale of agricultural production in the region; and the lagged yield was used to capture the state of technology in the region. These variables entered the model alone and were also interacted with both a year and a year-squared variable, where the year was normalized by subtracting 1961. Other explanatory variables were indicator variables to capture the idiosyncratic structural shifts in yield evident from exploratory yield plots.

Formally, the general structure of these nested models was:

$$\begin{aligned}
\ln\left(Y_{rct}\right) = {} & \sum_{r\in R}\alpha_r d_r + \alpha_S \frac{100\times A_{rct-1}}{\sum_{c\in C} A_{rct-1}} + \alpha_A \sum_{c\in C} A_{rct-1} + \alpha_{LY} Y_{rt-1} + \\
& \theta_{China\ Barley\, t\geq 2001} b_{China\ Barley\, t\geq 2001} + \theta_{Argentina\ Fruit\, t\geq 1980} b_{Argentina\ Fruit\, t\geq 1980} + \\
& \theta_{R\_LA\ Fruit\, t\geq 1985} b_{R\_LA\ Fruit\, t\geq 1985} + \theta_{ROW\ Fruit\, t\geq 1985} b_{ROW\ Fruit\, t\geq 1985} + \\
& \theta_{Brasil\ Seed\, Cotton\, t\geq 2001} b_{Brasil\ Seed\, Cotton\, t\geq 2001} + \theta_{EU12\ Seed\, Cotton\, t\geq 2001} b_{EU12\ Seed\, Cotton\, t\geq 2008} + \\
& \left(\sum_{r\in R}\beta_r d_r + \beta_S \frac{100\times A_{rct-1}}{\sum_{c\in C} A_{rct-1}} + \beta_A \sum_{c\in C} A_{rct-1} + \beta_{LY} Y_{rt-1} \right) \times \left(t-1961\right) + \\
& \left(\sum_{r\in R}\phi_r d_r + \phi_S \frac{100\times A_{rct-1}}{\sum_{c\in C} A_{rct-1}} + \phi_A \sum_{c\in C} A_{rct-1} + \phi_{LY} Y_{rt-1} \right) \times \left(t-1961\right)^2 + \varepsilon_{rct}
\end{aligned}$$

where *R* is the set of 16 production regions used in the analysis; *C* is the set of 16 crops; Y_{rct} is the yield for crop *c* in region *r* and year *t;* A_{rct} is the area of production for crop *c* in region *r* and year *t;* d_r is an indicator variable equal to 1 for region *r* and 0 otherwise; $b_{rct\geq T}$ is an indicator variable equal to one for crop *c* in region *r* when year *t* is greater than or equal to *T* and zero

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[18] Other lag structures were also examined, but we opted to maintain a more parsimonious approach.

otherwise; ε_{rct} is a normally distributed error with mean 0 and variance $\sigma_r^2 = \sqrt{e^{\sum_{r\in R}\lambda_r d_r}}$ for crop *c* in region *r* and year *t*; and the αs, βs, θs, ϕs and λs are estimable parameters. The parameters of the model were estimated separately for each crop using weighted maximum likelihood where the weights were equal to the world area share of crop *c* in region *r* and year *t* (i.e., $\frac{A_{rct}}{\sum_{r\in R} A_{rct}}$). Since the structural shifts in Brazilian and European Union seed cotton took place over multiple years, observations for 1999 and 2000 in Brazil and 2006 and 2007 in the European Union were dropped from the seed cotton analysis.

Given this general structure, the eight different models estimated for each crop can be described by the parameter restrictions that were imposed:

Model 1: Included no restrictions.

Model 2: Excluded lagged yields: $\alpha_{LY} = \beta_{LY} = \phi_{LY} = 0$.

Model 3: Excluded quadratic time trends and their interactions: $\phi_r = \phi_S = \phi_A = \phi_{LY} = 0$ for all $r \in R$.

Model 4: Excluded quadratic time trends and their interactions, and lagged yields: $\phi_r = \phi_S = \phi_A = \alpha_{LY} = \beta_{LY} = \phi_{LY} = 0$ for all $r \in R$.

Model 5: Excluded lagged crop area shares, crop area and yields: $\alpha_S = \alpha_A = \alpha_{LY} = \beta_S = \beta_A = \beta_{LY} = \phi_S = \phi_A = \phi_{LY} = 0$.

Model 6: Excluded quadratic time trends, and lagged crop area shares, crop area and yields: $\phi_r = \alpha_S = \alpha_A = \alpha_{LY} = \beta_S = \beta_A = \beta_{LY} = \phi_S = \phi_A = \phi_{LY} = 0$ for all $r \in R$.

Model 7: Assumed common linear and quadratic time trends: $\beta_r = \beta$ and $\phi_r = \phi$ for all $r \in R$.

Model 8: Excluded quadratic time trends and their interactions, and assumed common linear time trends: $\beta_r = \beta$ and $\phi_r = \phi_S = \phi_A = \phi_{LY} = 0$ for all $r \in R$.

This combination of models provided flexible fits to the observed data as is illustrated by Figure 6 for Sorghum in India. In this figure Models 4, 6 and 8, suggest that yields are increasing at an increasing rate. Model 3 suggests a fairly constant growth rate. Model 5 suggests yields are increasing at a decreasing rate. Models 1, 2 and 7 suggest yields will drop precipitously over time.

[Figure 6: *Indian Sorghum Yields for 1961 to 2010 and Yield Model Projections for 1961 to 2050*]

Each of these models was used to project yield trends from 1961 to 2050 as in Figure 6. These projections were compared for each region and crop separately. Models with implausible yield projections to 2050 (like Models 1, 2, 5 and 7 in Figure 6) were eliminated, including those that exhibited explosive yield growth, rapid yield decline, or other types of unreasonable or unstable dynamics.[19] Of the remaining plausible models, the one with the highest within sample R^2 was selected for each region and crop (Table 4). The selected models account for more than 90 percent of the 1981-2010 variation in yield for each of eleven crops; more than 80 percent for a further four crops; and 64.7 percent for one crop (sunflower seed). The selected models were not used to directly forecast yield; rather they are implemented within the structure of the landscape allocation model discussed below.

[Table 4: *Crop Model Specifications Used in the iAP Model*]

2.3.2 Reconciling Global Consumption and Production

The final step in implementing the iAP model derives a spatial allocation of crop production that meets the projected growth in consumption. In doing so, projected land use patterns are adjusted according to crop suitability criteria based on IIASA’s year-2000 global agro-ecological zones assessment (Fischer et al. 2000).

Accounting for Land Availability

Increases in the consumption of each crop could be met by increasing the area per crop, increasing yields, or both. In the iAP model, the amount of land suitable for cultivation is constrained, and crop production has a site-specificity because of agro-ecological factors.[20] To

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[19] In assessing the plausibility of these projected yield trajectories from 2010 to 2050 we took into account annual yield growth rates and yields in all regions from 1961 to 2010, and our collective knowledge of important socioeconomic and agronomic factors likely to affect yields. The yield effects of irrigation, increased use of improved seeds, fertilizer and other chemicals and mechanization are all implicit in the yield model specifications. Expert opinion on regional prospects for technology adoption informed our choices among alternative plausible crop-by-region specifications.

[20] Beddow et al. (2014) discuss the equally important role of spatially variable economic factors (e.g., input and output prices) in accounting for land use patterns.

account for land availability, we included only areas deemed either "suitable" or "very suitable" for cropping in mixed input systems according to Fischer et al. (2000), thus excluding lands that are relatively unproductive, used for infrastructure or settlement, or dominated by forest ecosystems.[21] While some forested areas exhibit high potential crop productivity, we assumed this land will not be cleared for agricultural purposes.

The model is initialized with an estimate of the available area for each crop in each region as of 2010, calculated based on the suitable area and FAO's estimate of land already under production. Available area is allocated to each crop in each region in proportion to the area currently used for that crop. Thus, we assume that countries will continue to grow crops that they currently produce (e.g., Russia is unlikely to start growing cotton, and rice production is unlikely to appear in the United Kingdom).

Land Allocation Dynamics: Deriving Cropping Patterns by Region

The land allocation procedure is summarized graphically in Figure 7 and was run in a stepwise, dynamic fashion for each year from 2011 through 2050. First, estimated yields for each year, *t*, are derived using the year *t*-1 yields and land allocation (see above). For 2010, the land allocation and yield are given by the 2010 FAO data, and are the model-estimated yield and allocation thereafter. Given these estimates of year-*t* yields, the model proceeds by determining if the projected demand for each crop can be met using the previous year's area within each of our 17 regions. For each crop, areas under production are adjusted such that output—determined as projected yield multiplied by allocated area—equals global consumption for each crop. If the projected output given the current year's projected yields is greater than the amount consumed, areas in all countries are scaled back such that consumption of the crop equals its production globally. The implicit assumption is that while comparative advantage drives increases in area, farmers everywhere are equally unwilling to idle land.

[Figure 7: *Overview of Crop Allocation Procedure*]

Conversely, if the previous year's total area produces less output than is consumed for each crop under the current year's projected yields, areas in each country are scaled up in proportion to potential production shares. Thus, countries that have more available area or a higher yield for a crop will increase their area more than countries that have little remaining area or relatively

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[21] Model results are largely insensitive to the inclusion of moderately suitable or even marginally suitable land. Specifically, we use the Fisher et al. (2000) "mixed input under rainfed and/or irrigation conditions" variable.

low yields. Since aggregate consumption and production worldwide are taken to be resolved by trade, our method draws on the notion that comparative advantage derives from having a large available area that is suitable for the crop or from having a relatively high crop yield.[22] These correspond roughly to Heckscher-Ohlin and Ricardian notions of comparative advantage, respectively. Finally, the new areas under production are removed from the available area pool for each crop in each region and the process cycles through again for year *t* + 1.

When integrated within the land use model, the crop yield equations (section 2.5) generate yield trajectories in response to endogenously changing land-use patterns. During the period 1961-1990, yields for most crops grew quickly ranging from annual growth rates of 0.66 percent per year for fruits to nearly 3.0 percent per year for wheat (Table 5). The subsequent two decades saw yield growth rates slow for all crop categories except fruits. Our estimates carry forward this generalized slowdown in crop yield growth rates, with annual growth rates ranging from 0.62 percent per year for rice to 1.33 percent per year for maize for the period 2010 to 2050.

[Table 5: *Past and Projected Global Average Growth in Crop Yields*]

3. Conclusion

The iAP model is implemented in a modular fashion, such that each component (i.e., yield projections model, land allocation, biofuels projections, calories consumed) is separable. This structure has several advantages. By design, the key iAP components are open to scrutiny because there are few feedback loops in the model components such that, for example, the calories consumed by way of plant- or animal-sources or the derived demand for crops by way of projected ethanol production can be assessed on their own terms. Further, each of the individual components can be refined as new data, methods and procedures emerge. Further, the modules can be modified to answer new questions without revising the entire model.

The model results include annual projections of the yield, area and output for each crop in each region. Figure 8 includes three panels that plot the global output, area and yield by crop for the entire period 1961-2050, using historical FAO (2012a) data for the 1961 to 2010 and the midline (medium fertility) results of the iAP model for 2011-2050. The figure reveals that the

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[22] A long-run model need not account for stocks since only the net variation in stocks over the projected period would affect total consumption. This net change would constitute only a small share of each year’s production.

projected global yield, area and output for each crop are a plausible continuation of past trends for these variables; that is, the model projections do not radically depart from past global trends. As described and discussed in Pardey et al. (2014), we project that growth in global agricultural production will be sufficient to satisfy the growth in agricultural consumption without the need to plow in substantial additional areas (and with no further loss of forest-dominated areas). This is true even with declining growth rates in crop yields and continuing growth in the production of biofuels, population and per-capita incomes.

[Figure 8: *Actual (1961-2009) and Projected (2010-2050) Yield, Area and Output, by Crop*]

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Appendix 1: Climate-cum-Weather Considerations

Agricultural production is an intrinsically biological phenomenon, and these inherently variable natural processes interact in complex ways with market factors to influence the pattern of agricultural production. Many of these biological processes are especially site sensitive and change over time in ways that are still not fully (and sometimes still poorly) understood, especially at national or global scales of assessment. Thus to meaningfully assess the consequences of climate on the likely (or even possible) futures of global agricultural production requires a) a set of global climatological projections that are relevant in terms of the range, reliability, and specificity of the climate variables that are required to plausibly model the effects of climate on crop and animal production, b) a settled body of knowledge about the effects that prospective changes in climate might have on agricultural production at spatially relevant (i.e., geographically extensive) scales of analysis, and c) an understanding of the (changing) location and timing of agricultural production worldwide, so that the relevant climatology (in terms of both the *location* of production and the *timing* of crop and livestock operations) is used in assessing the production consequences of climate.

Unfortunately, our understanding of the biology and science of the production processes at play linking climatology to global agricultural production is still in flux, adding even more uncertainty to the long-run implications of changes in climate on agricultural production. For example, in trying to assess the crop yield consequences of the elevated CO2 concentrations expected with future climate change, Parry et al. (2004) reported sizable, positive output effects when using crop growth models in conjunction with modeled changes in climate, whereas Lobel and Field (2008) applied statistical methods to historical (1959-2002), country-level averages of maize, wheat and rice yields and found it difficult to reveal any precise effects on crop yields of changing CO2 levels, which they deemed as "…one of the most uncertain and influential parameters in models used to assess climate change impacts [on crop yields] (p.39)." More recently, Reich and Hobbie (2013) reported the results of a 13-year field trial and found that nitrogen limitations—which are pervasive in natural as well as many agricultural systems—significantly curtailed the ability of elevated CO2 levels to increase plant biomass production.[23]

The weather varies over time and across space, so specifically where and when particular crops are planted or livestock is raised matters much for the consequences of that weather on crop or livestock production. Knowing, for example, that average temperatures are likely to increase, rainfall is likely to become more sporadic, and both variables are likely to exhibit more extreme occurrences (compared with the present ranges of temperature and rainfall) are of limited value in assessing the effects of these changes on, say, corn production. Average annual temperatures are not indicative of the temperature, flooding, or drought events affecting a crop at a particular stage of its growth cycle, and it is the latter that matters most in terms of the crop yield consequences of these weather events. Thus a drought or high heat event (or both) pre-

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[23] See also Long et al. (2006, p. 1918) who report that in field trials "…elevated [CO2] enhanced yield by ~50% less than in enclosure studies. This casts serious doubt on projections that rising [CO2] will fully offset losses due to climate change."

emergence will have a different consequence for corn yields than the same weather event at silking or some other stage of the crop's growth cycle (Beddow 2012). To meaningfully match weather (or climate) events to crop yields requires knowledge (or assumptions) about what crop is grown where and when. However, as Beddow (2012), Beddow and Pardey (2014), and Beddow, Pardey and Hurley (2014) show in the case of U.S. corn production, the location of agriculture varies markedly over time, and with it varies the specific weather-cum-climate that affects the crop in question. Moreover, farmer decisions as to what to grow, where and when (and how to grow those crops) are endogenous to weather and many other (including technological and economic) factors, making it doubly difficult to develop a plausible sense of the seasonal and location specific weather events that are relevant for meaningfully assessing climate-agricultural interactions at a global scale.[24]

Further, even if it were possible to project farmer and consequent yield responses to climate change, there is substantial uncertainty surrounding future climate scenarios. For example the Intergovernmental Panel on Climate Change (IPCC) currently maintains 42 climate change scenarios, each based on a different set of economic and environmental assumptions (van Oldenborgh et al. 2013, Table A1.1). While there is widespread agreement that the future climate will, on average, be hotter and more volatile, it is less clear what the climate will be at any particular location or at any particular point in time. It is possible to employ process-based crop models to project yields globally for a given climate change scenario, assuming that farmers do not change what they grow or where and how they grow it. But, the results of such models imply that yields will increase in some places and decrease in others, such that even if one is willing to assume a static (non-climate-responsive) landscape of production, there is no simple way to estimate a global effect of climate change on production and productivity.

Even current weather is not observed for all locations on the globe. While reasonable measurements are available from weather stations scattered across the globe, weather observations for locations without weather stations are not available. Thus, weather data for most locations are estimated based on station data. The network of weather stations is relatively sparse in some areas, and even recent weather data for locations in many areas are estimated with substantial errors; these errors are compounded when climate change projections (which have their own uncertainty) are applied to project future climate. Thus, reliable, spatially explicit, climate change projections are not available for many locations.

In light of these complex plant-crop management, and, especially, climate interactions, combined with the real problems of projecting forward modeled measures of climate at the spatial and temporal scales required to meaningfully assess their crop yield or other agricultural production consequences, we set aside any assessment of the impacts of climate change on global agricultural production at this juncture. Thus, in the context of this version of the iAP model, we judge that the best estimate of the world's "agricultural climate"—that is, the climate that actually affects agricultural productivity allowing for the timing and location aspects of

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[24] Neither the Cline (2007) nor the Nelson et al. (2010) studies meaningfully endogenized farmer behavior when assessing the consequences of prospective climate change on global agricultural supply.

farmers’ decisions regarding which crops to grow (or animals to raise) where, how, and when—over the coming decades is the actual climate over the past several decades.

Appendix 2: Mandates and Policy Goals for Biofuel Production by Country

To calibrate our biofuels projections we compiled information on present and prospective biofuels mandates and policies. What follows is the documentation we developed on these details.

United States

The statutory requirement to utilize prescribed amounts of biofuels in the U.S. motor fuel supply is given in the Energy Independence and Security Act of 2007 and is referred to as Renewable Fuels Standard 2 (RFS 2). The mandate divides renewable fuels into two categories, conventional biofuel and advanced biofuel. Conventional biofuel is ethanol derived from corn starch that achieves a greenhouse gas (GHG) emissions reduction compared to baseline lifecycle GHG emissions of at least 20 percent. Advanced biofuel is renewable fuel other than ethanol derived from corn starch that is derived from renewable biomass and achieves at least a 50 percent GHG emissions reduction. The three categories of advanced biofuel recognized in the law are cellulosic biofuel (which must have a GHG emissions reduction of at least 60 percent), biomass-based biodiesel, and undifferentiated advanced biofuel. The minimum quantity of conventional biofuel is mandated to increase from 12.6 billion gallons in 2012 to 15 billion gallons in 2015, and then remains steady through 2022. Advanced biofuels were legislated to increase from 1.35 billion gallons in 2011 to 21 billion gallons in 2022. The Environmental Protection Agency (EPA) is authorized to adjust mandated quantities of cellulosic biofuel and biodiesel each year based on feedstock supplies and available production capacity.

With the RFS 2 in place, questions were raised about the need for some of the incentives and protection that were in place for the domestic biofuel industry. Several have been dropped and appear unlikely to be reinstated. A blender’s credit of $0.45 per gallon of conventional ethanol and the tariff on imported ethanol of $0.54 per gallon were terminated in 2011. An incentive of up to $1.01 per gallon of cellulosic biofuel and $1.00 per gallon of biodiesel remain available through December 31, 2013. It seems unlikely that any of these incentives will be renewed in the current budget environment.

EU-27

The EU Energy and Climate Change Package (CCP), adopted in 2009, includes a set of mandatory goals for 2020. The goal of interest for this discussion is a 10 percent target for renewable energy consumed in road transportation fuels. That sector is estimated to have consumed 5.19 billion liters of ethanol and 13.24 billion liters of biodiesel fuel during 2010, representing blending rates for 2010 of about 2.61 percent and 5.1 percent for gasoline and diesel fuel, respectively. Fuel use in the transportation sector is expected to grow about 1 percent per year to 2020. Thus, considerable growth in biofuel production and/or imports will be required to meet the 10 percent mandate by 2020.

China

The government mandates that ten provinces implement an E10 program. Industry sources indicate that the blending rate within those ten provinces is between 8 and 12 percent, depending on the price of ethanol and petroleum. Ethanol producers have lowered the blending rate during periods when feedstock prices are high and government support is insufficient to make up the difference. There is no mandate for the other 20 provinces. The result for the country for 2010 was consumption of 78.2 billion liters of gasoline of which 2.13 billion liters was ethanol, an overall blending rate of less than 3 percent. The Chinese produced 73 percent of the ethanol from corn, 18 percent from wheat and 9 percent from cassava in 2010.

As in other countries, some Chinese consumers have objected to producing fuel from commodities that could be used for human food, arguing that use to produce biofuels raises food prices. In response, the government developed a guideline for biofuel development that applies to both ethanol and biodiesel. It states that biofuel development should not compete with crops intended for human consumption; and land for developing feedstocks should not compete with land for food and feed crop production.

In 2010, the government announced a national voluntary B5 blend rate. The reported diesel consumption for China in 2009 is 156.77 billion liters and biodiesel production is 227.2 million liters, much less than 1 percent of the diesel consumed. Producers have found that the cost of biofuel produced using waste fats and used cooking oils exceed the price of petroleum diesel, and they are asking for larger subsidies to make up the difference. Given the restrictions on using fats and oils suitable for human consumption, the Chinese are investigating the possibility of producing and using jatropha for biodiesel production. Until a nonfood supply of oil from jathropa or another crop is found, it doesn't appear these crops will be much of a factor in biodiesel production.

Present Chinese government policy is for non-fossil energy consumption to increase to 11.4 percent by 2015, 3.1 percent above the 2010 level, and to 15 percent by 2020. Non-fossil energy includes hydro, solar power, wind energy and biomass energy. Given the restrictions they have placed on feedstock use, it appears biofuel energy for the transportation sector will make up a limited part of achieving these goals.

India

The government of India approved a National Policy on Biofuels on December 24, 2009. The policy proposes achieving a target of E20 and B20 by 2017. India's biofuel strategy continues to focus on use of non-food feedstocks; namely sugar molasses for ethanol and jatropha for biodiesel. The government currently has a target of achieving an E5 blend. While the policy has encouraged the production of ethanol, about 1 billion liters of ethanol would currently be required to meet the 5 percent target. Actual blending has been 50 million liters in 2010 and is projected to be 250 and 300 million liters in 2011 and 2012.

India now produces about 140 to 300 million liters of biodiesel annually. A plan put into place in 2003 called for 11.2 to 13.4 million hectares of jatropha to be planted by 2011/12. By 2010, India had 0.5 million hectares planted to jatropha, of which two-thirds were new plantings needing 2 to 3 years to mature. The government is entering into memoranda of agreement to promote planting jatropha on wastelands. A recent industry study reported in USDA-FAO (July 2011) recommends the biodiesel procurement price be raised to a level that will sustain jatropha production but not so high that it will encourage shifting land from food to non-food production. It is unclear when the biodiesel target is likely to be achieved.

Latin America

- **Brazil.** Brazil's ethanol use mandate was changed on April 28, 2011 to a range from 18 to 25 percent (from a 20 to 25 percent range) due to an expected shortage in ethanol supply resulting from a drop in the sugar supply. Consumption of ethanol for fuel in 2010 was 22.16 billion liters. All of the ethanol in Brazil is made from sugar cane.

  The biodiesel mandate of B5 is enforced by the national government. Consumption of biodiesel during 2010 was 2.55 billion liters and production was at approximately the same level, 2.40 billion liters. Of the total production, 84 percent was produced from soybean oil, 15 percent from animal tallow and 1 percent from cottonseed oil.
- **Argentina.** Argentina mandated E5 and B5 beginning in 2010. The blending ratio for diesel was subsequently raised from B5 to B7 in July 2010. The country has produced ethanol from sugar through 2010, but will begin producing some ethanol from grain in late 2012 and 2013. Soybean oil is, and will continue to be, the main feedstock utilized in biodiesel production. Argentina has a large and efficient vegetable oil crushing industry. Meal is the main product and it is primarily exported. Soybean oil is considered a byproduct and Argentina is currently processing about 20 to 25 percent of its soybean oil to produce biodiesel. There is no alternative feedstock that can replace soybean oil in volume and cost.

  Argentina produced 122 million liters of ethanol and consumed 118 million liters during 2010. This represents a blend rate of about 2 percent, well below the E5 mandate. Ethanol production and consumption is expected to increase to 190 million liters in 2011 and to 260 million liters in 2012. The 2012 level of production, if achieved and blended, will increase the blend rate to almost 4 percent.

  Biodiesel production in 2010 was 2.1 billion liters. Argentina exported 1.54 billion liters and consumed 0.58 billion liters for a blend rate of about 3.5 percent. They expect to increase production to 2.56 billion liters in 2011 and 3.0 billion liters in 2012. They expect to consume 0.95 and 1.25 billion liters of biodiesel in 2011 and 2012 for blend rates of about 5.5 to 6.0 and greater than 7 percent, respectively.
- **Colombia.** The Colombian government has allowed the biofuels mix to increase as production increases. The government targets for ethanol and biodiesel blends are E10 in 2013 and B20 in 2015. Colombian ethanol is produced from sugar cane and biodiesel is produced from palm oil. Excessive rains caused a reduction in the sugar crop and a consequent decline in ethanol production from over 300 million liters in 2009 to 280 million liters in 2010. Production rebounded to 351 million liters in 2011, enough to achieve an E8 blending rate. They expect to increase production to 355 and 410 million liters in 2012 and 2013, respectively.

  Biodiesel production reached 420 million liters in 2010 and expanded to 537 million liters in 2011. It is projected to increase to 545 and 550 million liters in 2012 and 2013. They achieved a B5 to B7 blending rate in various areas of the country in 2011. Colombia neither imports nor exports biofuels at the current time. However, Colombia may become an exporter of biofuels over the next several years, particularly biodiesel from palm oil after the B20 goal is achieved.

Other OECD Countries

- **Australia.** The federal government had a production target of 350 million liters of ethanol, but the government no longer refers to this policy and it has effectively been dropped. At the state level, New South Wales has a mandate of E4 and Queensland had a mandate of E5, but suspended it effective December 31, 2010. Australia produced and consumed 380 million liters of ethanol in 2010. The production and consumption of fuel ethanol is expected to increase to 440 million liters and 450 million liters in 2011 and 2012, respectively. Australian ethanol is produced from grain, primarily wheat.

  Biodiesel production totaled about 80 million liters in 2010. It is produced primarily from tallow, and waste vegetable oil. The annual supply of waste vegetable oil is expected to remain roughly constant over time, but the supply of tallow may increase from slaughter of fatter cattle. However, projected production of biodiesel for 2011 and 2012 is expected to be about 80 to 90 million liters per year.

  Australia does not appear to be moving towards deploying second generation biofuels. They will probably follow other countries in the development of these fuels.

- **Canada**. The government implemented a federal E5 mandate effective August 23, 2010, and a D2 mandate became effective July 1, 2011. Canada estimates the mandates will require a minimum of 1.94 billion liters of ethanol and 600 million liters of biodiesel annually in the near term, and more as fuel consumption grows over time.

  Ethanol production in 2010 totaled 1.200 billion liters and, with imports, consumption totaled 1.69 billion liters. Production is expected to total 1.35 and 1.38 billion liters in 2011 and 2012, respectively. Gasoline consumption is expected to grow 5 percent per year, suggesting imports will grow over time. Eastern provinces produce ethanol from corn and western provinces use wheat as the feedstock. During 2011, 67 percent of ethanol was produced from corn, 31 percent from wheat and 2 percent from other sources (wood, straw, etc.).

  Biodiesel production totaled 140 million liters and consumption 126 million liters in 2010. Production is expected to grow to 158 and 475 million liters in 2011 and 2012, respectively. Of the total production in 2010, 16 percent was produced from rapeseed oil, 59 percent from animal fats, and 25 percent from mixed feedstock (a combination of soybean oil, rapeseed oil, waste vegetable oils, and animal fats). The percentage of biodiesel produced using these three feedstocks are expected to be 45, 34 and 21, respectively in 2012. Consumption is expected to increase to 145 million liters in 2011 and 550 million liters in 2012, implying that imports are also expected to grow.

  Canada is expected to be a leader in second generation biofuels.

- **Japan.** The government of Japan has financed numerous pilot plants to produce ethanol from sugar beets, rice, and wheat, but production is limited. Japan produced 50 million liters of ethanol in 2010, and projected production for 2011 and 2012 is 60 million liters per year. Imports of 299.8 million liters brought 2010 consumption to 349.8 million liters. Imports are projected to total 360 million liters in 2011 and 2012 bringing total consumption to 420 million liters in those years. Biodiesel production and consumption totaled 20 million liters in 2010 and they are expected to remain at the same level in 2011 and 2012.

The Japan Automobile Manufacture's Association estimated domestic fuel consumption of about 60 billion liters of gasoline and 36 billion liters of diesel per year. The ethanol blend (upper) limit is currently 3 percent, 1.8 billion liters per year. However, the blend rate achieved is only about 1 percent for ethanol and much less than 0.1 percent for biodiesel. Some consumers in Japan became concerned about the impact of biofuels on food prices in 2008. To address these concerns, the government increased emphasis on research and development of cellulosic technology that uses inputs that will not compete with the food supply, such as rice straw. They are also exploring the use of algae for biodiesel production.

- **Korea.** In 2009, the government of Korea decided not to move ahead with a mandate for ethanol because of the high cost of grain. They opted to focus on second generation biofuels. They are currently investigating seaweed as a potential feedstock for ethanol.

  The Koreans have been raising the biodiesel blend rate each year. It was 2 percent for 2010 and has been raised to 2.5 percent in 2011 and 3 percent in 2012. They produced and consumed 400 million liters of biodiesel in 2010. They have been importing approximately equal amounts of soybean and palm oil to produce 80 percent of the biodiesel. The remainder has been produced primarily from used cooking oil. Korea is exploring animal fats and domestically produced rapeseed as alternative feedstocks.
- **Mexico.** The Mexican government has defined the legal framework governing biofuel production and marketing, but they have not moved into commercial biofuel production. The ethanol they produce is a by-product of sugar cane milling and the output is used by the alcoholic beverage and pharmaceutical industries.

  Mexico has three small biodiesel plants. The output is used by the public transportation system of the cities of Tuxtla Guiterrez and Tapachula as fuel for their city busses and for research purposes. None of the output is commercially available. They also have a jatropha based production project underway.

Rest of World

Other Asian Countries

- **Indonesia.** The country had an E3 mandate but put it on hold in 2010 due to a disagreement on the market price between the Ministry of Energy and the producers. Production and consumption has been zero during 2010 and 2011. There is an indication the parties have agreed on an ethanol price and the program will be restarting during 2012. Ethanol is made from sugar cane and most of the output is sold for industrial uses.

  Indonesia has a B2.5 mandate. They produced 455 million liters of biodiesel in 2010 and 650 million liters in 2011. Consumption was 223 million liters in 2010 and 355 in 2011. They expect production and consumption to grow to 700 and 425 million liters, respectively in 2012. The difference between production and consumption is exported.

  All of the commercial production of biodiesel is from palm oil. They have been experimenting with production from jatropha. They report that jatropha yields have not been high enough to make biodiesel from jatropha competitive with biodiesel from palm oil.

- **Malaysia.** The government of Malaysia has started to implement a B5 mandate. B5 was only available at some stations in mid-2011, and they plan to add other stations and states over time. They consumed 1.14 million liters in 2010, 2.27 in 2011 and project consumption of 4.54 million liters in 2012.

  Production of biodiesel was much higher during 2008 and 2009, but declined to 90.89 million liters in 2010. It declined further in 2011 to 14.77 million liters and is projected to be about the same in 2012.
- **Taiwan.** The country has a B1 mandate in place.
- **Thailand.** The ministry of energy raised the biodiesel mandate from B2 to B3 in April 2011. They produce biodiesel from palm oil.

Africa

F.O. Lichts (2013) reported fuel ethanol production for the continent of 164.77 million liters in 2010 and 144.81 million liters in 2011. No production figures were obtained for biodiesel.

- **Ethiopia.** The country has an E10 mandate in place for the capital city of Addis Ababa. Ethanol is made from sugar molasses.
- **Kenya.** They have an E10 mandate in place in Kisumu, the country’s third largest city. The ethanol is made from sugar molasses.
- **Malawi.** The country has an E10 mandate in place, but the blending rate depends on availability. The ethanol is made from sugar molasses.
- **Nigeria.** The country has an E10 ethanol target, but no mandate. It manufactures ethanol from sugar molasses.
- **South Africa.** The government backed away from its E8 and B2 mandate for 2013. We were not successful in obtaining official statistics on production and consumption of ethanol and biodiesel for the country for 2010, through 2012. News stories over the past year indicate that grain ethanol plants have been closing down.

  Recent news stories indicate the South African Department of Energy will be publishing final mandatory blending regulations for both ethanol and biodiesel in the near future. Apparently the new mandates for ethanol will be designed for an ethanol industry based on sugar cane.

Source: Unless otherwise stated, Global Agricultural Information Network (GAIN) reports available at USDA, FAS (various years).

Appendix 3: Prospective Changes in Biofuels Technologies

Changes in Technology Incorporated into the Estimates

Our feedstock-to-fuel conversion ratios were adjusted over the 40-year projection period to reflect new technologies that are expected to increase the efficiency of biofuel production. These include technologies that will increase the amount of ethanol produced from grain over time. Specifically, the use of the recently patented "hot ethanol process" and conversion of the pericarp using cellulosic ethanol conversion processes were built into the conversion rates for ethanol produced from corn. The projections assume that the "hot ethanol process" will reach the adoption threshold of one percent in 2018 and that the conversion of the pericarp will reach this threshold in 2022. The first technology is expected to increase ethanol yields per unit of feedstock for adopting conversion plants by about 7.8 percent and the second an additional 7.0 percent. Simultaneous with these changes, the analysis assumes more of the corn oil will be removed from the distiller's grains and solubles and will be converted to biodiesel. The glycerin byproduct produced in this process, as well as glycerin produced by converting other vegetable oils to biodiesel, will be used to produce ethanol. All of the above changes are built into the analysis over time as the industry adopts these technologies. The analysis assumes these changes will also occur in other countries producing ethanol from corn and biodiesel from vegetable oils.

Our analysis assumes that India and Indonesia become successful in commercializing jatropha production for conversion to biodiesel at a cost that is competitive with production of biofuels from other vegetable oils.

Changes in Technology Not Incorporated

One change in technology that was not included is the potential shift of grain ethanol plants from ethanol to isobutanol. Isobutanol is an alcohol with a higher BTU content and a lower Reid's vapor pressure than ethanol. Because of its lower Reid's vapor pressure, it can be blended at a higher percentage than ethanol, and the resulting blended fuel can be handled more easily in the distribution system.

The first commercial isobutanol plant began production in Minnesota during the spring of 2012 using corn grain as the feedstock. Some industry observers argue that the grain ethanol industry, at least in the United States, will convert to isobutanol because it will be more profitable and doing so will reduce problems in integrating the alcohol produced into the fuel supply. We did not incorporate the potential effects of shifting to isobutanol production into the projections because producing biobutanol instead of ethanol would use about the same amount of corn, and produce about the same number of BTUs of liquid fuel and quantity of byproduct feed from a given amount of feedstock. Isobutanol can also be produced from cellulosic feedstocks, but it has not been done on a commercial scale at this time.

In summary, there seems to be a reasonable probability that some of the grain and cellulosic ethanol projected in this analysis may be replaced by isobutanol over the 40 year projection period. Such a change would affect the quantities and type of alcohol entering the fuel system, but would not impact the quantity of feedstocks used which is the focus in this study.

Two other changes in technology are implicit in the analysis. One is the ethanol yield (liters per ton of cellulosic biomass). This study did not estimate the quantity of cellulosic feedstocks used for cellulosic ethanol and for drop-in fuels. However, we expect cellulosic ethanol yields for the initial commercial plants to be about 77 gallons (291 liters) per metric ton of cellulose, increasing to 99 gallons (374 liters) over a decade of production history. It was not necessary for us to estimate the implied amount of cellulosic feedstock required to produce ethanol from this source because our projections model is unaffected by estimates of the amount of harvestable cellulosic materials produced.

The estimates of biofuel production also assume that new methods will become commercially viable to produce drop-in fuels (i.e., a fuel substitute rather than a fuel additive to replace methyl tertiary-butyl ether (MTBE) as a means to increase the octane ratings of gasoline). Two methods, pyrolysis and Fischer Tropsch, are currently the most promising, but neither has been successful in converting cellulosic biomass to fuel on a commercial scale. If these technologies to produce cellulosic ethanol and drop-in fuels do not become viable, it will place more pressure on the traditional feedstock sources such as starch, sugar, vegetable oils, waste cooking oils and animal fats to produce biofuels.

There is currently much interest in substituting biofuels for petroleum aviation fuels to reduce that industry’s GHG impacts. The International Energy Agency recently published shares of refinery production by product for the world in 2009. Of the products produced in refining petroleum, they estimate 24.2 percent was motor gasoline, 6.2 percent was aviation fuel, and 34.4 percent was middle distillates. To the extent the effort to produce biofuel for aviation moves forward, it may add to the crops produced. For example, there is interest in increasing camelina production in the northwestern part of the United States to produce feedstock for aviation fuel. Other countries are also interested in producing other crops that can be used to produce aviation fuel. If these changes occur, they may add to the biofuel production in several countries.

No effort was made to consider biofuel production from algae. The available economic studies suggest this technology will not be economically viable for the foreseeable future. It is difficult to judge when and to what extent this technology may begin to impact commercial biofuel production. The amount of biofuels produced from other feedstock sources may be reduced should algae become a major factor in biofuel production.

Appendix 4: Country-to-Region Mappings

	Aggregation		
Country	Consumption	Production	Income
Afghanistan	Asia&Pacific	R_Asia	Low income
Albania	EE&FSU	ROW	Upper middle income
Algeria	MENA	R_Af_ME	Upper middle income
Angola	SSA	R_Af_ME	Lower middle income
Argentina	LAC	Argentina	Upper middle income
Armenia	EE&FSU	R_FSU	Lower middle income
Aruba	High Income	R_LA	High income
Australia	High Income	Australia	High income
Austria	High Income	ROW	High income
Azerbaijan	EE&FSU	R_FSU	Upper middle income
Bahamas	High Income	R_LA	High income
Bahrain	High Income	R_Af_ME	High income
Bangladesh	Asia&Pacific	R_Asia	Low income
Barbados	High Income	R_LA	High income
Belarus	EE&FSU	R_FSU	Upper middle income
Belgium	High Income	EU12	High income
Belize	LAC	R_LA	Lower middle income
Benin	SSA	R_Af_ME	Low income
Bhutan	Asia&Pacific	R_Asia	Lower middle income
Bolivia (Plurinational State of)	LAC	R_LA	Lower middle income
Bosnia and Herzegovina	EE&FSU	ROW	Upper middle income
Botswana	SSA	R_Af_ME	Upper middle income
Brazil	LAC	Brazil	Upper middle income
Brunei Darussalam	High Income	R_Asia	High income
Bulgaria	EE&FSU	ROW	Upper middle income
Burkina Faso	SSA	R_Af_ME	Low income
Burundi	SSA	R_Af_ME	Low income
Côte d'Ivoire	SSA	R_Af_ME	Lower middle income
Cambodia	Asia&Pacific	R_Asia	Low income
Cameroon	SSA	R_Af_ME	Lower middle income
Canada	High Income	Canada	High income
Cape Verde	SSA	R_Af_ME	Lower middle income
Central African Republic	SSA	R_Af_ME	Low income
Chad	SSA	R_Af_ME	Low income
Chile	LAC	R_LA	Upper middle income
China	Asia&Pacific	China	Upper middle income
Colombia	LAC	R_LA	Upper middle income
Comoros	SSA	R_Af_ME	Low income
Congo	SSA	R_Af_ME	Lower middle income
Costa Rica	LAC	R_LA	Upper middle income
Croatia	EE&FSU	ROW	High income
Cuba	LAC	R_LA	Upper middle income
Cyprus	High Income	ROW	High income
Czech Republic	EE&FSU	EU12	High income
Democratic People's Republic of Korea	Asia&Pacific	R_Asia	Low income
Democratic Republic of the Congo	SSA	R_Af_ME	Low income

	Aggregation		
Country	Consumption	Production	Income
Denmark	High Income	ROW	High income
Djibouti	SSA	R_Af_ME	Lower middle income
Dominican Republic	LAC	R_LA	Upper middle income
Ecuador	LAC	R_LA	Upper middle income
Egypt	MENA	R_Af_ME	Lower middle income
El Salvador	LAC	R_LA	Lower middle income
Equatorial Guinea	High Income	R_Af_ME	High income
Eritrea	SSA	R_Af_ME	Low income
Estonia	EE&FSU	ROW	High income
Ethiopia	SSA	R_Af_ME	Low income
Fiji	Asia&Pacific	ROW	Lower middle income
Finland	High Income	ROW	High income
France	High Income	EU12	High income
French Guiana	High Income	R_LA	High income
Gabon	SSA	R_Af_ME	Upper middle income
Gambia	SSA	R_Af_ME	Low income
Georgia	EE&FSU	R_FSU	Lower middle income
Germany	High Income	EU12	High income
Ghana	SSA	R_Af_ME	Lower middle income
Greece	High Income	ROW	High income
Grenada	LAC	R_LA	Upper middle income
Guam	High Income	ROW	High income
Guatemala	LAC	R_LA	Lower middle income
Guinea	SSA	R_Af_ME	Low income
Guinea-Bissau	SSA	R_Af_ME	Low income
Guyana	LAC	R_LA	Lower middle income
Haiti	LAC	R_LA	Low income
Honduras	LAC	R_LA	Lower middle income
Hungary	EE&FSU	EU12	High income
Iceland	High Income	ROW	High income
India	Asia&Pacific	India	Lower middle income
Indonesia	Asia&Pacific	R_Asia	Lower middle income
Iran (Islamic Republic of)	MENA	R_Af_ME	Upper middle income
Iraq	MENA	R_Af_ME	Lower middle income
Ireland	High Income	ROW	High income
Israel	High Income	R_Af_ME	High income
Italy	High Income	EU12	High income
Jamaica	LAC	R_LA	Upper middle income
Japan	High Income	Japan	High income
Jordan	MENA	R_Af_ME	Upper middle income
Kazakhstan	EE&FSU	R_FSU	Upper middle income
Kenya	SSA	R_Af_ME	Low income
Kuwait	High Income	R_Af_ME	High income
Kyrgyzstan	EE&FSU	R_FSU	Low income
Lao People's Democratic Republic	Asia&Pacific	R_Asia	Lower middle income
Latvia	EE&FSU	ROW	Upper middle income
Lebanon	MENA	R_Af_ME	Upper middle income
Lesotho	SSA	R_Af_ME	lower middle income

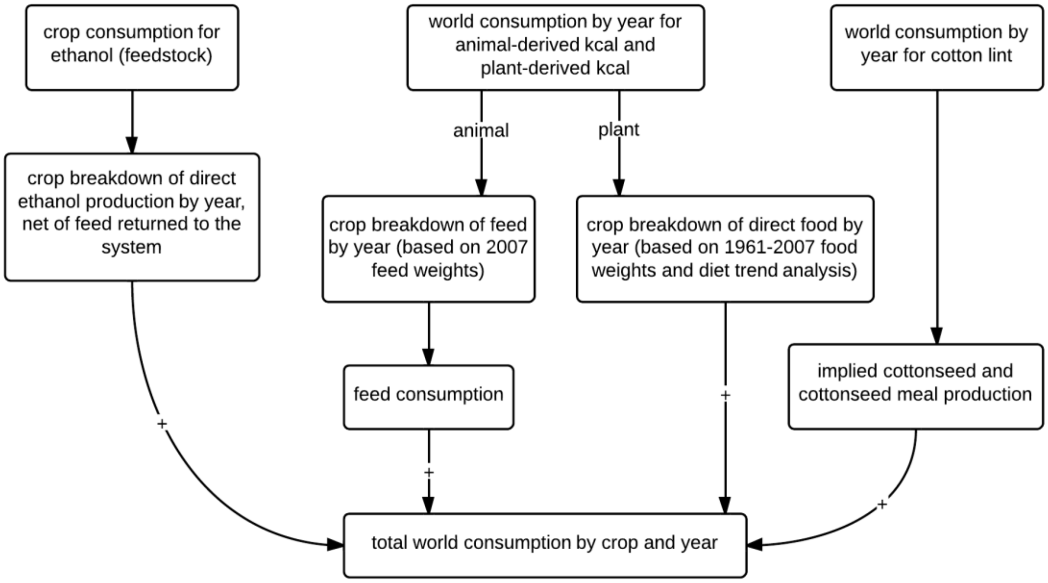
	Aggregation		
Country	Consumption	Production	Income
Liberia	SSA	R_Af_ME	Low income
Libya	MENA	R_Af_ME	Upper middle income
Lithuania	EE&FSU	ROW	Upper middle income
Luxembourg	High Income	ROW	High income
Madagascar	SSA	R_Af_ME	Low income
Malawi	SSA	R_Af_ME	Low income
Malaysia	Asia&Pacific	R_Asia	Upper middle income
Maldives	Asia&Pacific	R_Asia	Upper middle income
Mali	SSA	R_Af_ME	Low income
Malta	High Income	ROW	High income
Martinique	High Income	R_LA	High income
Mauritania	SSA	R_Af_ME	Lower middle income
Mauritius	SSA	R_Af_ME	Upper middle income
Mexico	LAC	Mexico	Upper middle income
Micronesia (Federated States of)	Asia&Pacific	ROW	Lower middle income
Mongolia	Asia&Pacific	R_Asia	Lower middle income
Montenegro	EE&FSU	ROW	Upper middle income
Morocco	MENA	R_Af_ME	Lower middle income
Mozambique	SSA	R_Af_ME	Low income
Myanmar	Asia&Pacific	R_Asia	Low income
Namibia	SSA	R_Af_ME	Upper middle income
Nepal	Asia&Pacific	R_Asia	Low income
Netherlands	High Income	EU12	High income
New Zealand	High Income	ROW	High income
Nicaragua	LAC	R_LA	Lower middle income
Niger	SSA	R_Af_ME	Low income
Nigeria	SSA	R_Af_ME	Lower middle income
Norway	High Income	ROW	High income
Occupied Palestinian Territory	MENA	R_Af_ME	Lower middle income
Oman	High Income	R_Af_ME	High income
Pakistan	Asia&Pacific	R_Asia	Lower middle income
Panama	LAC	R_LA	Upper middle income
Papua New Guinea	Asia&Pacific	ROW	Lower middle income
Paraguay	LAC	R_LA	Lower middle income
Peru	LAC	R_LA	Upper middle income
Philippines	Asia&Pacific	R_Asia	Lower middle income
Poland	EE&FSU	EU12	High income
Portugal	High Income	ROW	High income
Puerto Rico	High Income	R_LA	High income
Qatar	High Income	R_Af_ME	High income
Réunion	High Income	R_Af_ME	High income
Republic of Korea	High Income	R_Asia	High income
Republic of Moldova	EE&FSU	R_FSU	Lower middle income
Romania	EE&FSU	EU12	Upper middle income
Russian Federation	EE&FSU	Russia	Upper middle income
Rwanda	SSA	R_Af_ME	Low income
Saint Lucia	LAC	R_LA	Upper middle income
Saint Vincent and the Grenadines	LAC	R_LA	upper middle income

	Aggregation		
Country	Consumption	Production	Income
Samoa	Asia&Pacific	ROW	Lower middle income
Sao Tome and Principe	SSA	R_Af_ME	Lower middle income
Saudi Arabia	High Income	R_Af_ME	High income
Senegal	SSA	R_Af_ME	Lower middle income
Serbia	EE&FSU	ROW	Upper middle income
Sierra Leone	SSA	R_Af_ME	Low income
Singapore	High Income	R_Asia	High income
Slovakia	EE&FSU	ROW	High income
Slovenia	EE&FSU	EU12	High income
Solomon Islands	Asia&Pacific	ROW	Lower middle income
Somalia	SSA	R_Af_ME	Low income
South Africa	SSA	S_Africa	Upper middle income
Spain	High Income	EU12	High income
Sri Lanka	Asia&Pacific	R_Asia	Lower middle income
Suriname	LAC	R_LA	Upper middle income
Swaziland	SSA	R_Af_ME	Lower middle income
Sweden	High Income	ROW	High income
Switzerland	High Income	ROW	High income
Syrian Arab Republic	MENA	R_Af_ME	Lower middle income
Tajikistan	EE&FSU	R_FSU	Low income
Thailand	Asia&Pacific	R_Asia	Upper middle income
The former Yugoslav Republic of Macedonia	EE&FSU	ROW	Upper middle income
Timor-Leste	Asia&Pacific	R_Asia	Lower middle income
Togo	SSA	R_Af_ME	Low income
Tonga	Asia&Pacific	ROW	Lower middle income
Trinidad and Tobago	High Income	R_LA	High income
Tunisia	MENA	R_Af_ME	Upper middle income
Turkey	MENA	R_Af_ME	Upper middle income
Turkmenistan	EE&FSU	R_FSU	Lower middle income
Uganda	SSA	R_Af_ME	Low income
Ukraine	EE&FSU	R_FSU	Lower middle income
United Arab Emirates	High Income	R_Af_ME	High income
United Kingdom	High Income	EU12	High income
United Republic of Tanzania	SSA	R_Af_ME	Low income
United States of America	High Income	USA	High income
United States Virgin Islands	High Income	R_LA	High income
Uruguay	LAC	R_LA	Upper middle income
Uzbekistan	EE&FSU	R_FSU	Lower middle income
Vanuatu	Asia&Pacific	ROW	Lower middle income
Venezuela (Bolivarian Republic of)	LAC	R_LA	Upper middle income
Viet Nam	Asia&Pacific	R_Asia	Lower middle income
Yemen	MENA	R_Af_ME	Lower middle income
Zambia	SSA	R_Af_ME	Lower middle income
Zimbabwe	SSA	R_Af_ME	Low income

Source: Developed by authors.

Note: Country names are FAO (2012a) designations.

Figure 1: Estimation of Crop Consumption

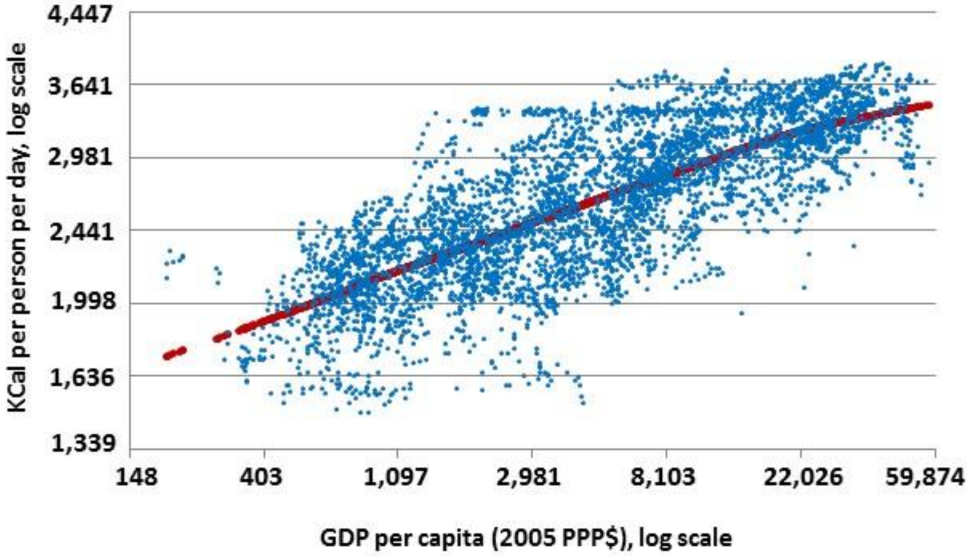


Source: Developed by authors.

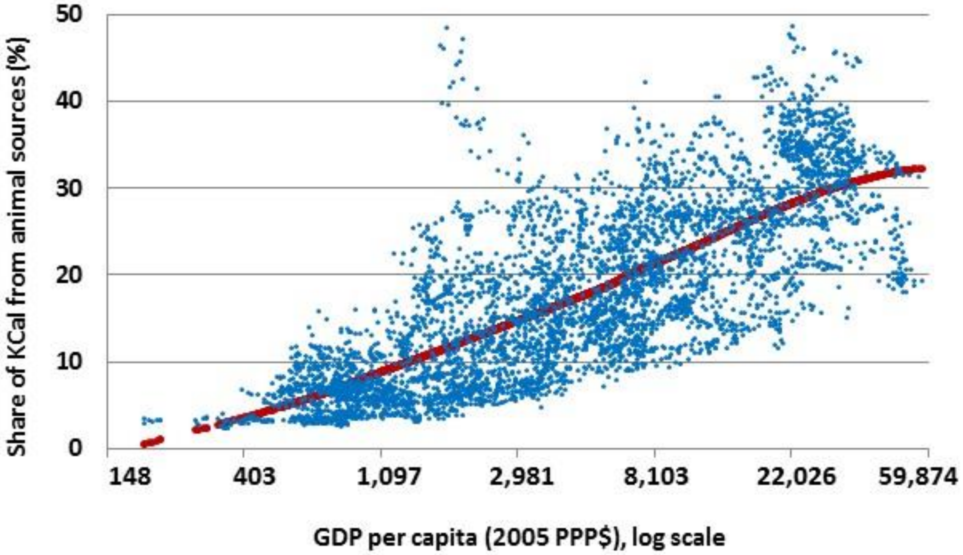
Note: See also Figure 4 in the main text.

Figure 2: Global Calorie Consumption, 1980-2009

Panel a: Total calories consumed per person per day



Panel b: Share of calories consumed from animal sources

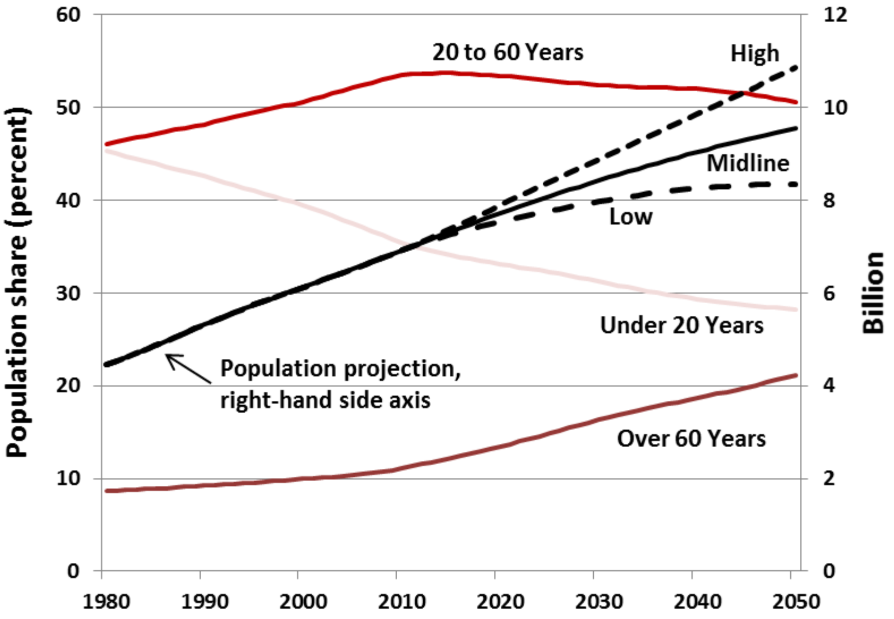


Source: Developed by authors based on data as described in the text.

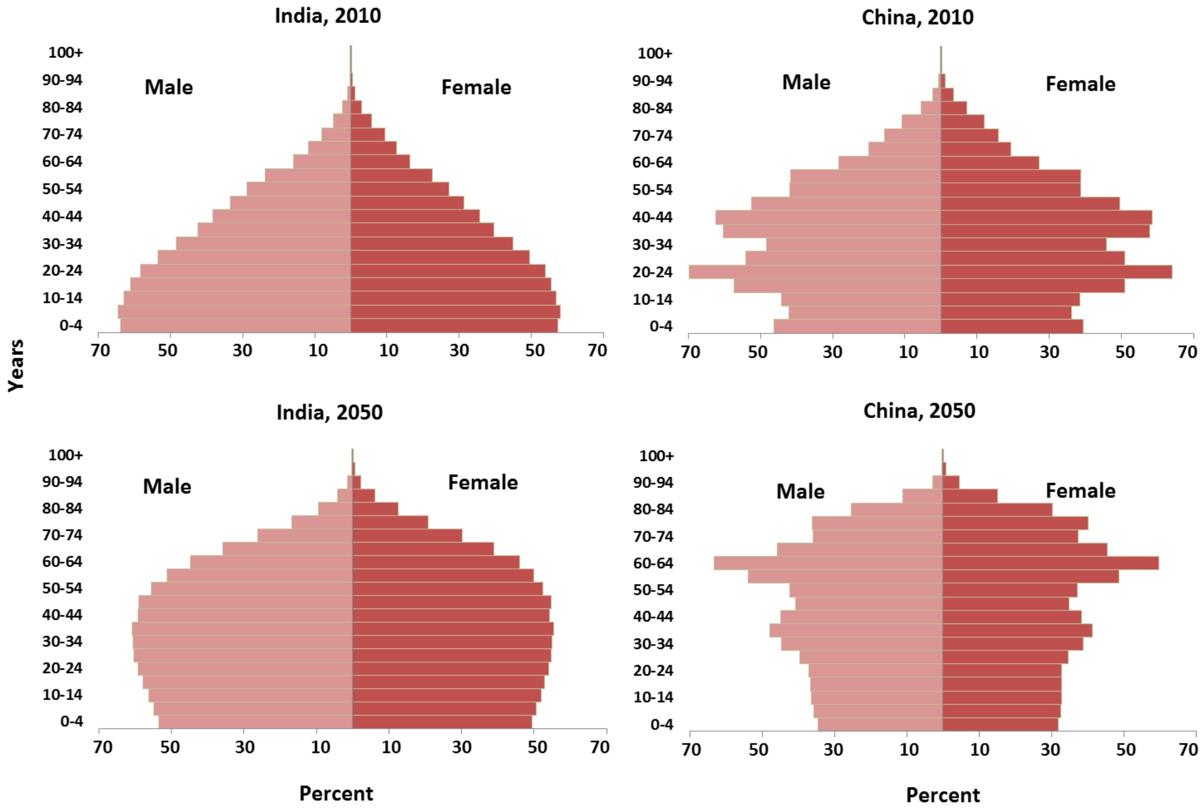
Note: Data points represent country-specific, annual observations. The plotted line is a Loess-smoothed fit to the data.

Figure 3: Global Demographics

Panel a: Size and age structure of world population



Panel b: Age distributions for India and China, 2010 and 2050



Source: Developed by authors using data from U.N. (2013a and 2013b).

Table 1: Consumption Model Point Estimates

Variable	Share from Animal Sources	Total Calories
	parameter estimate (standard error)	
Log(pcGDP)	0.030 (0.005)**	0.130 (0.009)**
Age: Share below 20	-0.013 (0.021)	-0.628 (0.042)**
Age: Share over 60	0.394 (0.042)**	-0.520 (0.079)**
Log(pcGDP)*Low Income	-0.012 (0.007)	-0.037 (0.012)**
Log(pcGDP)*Lower Middle Income	-0.001 (0.006)	-0.024 (0.010) *
Log(pcGDP)*Upper Middle Income	0.005 (0.006)	-0.066 (0.010)**
Low Income	0.055 (0.058)	0.283 (0.104)**
Lower Middle Income	-0.008 (0.054)	0.195 (0.095) *
Upper Middle Income	-0.022 (0.052)	0.600 (0.090)**
Asia & Pacific	0.008 (0.007)	0.028 (0.014) *
Eastern Europe & Former Soviet Union	0.033 (0.006)**	0.105 (0.013)**
Latin American & Caribbean	0.007 (0.007)	0.025 (0.014)
Middle East & North Africa	-0.055 (0.007)**	0.205 (0.015)**
Sub-Saharan Africa	-0.013 (0.007)	0.057 (0.015)**
United States	0.036 (0.004)**	
India	-0.025 (0.002)**	
European Union	0.054 (0.003)**	
Constant	-0.133 (0.054) *	7.048 (0.095)**
N	4,802	4,802
Adjusted R2	0.820	0.818

Source: Developed by authors based on data as described in the text.

Note: The annotations are defined as: * $p<0.05$; ** $p<0.01$

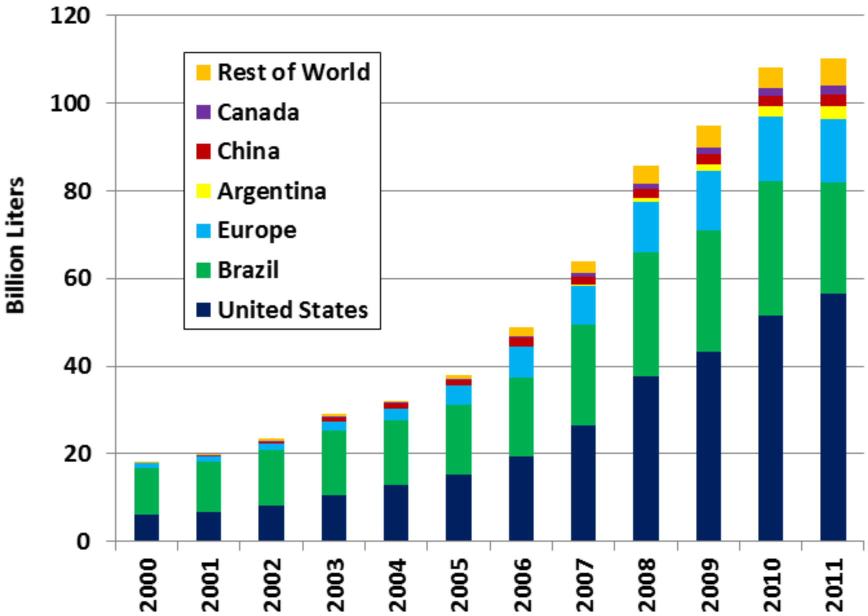
Table 2: Global Calorie Consumption Projections

	Caloric Source		
Year	Animal	Plant	Total
	kcal per person per day		
2010	512	2,316	2,829
2011	520	2,320	2,840
2012	528	2,325	2,853
2013	536	2,327	2,862
2014	543	2,329	2,871
2015	550	2,330	2,880
2016	557	2,332	2,889
2017	563	2,333	2,896
2018	570	2,334	2,904
2019	576	2,335	2,911
2020	583	2,336	2,919
2021	590	2,336	2,926
2022	597	2,336	2,932
2023	604	2,335	2,939
2024	611	2,335	2,945
2025	618	2,335	2,952
2026	625	2,334	2,959
2027	632	2,334	2,966
2028	639	2,334	2,973
2029	646	2,334	2,981
2030	654	2,335	2,988
2031	661	2,335	2,996
2032	668	2,336	3,004
2033	675	2,337	3,012
2034	682	2,338	3,020
2035	688	2,339	3,028
2036	695	2,341	3,036
2037	701	2,343	3,044
2038	707	2,345	3,052
2039	713	2,347	3,060
2040	719	2,348	3,068
2041	725	2,349	3,074
2042	734	2,350	3,085
2043	740	2,351	3,091
2044	746	2,350	3,097
2045	753	2,350	3,102
2046	759	2,349	3,107
2047	765	2,347	3,112
2048	771	2,345	3,117
2049	778	2,344	3,122
2050	784	2,343	3,127

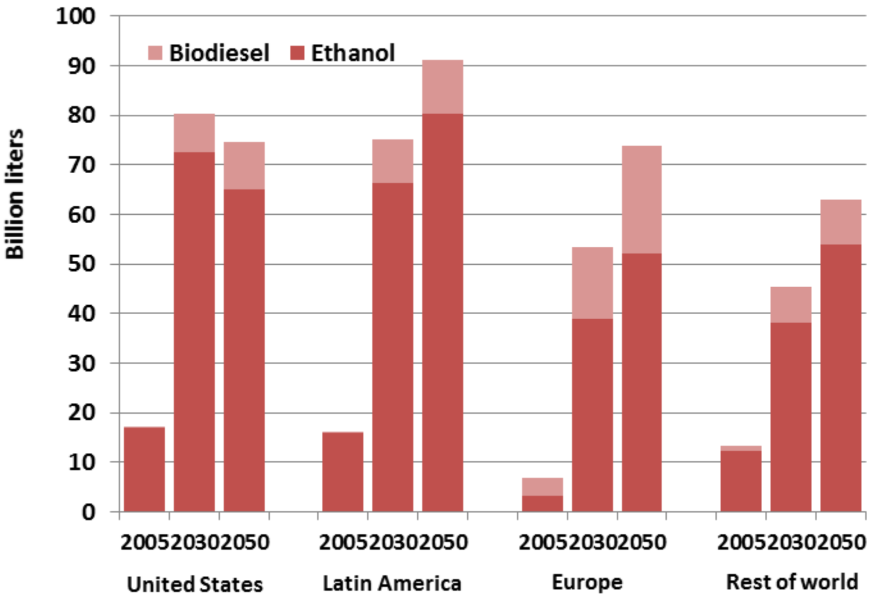
Source: Developed by authors based on data as described in the text.

Figure 4: Global Biofuels Production, 2000-2050

Panel a: Biofuels production by region, 2000-2011



Panel b: Biodiesel and bioethanol production, 2005, 2030 and 2050



Source: Developed by authors using data from OECD-FAO (2012) and iAP estimates for panel b for years 2030 and 2050.

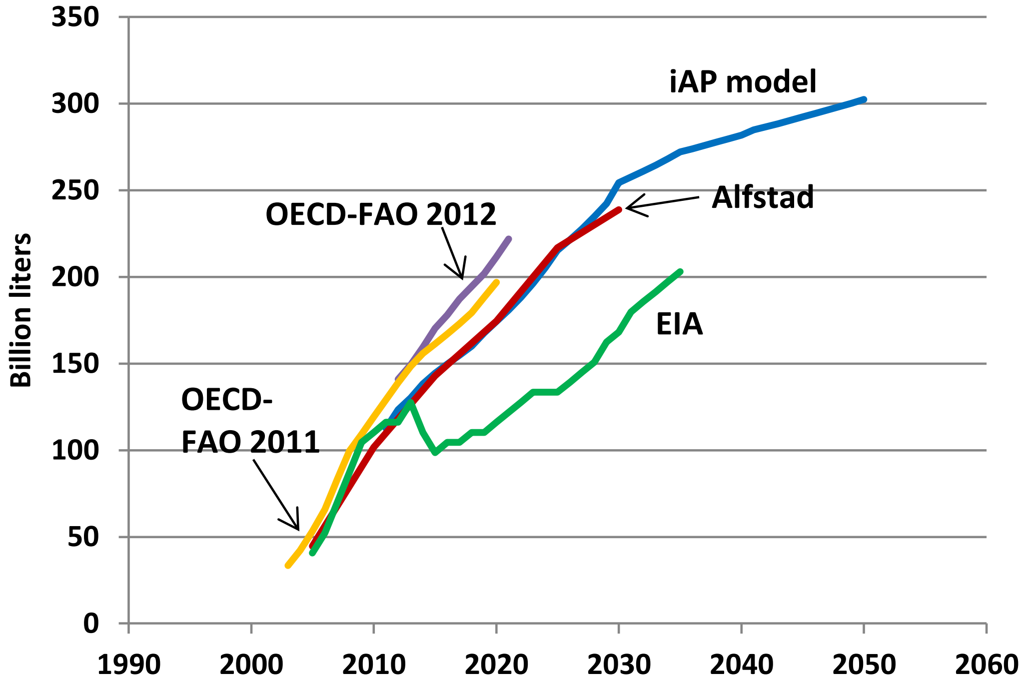
Table 3: Yield per Bushel of Corn, by Ethanol Production Technology

Technology	Ethanol	Biodiesel	DDGS
	gallons		*pounds*
Conventional Dry Mill	2.80	0.00	16.7
Conventional Dry Mill, with Oil Extraction	2.87	0.08	16.1
Wet Mill	2.60	0.00	0.0
New Dry Mill (hot process)	3.02	0.11	15.7
New Dry Mill (pericarp conversion)	3.23	0.11	9.7

Source: Developed by authors based on data as described in the text.

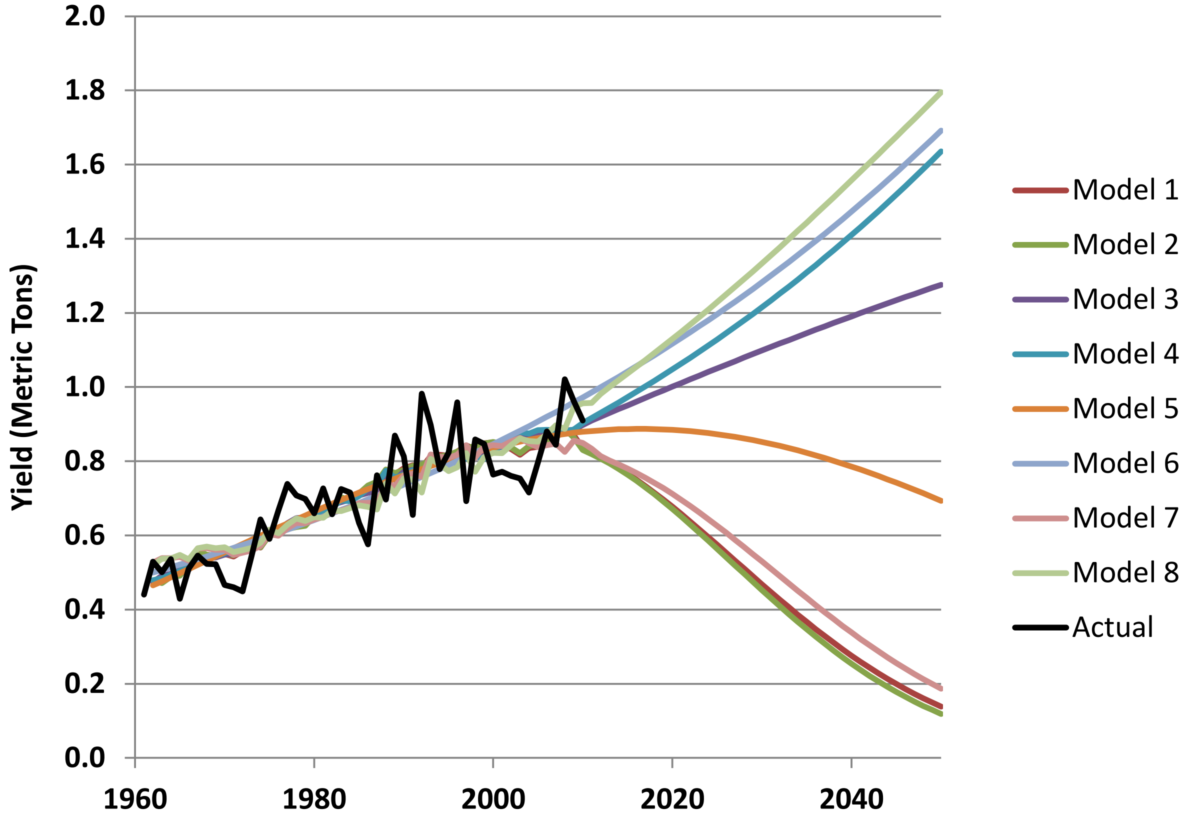
Note: Other outputs are also considered, including corn oil, glycerin and zein protein.

Figure 5: Global Biofuels Prospects, 2003-2050



Source: Developed by authors based on data as described in the text. .

Figure 6: Indian Sorghum Yields for 1961 to 2010 and Yield Model Projections for 1961 to 2050



Source: Developed by authors based on data as described in the text.

Note: This figure shows each model specification for only one of the 256 crop-region combinations (16 regions by 16 crops).

Table 4: Crop Model Specifications Used in the iAP Model

	Commodity								
Region	Barley	Cereals	Fruit	Maize	Millet	Pulses	Rapeseed	Rice	Roots
Africa & Middle East, NEC	4	7	6	4	7	8	3	1	3
Argentina	1	3	4	3	1	1	4	1	4
Asia, NEC	3	6	3	3	8	1	3	3	7
Australia	3	8	3	3	2	8	7	4	2
Brazil	1	4	4	3	N/A	3	3	7	7
Canada	8	6	3	6	N/A	5	2		2
China	3	3	6	7	8	5	3	1	7
EU (12)	3	3	1	3	4	8	6	4	6
Former Soviet Union	1	3	6	6	6	6	3	1	2
India	3		4	3	4	8	2	1	7
Japan	3	3	1	3	3	6	8	6	4
Latin America, NEC	1	3	4	6		1	4	3	3
Mexico	3	3	4	3	3	3	3	1	4
South Africa	3	8	4	3	3	7	8	3	2
United States	3	6	4	5	6	5	8	1	2
Rest of World	3	3	8	3	4	7	4	1	6

Table 4: Crop Model Specifications Used in the iAP Model (continued)

	Commodity						
Region	Seedcotton	Sorghum	Soybeans	Sugarcane	Sunflower	Vegetables	Wheat
Africa & Mid. East, NEC	3	3	3	8	6	8	3
Argentina	3	3	3	3	8	6	6
Asia, NEC	3	3	3	2	8	8	3
Australia	8	6	8	6	3	6	6
Brazil	6	8	3	3	3	5	2
Canada	N/A	N/A	4	N/A	3	1	4
China	1	3	3	3	3	3	3
EU (12)	1	3	7	1	3	2	3
Former Soviet Union	3	6	6	N/A	7	1	3
India	3	3	8	3	3	1	8
Japan	N/A	N/A	3	6	N/A	3	3
Latin America, NEC	3	3	3	8	3	3	8
Mexico	6	1	6	4	8	1	3
South Africa	3	3	8	1	8	1	3
United States	4	4	3	3	4	5	3
Rest of World	3	8	3	4	3	1	3

Source: Developed by authors based on data as described in the text.

Figure 7: Overview of Land Allocation Procedure

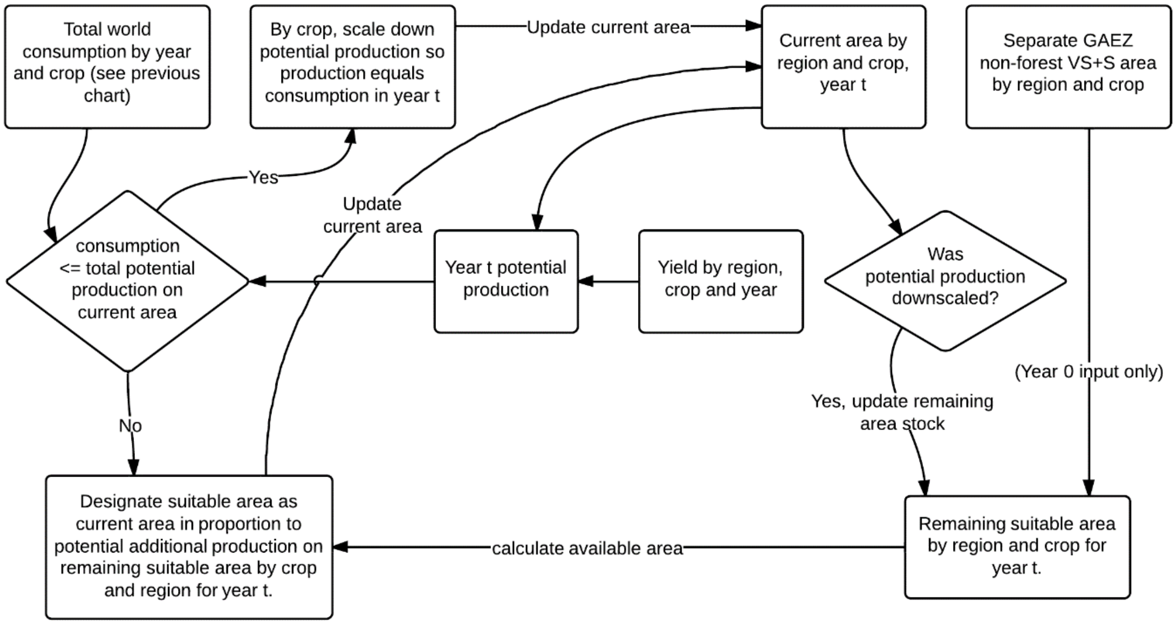
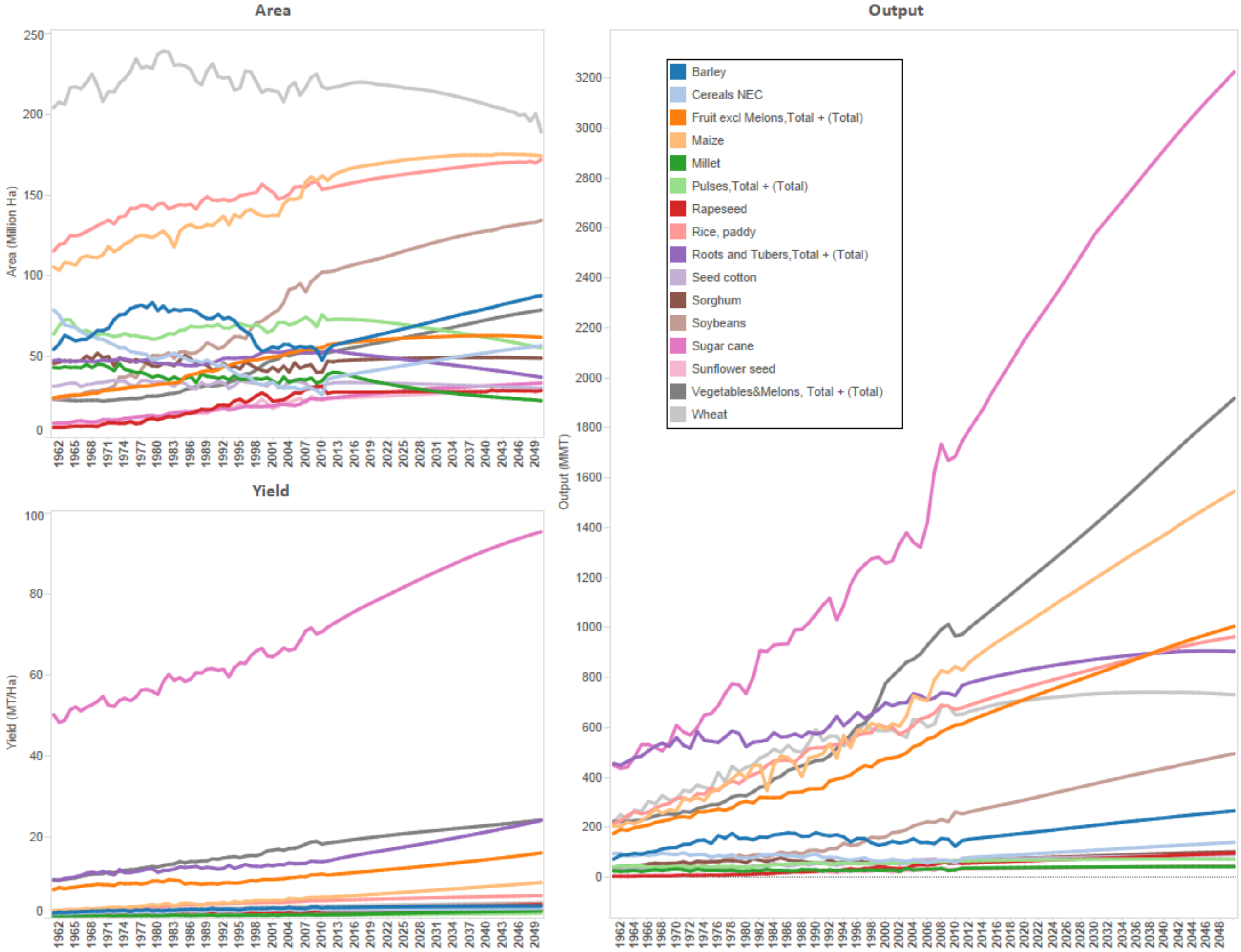


Table 5: Past and Projected Global Average Growth in Crop Yields

Crop	1961-1990	1990-2010	2010-2050
		(*percent per year*)	
Maize	2.20	1.74	1.33
Rice	2.19	1.07	0.62
Wheat	2.95	0.79	0.63
Soybeans	1.79	1.49	0.91
Sugarcane	0.70	0.69	0.75
Vegetables	1.55	1.10	0.71
Fruits	0.66	1.21	0.97

Source: Developed by authors based on data as described in the text.

Figure 8: Actual (1961-2009) and Projected (2010-2050) Yield, Area and Output, by Crop



Source: Developed by authors based on data as described in the text.

Note: The figure shows past (1961-2010) and projected (2011-2050) area, yield and output for each crop, aggregated to the global level. The iAP model is actually resolved at the regional level. The projected values represent the midline scenario.