A Bounds Analysis of World Food Futures: Global Agriculture Through to 2050*

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The notion that global agricultural output needs to double by 2050 is oft repeated. Using a new International Agricultural Prospects (iAP) Model, to project global agricultural consumption and production, we find in favour of a future where aggregate agricultural consumption (in tonnes) increases more modestly, by around 69 per cent (1.3 per cent per year) from 2010 to 2050. The principal driver of this result is a deceleration in population growth in the decades ahead. Per capita income growth and changing demographics (generally ageing population) have significant but secondary roles in spurring growth in agricultural consumption, as does our projected growth in the use of agricultural feedstocks to meet the growth we envisage in biofuel demand. Worldwide (but not equally everywhere), crop yield growth has generally slowed over the past decade or so. Notwithstanding a projected continuance of this slowdown, the prospective improvements in crop productivity are still sufficient to reduce per capita cropland use, such that land devoted to crops would need to increase by less than 10 per cent. Even in our upper-bound (high-consumption) scenario, we estimate that there remains sufficient productive agricultural land to more than meet the demand without ploughing-in additional forest-dominated lands.

Key words: biofuels, calories, consumption, demographics, income, production.

> "It is better to be vaguely right than exactly wrong."
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> Carveth Read (1898, p. 351)

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* The authors thank Connie Chan-Kang, Michelle Hallaway and Bess Rubin for their excellent research assistance, and Brian Fisher and two anonymous reviewers for their helpful comments and suggestions. This paper was prepared with support from the University of Minnesota and the Bill and Melinda Gates Foundation by way of the HarvestChoice project.

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1. Introduction

The global agricultural economy of today bears little resemblance to its counterpart two centuries ago. In 1800, the planet's population was a mere 890 to 989 million (Clark 1967, table III.15; Thomlinson 1975; McEvedy and Jones 1978; Goldewijk *et al.* 2010, table 2), most people lived in rural areas and 75–80 per cent (Bairoch 1988, p. 287) of those working earned their livelihoods from agriculture (U.N. 1999, table 1; Federico 2005; Goldewijk *et al.* 2011, table 4). Around one person was being fed per hectare-in-agriculture, and average life expectancy at birth was only 26 years (Maddison 2001, tables 1–5a).[1] By 2010, the world's population had increased more than sixfold to 6.9 billion; land in agriculture increased more slowly, such that the population-to-land ratio was 1.41 persons per agricultural-hectare. More than half that population was living in urban areas, less than 40 per cent of the working population was employed in primary production, and the average person lived almost 69 years (FAO 2012a; U.N. 2013a, table III.1).[2] The midline estimated number of people on the planet is expected to grow to 9.6 billion by 2050, resulting in an agricultural population-to-land ratio of 1.96 persons per agricultural-hectare (about double that of 1800) if the amount of agricultural land stays at its 2010 total.[3]

Looking forward, the notion that global agricultural production needs to double by 2050 to meet a doubling of demand is repeated often enough to seem a truism (see, e.g., Tillman *et al.* 2011; Ray *et al.* 2013). Yet, there are considerable uncertainties about many of the fundamental drivers of global agricultural consumption and production growth, with consequences for changes in the amount, composition and (country) location of these aggregate quantities that set the bounds for the world's food future. Our objective is to explore these bounds and consider what we can and cannot say about the likely state of global agricultural consumption and production through to 2050. To accomplish this objective, we opted for a parsimonious approach to projecting global agricultural consumption and production, placing an

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[1] Goldewijk *et al.*'s (2011, table 3) baseline estimates have 9.12 million km^2 (or 912 million hectares) devoted to agriculture worldwide in 1800 (3.99 million km^2 in crops and 5.13 million km^2 in pastures). FAO (2012a) report 1.54 billion hectares were cropped worldwide in 2010, and there were 3.35 billion hectares of pastureland for a total of 4.89 billion hectares in agriculture.

[2] Moreover, only 3.2 per cent of the working population in high-income countries was employed in agriculture, versus 64.5 per cent of those in low-income countries (FAO 2012a). The reported 2010 life expectancy is the worldwide median for the period 2005–2010 from U.N. (2013a, table III.2).

[3] This view of the agricultural consumption–production relationship arguably puts undue emphasis on land as a constraint to increasing agricultural output. Many years ago, Schultz (1951) foresaw a continued decline in the economic importance of land in agriculture, particularly as the technical changes affecting agriculture enabled other inputs (like fertilizers, improved seeds and machinery) to substitute for land while increasing agricultural output in total and per unit of land. See also Johnson (1997, 2000).

emphasis on assessing the robustness of the results in light of plausible and in some cases substantial, differences in the underlying trends of major drivers of consumption and production. Two distinct and novel features of our approach compared with those previously used for similar purposes are: (i) we take explicit account of demographics in forming our consumption projections and (ii) we use a spatially sensitive approach in modelling commodity-specific production trajectories.

2. Projecting global agriculture

2.1. Prior projections (models)

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)...'[4] Perhaps the most oft 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, and the latest was published in 2012 by Alexandratos and Bruinsma (2012) who report estimates for 2 years, 2030 and 2050, updating prior projections; one by FAO (2006) for the same 2 years and another by Bruinsma (2003) for 2015 and 2030. The revised 2012 estimates suggest that world agricultural output is expected to increase by 60 per cent from 2005/07 to 2050 (or 1.07 per cent per year), down from the 70 per cent projected increase (or 1.21 per cent per year) over the same period reported by FAO (2006).[5]

The International Food Policy Research Institute (IFPRI) has maintained a long standing and widely cited effort to project global food trends, beginning with two reports published almost a decade apart; IFPRI (1997) and Paulino (1986). In the 1977 report, developing-country production and consumption were projected to 1990, and to 2000 in the subsequent 1986 report. Thereafter, IFPRI's projections centred on evolving versions of a recursive-dynamic, global, partial equilibrium model dubbed IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) (see Rosegrant *et al.* 2012). The first projections in this series were by Rosegrant *et al.* (1995). The most recent projections in Rosegrant *et al.*

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

[5] The 2006 and 2012 projections yield roughly the same aggregate volume of world production in 2050, although '... the commodity composition and pattern of uses (food, feed, etc.) is different (e.g. somewhat less meat but the same 3.0 billion tonnes of cereals with a smaller share going to feed and more to biofuels) (Alexandratos and Bruinsma 2012, p. 7)'. The slower 2005/07 to 2050 growth in the 2012 projections is attributable to an upward revision in the 2005/07 average volume of global agricultural production compared with the benchmark 2005/07 estimate used to form the previously projected changes in aggregate output.

(2013) had baseline world cereal production growing from 2.12 billion tonnes in 2010 to 3.22 billion tonnes in 2050 (1.04 per cent growth per year).[6]

2.2. Challenges with assessing future agricultural consumption and production

Developing long-run projections of our global food future is inherently challenging because of uncertainties surrounding the future trends of major drivers of agricultural consumption and production. Consider the population trends that lie at the heart of any consumption projection exercise. While the U.N.'s medium fertility projection has the numbers of mouths to feed growing to 10.9 billion by 2100 (U.N. 2013a, table I.1), there is substantial variation around this trend. The U.N.'s most recent high-fertility projection yields 16.6 billion, while their low projection peaks at 8.3 billion around 2050, then gradually drops to only 6.8 billion by 2100 (U.N. ibid). Uncertainties about future fertility and mortality rates and international migration contribute to the differences in these projections (U.N 2013a; section V).[7]

Per capita income, and hence GDP (gross domestic product), is another major driver of agricultural consumption, but whether or not changes in the political, infrastructural and institutional landscapes in populous countries such as China, India and Indonesia will continue to sustain higher than average global GDP growth rates for decades to come is important to solving the global agriculture projections puzzle. While projecting GDP is difficult, assembling comparable country-specific measures of past and present GDP is also problematic. For example, Feenstra *et al.* (2012) examined the large mark down of China's 2005 GDP that occurred between the 2007 and 2008 versions of the World Bank's *World Development Indicators*. Methodological differences between the two versions led Feenstra *et al.* (2012, p. 4) to conclude '. . . that real GDP in China relative to the United States is quite plausibly 50% higher than estimated by the World Bank (2008)'.

Economists have long established reasonably robust, albeit not entirely settled, statistical and behavioural regularities between food consumption

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[6] Other regular projections or outlook efforts include those by the USDA dating back to 1993 (see USDA, ERS 2014a), and the Food and Agricultural Policy Research Institute, FAPRI, since 1984 (see FAPRI 2013 for the latest such effort), joint OECD-FAO efforts by way of the AGLINK-COSIMO model (OECD 2007), and some less regular efforts using multi-region computable general-equilibrium (CGE) models developed at the World Bank, including the ENVISAGE (ENVironmental Impact and Sustainability Applied General Equilibrium) (see van der Mensbrugghe 2009) and the LINKAGE models (see van der Mensbrugghe 2011). See Tweeten and Thompson (2008) and Tillman *et al.* (2011) for recent examples of one-off projections efforts.

[7] All of the U.N.'s population projections (high, medium and low) assume substantial and widespread reductions in fertility rates relative to historical norms for all regions of the world except those (for example, more developed) countries that are considered to be in a 'post-transition low-fertility phase' where the total fertility rate is projected to converge towards and oscillate around replacement rates (Alkema *et al.* 2011; U.N. 2013a). If each country's present fertility rate persisted, the projected world population in 2050 would be 11.1 billion, and 28.7 billion by 2100 (U.N. 2013a, table I.1).

and per capita income, population size (and structure) and various other variables, especially at aggregate country or global scales.[8] But there are some new policy-sensitive, price-sensitive and technologically sensitive sources of agricultural consumption deriving from biofuels and other industrial uses of agricultural biomass that are growing and add to the prevailing uncertainties in assessing the overall consumption of agricultural outputs.

Projecting agricultural production is potentially even more problematic than assessing the future trajectory of consumption. Agricultural production is an intrinsically biological phenomenon in which inherently variable natural processes interact in complex ways with market factors to influence the pattern of production. Many of these biological processes are especially site sensitive and change over time in ways that are still not fully understood, especially at national or global scales. Thus, precisely what is produced where, when and how has potentially significant, but uncertain implications for projected agricultural output over both short and long periods of time.

To illustrate the likely magnitude of supply-side complexities, consider that in 1961 35.1 per cent of the world's US$746 billion (2004–6 average PPP agricultural prices) of agricultural output came from North America and Western Europe, while 24.2 per cent came from the Asia & Pacific region (FAO 2012a). Half a century later, in 2010, the real value of global agricultural output had almost tripled to US$2309 billion, of which 44.3 per cent now came from the Asia & Pacific region while the North American and Western European share had fallen to 21 per cent. As Beddow and Pardey (2014) show, given the influence of site-specific factors (like climate, soil and terrain), the shifting location of agricultural production, in and of itself, has important consequences for agricultural output. For example, they estimated that around one-fifth of the growth in U.S. maize production during the 20th century was associated with changes in where maize is grown. This crop movement makes it doubly difficult to predict the effects of changes in climate (and other natural factors, like agricultural pests and diseases) on *aggregate long-run* trends in agricultural production. It also supports the choice of an approach to global output projections that makes explicit the (changing) location of agricultural production.

2.3. The international agricultural prospects model[9]

To assess the global prospects for agriculture over the following three decades, we opted to project global agricultural outcomes by parsimoniously focusing

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[8] Most notably, Engel's law is one of the oldest empirical regularities in economics; one version says that as household resources increase, the share of expenditure devoted to food declines. This relationship has been found both across and within countries at the micro and macro levels (see Stigler 1954; Houthakker 1957; Prais and Houthakker 1971).

[9] The version (2.1) of the iAP Model reported in this paper was developed by faculty in the University of Minnesota's International Science and Technology Practice and Policy (InSTePP) center and the Food Industry Center.

on those factors expected to be the most important determinants of consumption and production through to 2050, and for which plausible projections of those factors were to hand or within reach.[10] To reveal the robustness (or fragility) of our agricultural projections, we also report bounds to the variation in our projections arising from the empirical uncertainties inherent in these important drivers of global agricultural consumption and production.

The consumption side of the International Agricultural Prospects Model (hereafter dubbed the iAP Model) is anchored by two distinct components: an econometrically estimated calorie-based food consumption projection model and a set of crop-based biofuels projections derived using data and informed judgment. The production side of our model is anchored by a set of econometrically estimated crop- and region-specific yield growth projections models. Having developed a quantitative sense of a likely trajectory of aggregate agricultural consumption worldwide, how production might satisfy that consumption is dynamically derived via a spatially explicit determination of the location of production subject to the available agricultural cropland and the likely trajectory of 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 of 17 regions. Thus, in each year, global, aggregate agricultural consumption resolves with agricultural production by way of inter-regional trade and a plausible spatial allocation of the location of crop production within each region informed by both Ricardian and Heckscher-Ohlin notions of comparative advantage.

This approach sidesteps the considerable difficulties of obtaining – or, in the case of some models, inferring (Valin *et al.* 2014) – the long-run supply and demand elasticities that are inherent in using partial- or general-equilibrium market models for agricultural projections purposes.[11] However, by doing so, it means we are agnostic as to the path of future prices implied by our global, aggregate futures. Further, it is our judgment that credible,

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[10] For the reasons described above, and others in Pardey *et al.* (2014, appendix 1), the implicit climate assumption in our production (and consumption) projections is that the best estimate of the world's 'agricultural climate' over the coming decades is given by the actual climate over the past several decades. That is, while climate change may have important local and regional consequences, we do not foresee any predictable changes in the average global climate under which crops are grown as determined by the timing and location aspects of farmers' decisions regarding which crops to grow (or animals to raise) where, how and when (see Beddow 2012; Beddow and Pardey 2014).

[11] For example, Rosegrant (2012) report that the 2012 version of the IFPRI IMPACT model is calibrated on demand elasticities taken from a 1998 compilation made available online by USDA. The latest version of that database, which was last updated in 2006, is available at USDA, ERS (2014b). Valin *et al.* (2014) and von Lampe *et al.* (2014) both identify variation in the baseline parameterization of price and income (and presumably substitution) elasticities, and their variation over time, as a notable source of variance in the global food consumption and demand projections resulting from the 10 global economic models they compared. In Hertel's (2011) assessment of the long-run supply and demand for agricultural land he observed '...the prices at which this 'perfect storm' in the global land markets will be resolved depend *critically* [italics added] on the long-run supply and demand elasticities in agricultural markets (p. 271)'.

spatially explicit estimates of the potential effects of climate change on agricultural production and productivity are not presently available and are difficult to assess with reasonable levels of confidence since both farmers and technology respond to changing conditions. Thus, we do not consider the production (or consumption) consequences of prospective changes in climate in this version of the iAP Model. More details on each of the interrelated components of this model are discussed in some depth in Pardey *et al.* (2014) available at http://purl.umn.edu/182192.

3. Findings

Projecting agricultural production and productivity is fraught with uncertainty. Even those who are deeply knowledgeable about the long-run drivers of global agriculture can get it wrong. For example, Colin Clark, writing in 1954, surmised that '[t]he United States in 1975…will probably be importing one half of all [its] requirements of farm produce (p. 273)'. Rather, as Black (1955) largely anticipated, U.S. agricultural productivity and production surged, especially in the decades immediately following World War II (Alston *et al.* 2010), and by 2010, the U.S. produced over one-third of the entire world's maize and soya bean crops, was the third largest producer of all crops (by value), the second largest producer of all livestock products and a major exporter of many agricultural commodities (Alston and Pardey 2014).

Here, we present some key findings about global agricultural futures afforded by the projections made with the present version (2.1) of the iAP Model. Keeping in mind the inherent uncertainty in projecting agricultural futures, we emphasize the sensitivity of our projected futures to plausible variations in the underlying consumption and production drivers used to form these estimates, and present a plausible range of agricultural futures. We begin by projecting the aggregate consumption of food, both the total per capita kilocalories consumed and the source of those calories (i.e. from animal- or plant-based calories).

3.1. Agricultural consumption futures

We foresee global average per capita consumption of 3129 kcal per person per day in 2050, up from about 2831 kcal per day in 2009 (based on FAO's food balance sheets).[12] Over 25 per cent of projected 2050 calories derive from animal sources, up from 15.4 per cent in 1961 (Table 1). Our projected per capita calorie consumption estimates are slightly higher than the revised forecasts published by FAO in 2012. To compare, FAO projects aggregate global consumption of just over 3070 kcal per person per day in 2050

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[12] Ignoring potential dependencies between regional outcomes, the bootstrapped 90 per cent confidence intervals around this estimate imply that 2050 per capita daily consumption will range between 2940 and 3474 kcal.

(Alexandratos and Bruinsma 2012, table 2.1). Our projected consumption for low-income countries is 2634 kcal per day in 2050, compared with 3408 kcal per day for high-income countries.

On average, the projected world in 2050 will be similar in both per capita income and calories consumed to a high-income country of today. The projected global average per capita GDP in 2050 is US$29,735, versus a high-income country average of US$32,639 in 2009 (both in 2005 prices). The projected 3129 kcal per person global average daily consumption is a little lower than the 3410 kcal consumed per person in high-income countries in 2009, and the share derived from animal sources is lower (25.1 per cent for the world average in 2050 versus 26.8 per cent in the high-income countries in 2009).

Drawing on data in FAO (2012b), we estimate that the total number of calories consumed worldwide grew by around 2.1 per cent per year over the past half century, increasing from just under 2.5 quadrillion kilocalories in 1961 to nearly 6.9 quadrillion kilocalories in 2009 (an increase of 29 per cent in the average amount of calories consumed per person per day over this 48 year period) (Figure 1, solid line). By this metric, global caloric consumption grew considerably faster than population (2.19 and 1.64 per cent per year, respectively), reflecting a 642 kcal per day increase in the worldwide average number of calories consumed per person. Projecting forward, we anticipate that the rate of growth in total caloric consumption will slow, with a midline 2010–2050 growth rate of 1.1 per cent per year, for an overall increase in

Table 1 Global calorie consumption, 1961–2050

Year	Source		Total
	Animal	Plant	
Per capita consumption		(kcal/person/day)	
1961	338	1851	2189
2009	501	2330	2831
2010	513	2318	2830
2030	654	2336	2990
2050	784	2345	3129
Total consumption		(trillion kcal/year)	
2010	1294	5851	7145
2030	2012	7184	9196
2050	2734	8175	10,908
Changes in per capita consumption		(kcal/person/day)	
1961–2009	163	479	642
2010–2030	142	18	160
2010–2050	272	27	299
		(growth, % per year)	
1961–2009	0.82	0.48	0.54
2010–2030	1.22	0.04	0.27
2010–2050	1.06	0.03	0.25

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

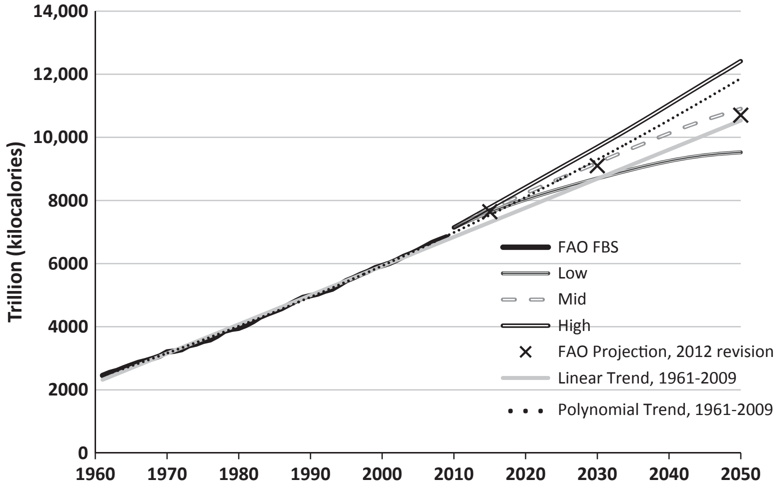

Figure 1 Past and projected global calorie consumption. Source: Developed by authors based on data as described in Pardey *et al.* (2014). The FAO projections (crosses) are from Alexandratos and Bruinsma (2012). FAO FBS represents annual global per capita caloric consumption from FAO multiplied by the population of the relevant year (FAO 2012b). Notes: The low, mid and high projections for the period 2010–2050 are constructed by the authors using version 2.1 of the iAP model.

caloric consumption of nearly 53 per cent from 2010 to 2050 (Figure 1, dashed line). Nevertheless, the midline projections have population growing more slowly than calorie consumption, such that the worldwide average per capita daily consumption will increase by 298 kcal between 2010 and 2050 (an increase of 10.6 per cent in calories consumed per person per day over this period).

Our midline 2030 and 2050 projections approximately line up with the FAO projections of Alexandratos and Bruinsma (2012), and our 2050 midline estimate of the average global calories consumed (10.9 quadrillion calories) is just 3.5 per cent greater than a linear projection of the 1960–2009 series would suggest. If population growth rates track the U.N. (2013b) low-fertility scenario then the world consumption of calories in 2050 is projected to be 9.5 quadrillion calories, 12.8 per cent lower than obtained using the U.N.'s present midline population projections. If population grew in line with the U.N.'s high-end projections then global calorie consumption in 2050 is projected to be 12.4 quadrillion calories; 13.8 per cent more than the corresponding projection of global calorie consumption using the UN's midline population scenario, and just slightly higher than a projection forward of the 1960–2009 series using a polynomial trend.

The projections of calories consumed for human consumption include estimates of animal- and plant-derived calories. About three-quarters of the increase in calorie consumption between 1961 and 2010 derives from plant sources. Our projections have per capita calories consumed directly from plant sources increasing relatively little on average – about 27 kcal per day – by mid-century, with almost all (about 91 per cent) of the projected worldwide increase in average caloric intake through 2050 coming from increased consumption of meat and other animal products. This relative shift towards consumption of animal products is largely due to a projected increase in the rate of average per capita income growth, from about 1.6 per cent per year between 1980 and 2010 to over 2.7 per cent per year between 2010 and 2050 (Fouré *et al.* 2012). This is consistent with the recent growth in calories consumed from animal sources in Asia coincident with rapid economic development in the region. In China, total per capita calories increased by 474 kcal per day between 1990 and 2009. Of that increase, 387 kcal (or roughly 82 per cent of the total) was due to increased calories from animal sources (FAO 2012b). To the extent that the average person in 2050 will have a per capita GDP in the range of many high-income countries of today, our model predicts a similar pattern of consumption (adjusted for region and initial starting conditions).

In running the iAP model, we convert consumption (measured in kilocalories of animal- and plant-derived products) into the volume of crops needed to fulfil that consumption (measured in tonnes). The overall quantity consumed for the crops in the iAP Model totalled 2.3 billion tonnes in 1961, roughly tripling (or increasing by 2.3 per cent per year), to 6.9 billion tonnes in 2010 (Figure 2). Our midline projections have the quantity of global agricultural consumption increasing by a further 69 per cent by 2050, to 11.6 billion tonnes. Notably, projected consumption measured in tonnes grows marginally faster (1.3 per cent per year) than consumption measured in calories (1.1 per cent per year), reflecting prospective changes in the composition of the average diet, and the effects of demand for non-food uses.

Increasing the relative consumption of animal-derived calories shifts the composition of crop demand towards commodities that are used as animal feed.[13] Further, we take account of major trends in plant consumption by shifting the diet towards fruits, vegetables and sugarcane, and thus (in relative terms) away from other crops, notably the cereal grains and root crops (see Pardey *et al.* 2014 for details). Biofuels consumption also affects the composition of crop consumption, both directly (e.g. maize used to produce ethanol) and indirectly via the substitution of ethanol by-products for animal feed.[14] On net, these projected changes imply that while the consumption of rice, wheat, pulses and roots and tubers will continue to grow, these crops will decrease in *relative* importance (as part of overall consumption baskets) by

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[13] To the extent that future global livestock production evolves towards using relatively more crop-derived feeds (and thus, less pasture- and rangeland-sourced feed), we may underestimate the crop consumption consequences induced by changes in the demand for animal-derived calories.

[14] Cotton also affects the composition of crop demand, although in this implementation of the iAP Model, relative increases in the consumption of cotton are not offset by declines in the consumption of other (food and feed) crops.

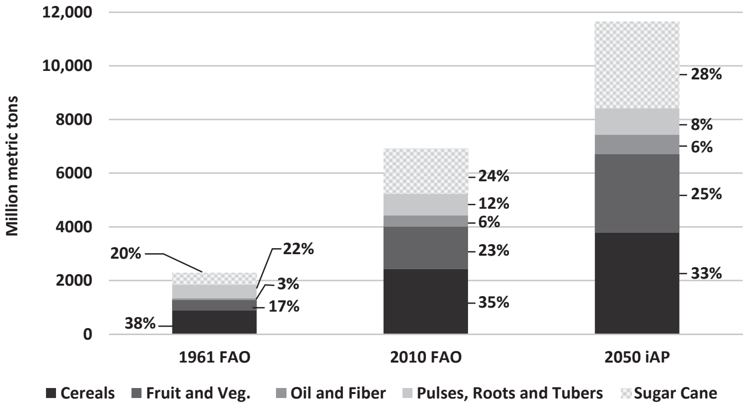

Figure 2 Past and projected quantities of crop production, 1961, 2010 and 2050. Source: Developed by the authors. Data for 1961 and 2010 are from FAO (2012a). 2050 data were derived by the authors using data and procedures as described in Pardey *et al*. (2014). Note: '2050 iAP' represents the midline population scenario in the iAP Model.

2050. The other crop categories either sustain (more or less) their 2010 consumption *shares* or increase in relative importance, notably vegetables and maize, which increase their shares by 3.1 and 1.3 per cent, respectively.

3.2. Consequences of demographic adjustments on calorie consumption

The world's population will not only continue to grow but will also continue to age; however, neither of these demographic shifts will occur equally everywhere. Figure 3 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 20 and 60 years and over 60 years (left-hand axis). Notably, while the share of the world's population between 20 and 60 varies only slightly over the period, the share of the population under 20 years old declines from 45 per cent in 1980 to an estimated 28 per cent in 2050. Moreover, the share of the global population over 60 years old increases from 8.6 per cent to 21 per cent over the same period.

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 some attention. Consistent with the point estimates from our econometrically estimated Engel-style calorie consumption model (see Pardey *et al*. 2014), if these demographic variables were omitted, the implied calorie consumption per person per day in 2050 would be slightly higher, totalling 3193 kcal per person per day, but the implied share of calories from animal sources would be somewhat lower, at 21.4 per cent (versus 24.4 per cent when demographic effects are taken into account). One potential caveat is that our measures of demographics may be capturing further nonlinearities between calorie consumption and per capita GDP. In other words, correlations

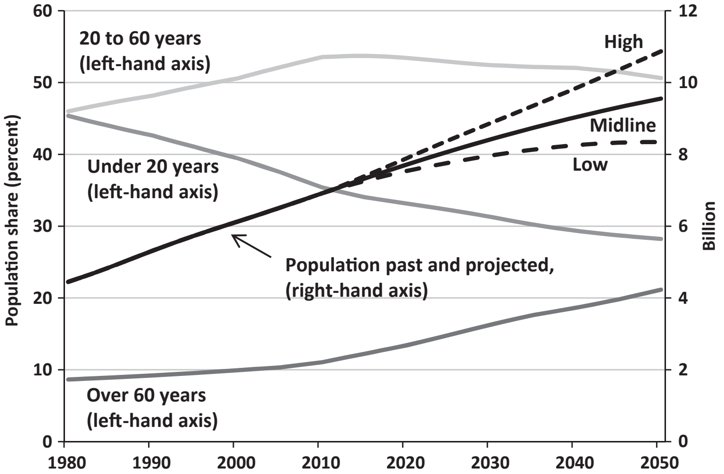

Figure 3 Global demographics. Source: Developed by authors using data from U.N. (2013a,b).

between the age distribution and GDP per capita may be driving estimates (we observe poor/young countries and wealthy/old countries but relatively few poor/old or wealthy/young countries). In sum, including demographics has a small but statistically significant effect on our calorie consumption projections.

3.3. Ploughing in the planet?

There is widespread concern that meeting the future global demand for agricultural output will come at the cost of ploughing in substantial new lands, with consequences for key natural assets and non-agricultural landscapes (see, e.g. Buringh 1985; Foley 2011; Brown 2012, p. 15). Our estimates, and those of others, indicate these concerns appear overblown. To be sure, there are areas presently in agriculture that would be better taken out of production or that require substantial and sustained changes in agricultural practices to ameliorate the negative environmental effects of production that impose costly externalities on sectors outside of agriculture or undercut the longer-term productivity performance of the agricultural sector itself. But our projections do not support the spectre of significant new land coming into agriculture over the decades ahead.

Juxtaposing IIASA's (2000) estimates of the amount of land suitable for agricultural production against FAO agricultural land use data reveals that about 43 per cent of the world's crop-suitable land was harvested in 2010. The iAP Model projects that between 41 per cent and 56 per cent of IIASA's suitable crop production areas will be required to meet projected 2050 consumption, depending on the population scenario. The outcome of the low-population scenario is to reduce the amount of land devoted to crops by 4.5 per cent of the 2010 area. In the high-consumption scenario, land use increases by 28.5 per cent, just slightly more than the percentage increase seen over the previous 50 years. In the midline consumption scenario, cropland increases by 111.5 million hectares (9.8 per cent) between 2010 and 2050, leaving some 1.4 billion suitable hectares unutilized for crop production (Figure 4). In all cases, projected global consumption is met even after setting aside areas presently dominated by forest ecosystems that are also deemed suitable for crop production (an additional 571 million hectares).

The majority of the projected changes in cropland are geographically concentrated, such that there is relatively little change in some regions, while other regions see substantial shifts in hectarage (Figure 5). The high-income countries contribute about 47.9 million hectares to the projected 111.5 million hectare increase in cropland. Among the remaining countries, those in Latin America and Africa account for the preponderance of the new hectarage (97.1 million hectares), offset by a decline of 35.2 million hectares in Asia, representing a 7.8 per cent contraction in that region's cropped area. Notably, China and India together account for 88 per cent of the decrease in Asia, while the cropped area expansion in Brazil accounts for 58 per cent of the projected increase in Latin America.

3.4. Food versus fuel

We estimate that about 566 million tonnes of crop output was devoted to biofuels production in 2011 (8 per cent of the total by weight), the by-products of which returned 81 million tonnes to animal feed. By 2050, we project that biofuels demand will increase, such that 1038 million tonnes of crop output will be devoted to fuels production (with 135 million tonnes of feed by-products). In 2050, we expect the principal crop feedstock for biofuels to remain sugarcane, which will account for 73.3 per cent of global biofuels feedstock (compared with 62.4 per cent of the total in 2011). In 2011, an estimated 133 million tonnes of maize was used in biofuels production; we anticipate a shift in the composition of biofuels feedstock such that fuel produced using maize decreases to about 95 million tonnes by 2050, which is more than offset by increases in fuels derived from oilcrops such as rapeseed and soya beans. On net, projected changes in biofuels demand will have a negligible effect on total land use, owing both to shifts in the composition of the crops and other feedstocks used to produce these fuels, and the already relatively small portion of the agricultural land devoted to fuels production worldwide.

4. Conclusion

The seeming truism that the global demand for agricultural output 'will' double by 2050 is simply not the most plausible future we (and others)

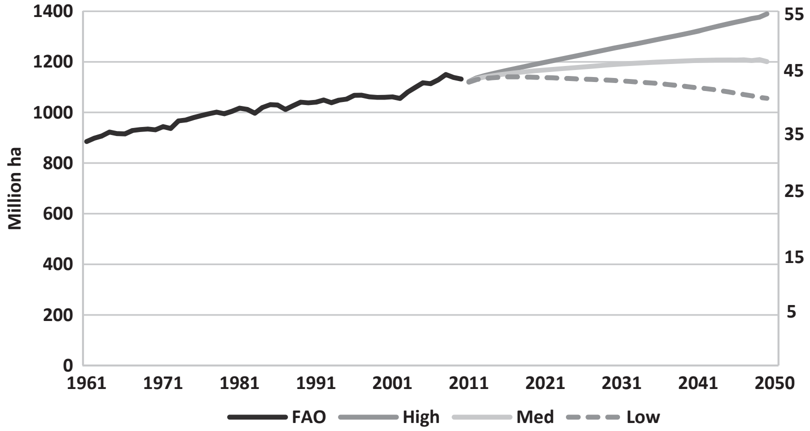

Figure 4 Past and projected global cropland use, 1961–2050. Source: Developed by the authors. Data for 1961 and 2010 are from FAO (2012a). 2010–2050 data were derived by the authors using data and procedures as described in Pardey *et al.* (2014).

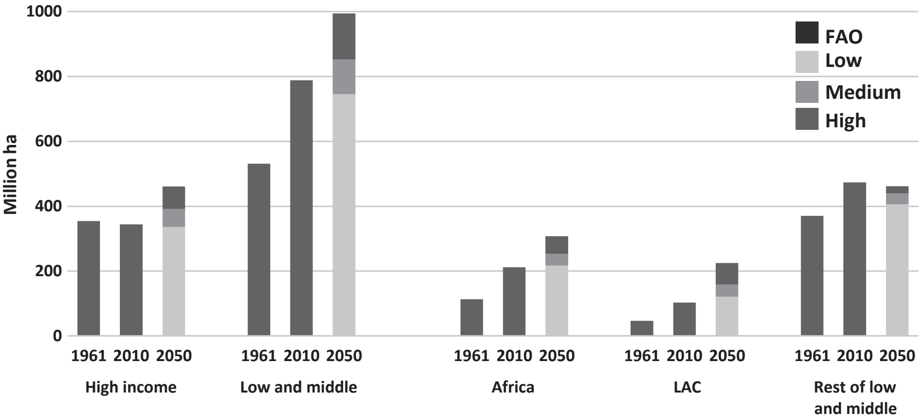

Figure 5 Regional changes in harvested area, 1961, 2010 and 2050. Source: Developed by the authors. Data for 1961 and 2010 are from FAO (2012a). 2050 data were derived by the authors using data and procedures as described in Pardey *et al.* (2014). Note: The low, medium and high values represent the projected land use implications of the corresponding U.N. population projections.

envisage. Our results reinforce the emerging consensus that feeding the world in 2050 will likely require a sizable but more modest increase in global production. For sure, aggregate agricultural consumption increased by 202.5 per cent over the 49-year period 1961–2010. However, our midline projections have global agricultural consumption for food, feed and biofuel uses increasing by only 68.6 per cent from 2010 to 2050: with a 91.0 per cent increase if population were to grow at the upper end of the U.N. projected rates of growth, or just a 48.0 per cent increase if the U.N.'s low-population trajectory scenario were to materialize.[15] This compares with an implied 55.3 per cent increase in agricultural consumption over the same period using FAO's revised 2012 projections (Alexandratos and Bruinsma 2012, p. 7).

The mainstream view (as represented by U.N. population projections) is that population totals are transitioning from a convex trajectory (implying accelerating rates of population growth over the past century) to a concave trajectory (implying decelerating rates of population growth) over the next century. Over 70 per cent of our midline projected change in calorie consumption is attributable to the change in population alone. Per capita changes associated with projected increases in average per capita income or the changing demographic (age structure) of the global population are, while important, not the primary drivers of future agricultural consumption totals.

Although our midline projected percentage increase in global agricultural consumption from 2010 to 2050 is more muted than some imagine, the absolute magnitude of the projected agricultural consumption growth over the next four decades is daunting, especially when compared with the past. Our projection has aggregate crop consumption growing by an average of 100.5 million tonnes per year during the 2040s compared with just 78.7 million tonnes per year during the 1960s (a 28 per cent increase in the absolute annual increase across these decades). Thus our projections imply that total consumption of agricultural output during the decade beginning in 2040 will exceed the total amount consumed during the three decades beginning in 1961.

Notwithstanding the continuing slowdown in agricultural productivity (or, more precisely, crop yield) growth underpinning these projections, our projected midline growth in agricultural consumption can be met by a commensurate growth in agricultural production, with only modest increases in the land used for agriculture (9.8 per cent between 2010 and 2050). One possible inference from this finding is that concerns about a decline in agricultural productivity performance are overblown, thus obviating the need to revitalize (public) investments in agricultural R&D (see, e.g. Pardey *et al.* 2013a). This is a risky policy position to hold for several reasons.

First, although we project slower crop yield growth rates for the forty year period 2010–2050 than in recent decades, they are still well in excess of the global rates of crop yield growth observed in the pre-Green Revolution period (i.e. the forty year period beginning in 1910 that witnessed the initial

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[15] The U.N.'s high-, middle- and low-population projections vary based on different assumptions about future fertility trends. Which fertility assumption is most likely is not evaluated; though the U.N.'s medium population projections closely track the median projections resulting from recent efforts to develop probabilistic assessments of population growth based on statistical time-series projections of fertility and mortality trends (Raftery *et al.* 2012). The U.N.'s high and low projections reasonably track the 95th percentile prediction intervals for some countries in the Raferty *et al.* study, but are substantially wider or narrower than the 95th percentile prediction intervals for some other countries and regions. Therefore, while it appears reasonable to interpret the U.N.'s middle projection as the central tendency of future population growth, a probabilistic interpretation of the high and low projections is more elusive.

uptake of scientifically bred varieties and a whole host of other output enhancing technologies, including an array of agricultural chemicals, farm mechanization and improved crop management methods). For example, our projected rate of U.S. maize yield growth from 2010 to 2050 is 0.93 per cent per year (compared with 0.78 per cent per year for U.S. maize yields during the period 1910–1950). Similarly, the U.S. cereals aggregate (including barley, maize, rice and wheat) grew by just 0.48 per cent per year over the earlier period, compared with our 2010–2050 projected rate of 0.91 per cent per year.

Second, increasing yields is one thing, sustaining past yield gains is a different, and equally difficult, matter. Ruttan (1982, p. 60), observed that as the level of crop yields increases, an increasing share of research effort is necessary just to maintain the past gains in yields embodied in present yield levels. This is especially true for biological production processes like agriculture that are subject to never-ending, co-evolutionary pressures from crop pests and diseases, which naturally 'invent' their way around the chemical, mechanical and biological means of crop protection arising from R&D (see, e.g. Pardey *et al.* 2013b). These evolutionary processes can thus require research to run harder in order to simply stand still. Moreover, the deployment of modern means of controlling the yield-reducing effects of these crop pests (like substituting biological forms of control via bio-engineered varieties for chemical or management forms of control) does not eliminate these long-standing biological realities of agricultural crop production (see, e.g. Frisvold *et al.* 2009). Going forward, the added challenges posed by climate change will not only require additional maintenance research to deal with the crop yield consequences directly attributable to changes in climate (such as changing, and likely more volatile, patterns of drought, heat stress or flooding), but also the indirect consequences of a changing climate on the pattern of pest pressures affecting crops in specific locales. That is, the problem of sustaining and growing crop yields is likely to get harder over the decades ahead compared with the challenges faced in dealing with these forms of 'biological obsolescence' over the past fifty years or more.

Our examination of variations in the projected aggregate consumption of agricultural products associated with projected differences in some of the key factors (especially population) that shift consumption trajectories help bound the dimensions of the global production responses required to meet these consumption futures. Sustainably feeding the world's still growing, increasingly richer, more urbanized and overall (but not equally, everywhere) ageing population during the decades ahead will still be a tall order. These projections indicate the task is doable, but by no means is complacency in order.

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