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Climate Change and Food Security to 2030: A Global Economy-wide Perspective

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Abstract

Recent analyses of the possible adverse effects of climate change on agriculture in developing countries have raised food security concerns, especially for farm households who comprise most of the world's poor and whose crop productivity is expected to fall. The present study uses a global economy-wide model to assess the expected (in some cases positive) effects on temperate zone crop productivity and the upward pressure on farm product prices from yield falls in developing countries. Also modelled is an expected adverse effect of higher temperatures and humidity in the tropics on the productivity of unskilled workers in developing countries. The net effect of those combined shocks on the agricultural sector's competitiveness in any developing country is an economy-wide empirical matter, since unskilled workers are employed in nonfarm as well as farm activities. Given the degrees of uncertainty about plausible effects of climate change, our modelling accounts for a range of yield productivity and labor shocks. The results provide a range of consequences for international agricultural prices and for national food consumption, net farm income and economic welfare.

Keywords: Climate change, crop and labour productivity growth, global economy-wide model projections

JEL codes: D58, F17, Q17, Q24, Q54

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1. Introduction

Following the upward spike in international prices of many primary commodities in 2008, and in light of on-going climate changes, policy makers and the general public have once again become concerned about food security at both national and global levels. While prices in international markets for food and energy raw materials came down quickly from their mid-2008 peaks, they rose again in 2010-11 and they remain high by historical standards. More than that, the trend in food prices has been noticeably upward over the past decade, in contrast to its downward trend over most of the 20th century; and, since the introduction of biofuel subsidies and mandates particularly in the US and EU a few years ago, food prices seem to be closely tracking fossil fuel prices – again in contrast to most of the second half of the 20th century (Figure 1).

While affluent people in high-income countries can cope with higher prices of farm products, the poorest households of those countries, and a far higher proportion of non-farm households in developing countries, suffer when food prices are high. Even some farm households can be worse off, for example those who produce predominantly cash crops whose prices have not risen with those for staple food crops, or who earn the majority of their income from off-farm activities. Food crises can erupt into urban riots, as happened in numerous food-deficit developing countries in 2008 and 2011, and can even bring down governments. When followed by natural disasters (as with the earthquake in Haiti and floods in Pakistan in 2010), the outcome can be catastrophic.

Climate change is expected to add to these food security concerns over the next two decades even if global strategies to mitigate greenhouse gas emissions were to be introduced immediately. Warmer temperatures and altered precipitation patterns and thus water availability are expected, as are more-frequent extreme weather events. The associated crop

productivity changes may be beneficial initially in some cooler temperate regions in the higher latitudes and altitudes, but climate change is widely expected to reduce farm land and labour productivity in the tropics – and globally, notwithstanding expected improvements in some cool areas (see, e.g., Cline 2007, Kjellstrom et al. 2009, Mendelsohn 2009, Nelson et al. 2010).

What would be the market, economic welfare and food self sufficiency effects of these expected changes in productivity of global agricultural resources? If they were progressively to lower world food output, the international food price trend would move onto a higher trajectory, depending on how each country and commodity market responded to climate change. Thus it is not necessarily the case that most farm families in developing countries are going to be losers economically from climate change: it is always possible that the change in the price of their output more than compensates for any fall in their farm productivity. Even so, food security concerns may increase if food prices are higher and self-sufficiency ratios are lower, particularly in net food-importing developing countries (Hertel and Rosch 2010).

This paper seeks to provide a sense of how climate change might impact on the world's markets for farm products if there is no mitigation or adaptation other than in response to price changes. We make use of a global economy-wide model, the global GTAP model (Hertel 1997), first to provide a projection of the world economy to 2030 without any climate or policy changes, and then to compare that baseline with projections which incorporate assumed impacts of climate change over the next two decades on productivity (based on damage function analyses reported in recent studies). Only the two most direct biophysical changes that affect agriculture are modelled. The first is in crop land productivity, drawing on the interpretation of damage functions by Hertel, Burke and Lobell (2010), which in turn is informed by the careful assessment of the scientific evidence by Lobell and Burke (2008).[1] The second relates to the impact of higher temperatures and humidity on the productivity of unskilled labour in the already hot and humid tropics, drawing on the interpretation of its debilitating effects by van der Mensbrugghe and Roson (2010) which in turn draws on Kjellstrom et al. (2009).

National and global economic welfare effects (equivalent variations of income) also are estimated in the GTAP model. Their magnitudes are shown to be small with respect to

[1] These authors define three productivity scenarios: low, medium and high. The low (high) productivity scenario is a world with rapid (slow) temperature increase, high (low) sensitivity of crops to warming and a lower (higher) bound of CO_2 fertilization effect.

projected real income, suggesting that there must be other costs of climate change not examined here to warrant the sorts of major policy responses being called for (such as carbon emission taxes and border tax adjustments). However, it needs to be kept in mind from the outset that we are imposing only that subset of shocks expected to come from climate change that affects farming most, and we are using a comparative static model that – unlike a dynamic stochastic model – cannot capture the sporadic additional costs to farmers and others of more-frequent extreme weather events, such as floods, droughts, frosts, hail and wind.

The paper begins in Section 2 by describing the GTAP model and how we use it to project the world economy to 2030 (the baseline scenario). Section 3 presents two main alternative scenarios for 2030, to represent expected features of climate change that directly affect agriculture: one involving just crop productivity changes, the other also allowing for changes in unskilled labor productivity in developing countries. We implement variations in the magnitude of these shocks to assess the robustness and linearity of results. Like all such modelling, the results depend on various assumptions, so a number of caveats are discussed in Section 4 before the paper concludes with some implications for food security and farm policies.

2. Projecting a baseline to 2030 with the GTAP model

The standard GTAP model (Hertel 1997) is perhaps the world's most widely used economy wide model for economy-wide global market analysis, in part due to its robust and explicit assumptions. In its simplest form, the model as used here is comparative static and assumes perfect competition and constant returns to scale in production. The functional forms are nested constant elasticities of substitution (CES) production functions. Land and other natural resources, labour (skilled and unskilled), and produced physical capital substitute for one another in a value added aggregate, and composite intermediate inputs substitute for value-added at the next CES level in fixed proportions. Land is specific to agriculture in the GTAP database, and is allowed to be highly mobile amongst alternative agricultural uses. A Constant Elasticity of Transformation (CET) revenue function transforms land from one use to another. There is also a very low elasticity of transformation between alternative uses of other natural resources. In the default GTAP closure, labour and capital are assumed to be mobile across all uses within a country but immobile internationally.

On the demand side there is a regional representative household whose expenditure is governed by Cobb-Douglas aggregate utility function which allocates net national expenditures across private, government, and saving activities. The greatest advantage of this regional household representation is the unambiguous indicator of economic welfare dictated by the regional utility function, expressed as an equivalent variation in income. Government demand across composite goods is determined by a Cobb-Douglas assumption (fixed budget shares). Private household demand is represented by a Constant Difference of Elasticities (CDE) functional form, which has the virtue of capturing the non-homothetic nature of private household demands as well as permitting the user to calibrate the model to specific own-price elasticities of demand. For present purposes, we recalibrate the income elasticities of China and India to account for their projected very rapid income growth.

Bilateral international trade flows are handled through the Armington (1969) specification by which products are differentiated by country of origin. These Armington elasticities are the same across regions but are sector-specific, and the import-import elasticities have been estimated at the disaggregated GTAP commodity level (Hertel et al. 2007). We follow the practice of many other GTAP users to deal with long-term changes by doubling the standard short-to-medium term Armington elasticities.

The standard macro-economic closure assumes that the levels of each region's employment of each of the productive factors is unchanged in aggregate, and that the regional balance of trade is determined by the relationship between regional investment and savings, where foreign investment is allocated in fixed shares across regions so that it moves in line with global savings. This fixed shares mechanism, which could be interpreted as a partial long-run equilibrium, with international capital reallocation left out, is more predictable (conservative) than the standard rate of return closure.

The full GTAP 7.0 database comprises 113 regions in addition to the 57 sectors/product groups, but to make the model more manageable we have aggregated it to 23 sectors/product groups and 23 regions (see Appendix Tables A1 and A2). It is initially calibrated to the year 2004. The standard GTAP protection database (see Narayanan and Walmsley 2008) has been altered to include a more-complete set of estimates of distortions to agricultural prices in developing countries, based on Valenzuela and Anderson (2008).[2] Those distortion estimates suggest that, despite reforms of the past 25 years, there was still a considerable range of industry assistance rates across commodities and countries in 2004,

[2] That distortions database is documented fully in Anderson and Valenzuela (2008) and is based on the methodology summarized in Anderson et al. (2008).

including a strong anti-trade bias in national agricultural and trade policies for many developing countries. Furthermore, non-agricultural protectionism is still rife in some developing countries, and agricultural price supports in some high-income countries[3] remain high.

To project the world economy to 2030 using this comparative static model, we assume policies as of 2004 and the stock of agricultural land and mineral reserves do not change in each region but that population, labour, capital and real GDP grow at the rates shown in Appendix Table A3, from which the implied rates of total factor productivity and GDP per capita growth are derived as shown in the final two columns of that table.[4] The exogenous growth rates are based on World Bank and OECD projections (see, e.g., van der Mensbrugghe and Roson 2010; Duval and de la Maisonneuve 2009).[5] The rate of total factor productivity growth is assumed to be the same in each of the non-primary sectors, and to be somewhat higher in the primary sectors as detailed in the footnote to Appendix Table A3. Higher productivity growth rates for primary activities were characteristic of the latter half of the 20th century (Martin and Mitra 2001), and are necessary in this projection if real international prices of primary products (relative to the aggregate change for all products) are to follow a flat trend.[6]

The differences across regions in rates of growth of endowments and total factor productivity, and the fact that sectors differ in their relative factor intensities, ensure that the

[3] High-income countries are defined in this paper to include also Russia and other East European and Central Asian countries that are not members of EU27.

[4] Economically exploitable mineral reserves are depleted each year but they are also added to through new discoveries and improvements in exploitation technologies. In recent decades those reserves have tended to increase rather than fall (BP 2010), so our assumption of no change will project higher mineral and energy prices than would prevail if past reserves trends were to continue. Since 1990, arable land used for farming has shrunk slightly (less than 2 percent per year) in high-income and transition countries, has changed little in South and Southeast Asia and in North Africa and the Middle East, but has grown slightly (at less than 2 percent per year) in East Asia, Latin America and Sub-Saharan Africa (Deininger and Byerlee 2011, Table 1.1 based on FAOSTAT data). Had those rates of change been assumed to continue for another two decades, in place of our assumption of no change in land area, they would have changed the aggregate results reported below only only slightly.

[5] Since completing this study, a new set of preliminary projections to 2050 have been released by CEPII in Paris (Fouré, Benassy-Quéré and Fontagné 2010). The exogenous assumptions in the present study are broadly in line with that CEPII study.

[6] The reason for choosing that calibration, as explained in Valenzuela and Anderson (2011), is to be consistent with the World Bank projections over the next two decades in van der Mensbrugghe and Roson (2010). An alternative in which primary product prices fall, as projected in GTAP-based projection studies in the late 20th century (e.g., Anderson et al. 1997), is considered unlikely over the next two decades given the slowdown in agricultural R&D investment since 1990 and its consequent delayed slowing of farm productivity growth (Alston, Babcock and Pardey 2010). Our assumed total factor productivity growth for agriculture between 2004 and 2030 of around 2.0 and 2.4 percent for high-income and developing countries, compares with estimated rates for 1967 to 1992 of 3.4 percent for high-income countries and between 1.8 and 2.6 percent for developing countries (Martin and Mitra 2001).

structures of production, consumption and trade across sectors within countries, and also between countries, is going to be different in 2030 than in 2004. Those changes are reported in detail in a companion background paper by Valenzuela and Anderson (2011). The faster-growing developing countries (especially those of Asia) become a considerably larger share of the projected global economy over the next two decades. Their share of world GDP rises from 20 percent in 2004 to 30 percent by 2030.

The developing country share of global exports of all products increases from just under one-third in 2004 to a little over one-half by 2030. China's shares alone grow from 4 to 8 percent of global GDP and from 7 to 16 percent of global exports. China's export growth is largely at the expense of high-income countries rather than any developing country regions. The developing country share of global exports of agricultural products, by contrast, falls slightly. It drops from 33 to 27 percent between 2004 and 2030, while the developing country share of global farm imports rises dramatically, from 32 to 56 percent. Recall, though, that we are assuming no change in agricultural or trade policies over the projection period.[7]

With real prices of primary products not falling as they did in the 20th century, the normal transition from primary to manufacturing and service sector activities occurs less rapidly in our projection to 2030, at least for developing countries. Sectoral shares of national exports and imports, however, change somewhat more. For developing countries, farm and other primary products become less important in their overall exports and more important in their overall imports, and conversely for high-income countries (Tables 9 and 10 of Valenzuela and Anderson 2011). Thus in the baseline projection has agricultural self-sufficiency in developing countries falling from 98 percent in 2004 to 93 percent by 2030, with most of that fall concentrated in East and South Asia (first two columns of Table 1). Even so, the developing countries' share of global agricultural GDP rises from 50 percent in 2004 to a projected 65 percent by 2030. It shares of GDP from other primary products and from manufactures also rise, from 54 to 63 percent and from 25 to 39 percent, respectively (Table 11 of Valenzuela and Anderson 2011), reflecting the much higher GDP growth rate assumed for developing countries, particularly China but, in the case of agriculture, also India.

[7] Perhaps a more likely scenario, especially for rapidly growing Asia, would be a steady rise in agricultural protection to slow the decline in food self sufficiency – as has happened over the past 50 years in the most-advanced Asian economies (Anderson 2009).

3. Alternative scenarios for 2030

Given the baseline projections summarized above, we use the GTAP model to simulate the market and welfare effects first of the direct impact of climate change on crop yields in different parts of the world, and then also of the projected impacts of climate change on unskilled labour productivity in tropical developing countries.

3.1 Crop productivity effects

The direct impacts of climate change on crop productivity have been examined by many analysts, and there still remains considerable uncertainty as to even their sign let alone their magnitude (Gornall et al. 2010). Nonetheless, for present purposes we adopt the same rates for the period from 2004 to 2030 as the rates used by Hertel, Burke and Lobell (2010) following their extensive review of the scientific literature. We make only a few minor adjustments, such as for Australia so as to be more consistent with the *Garnaut Climate Change Review* (Garnaut 2008; see also Gunasekera et al. 2007). Those yield shocks are summarized in Appendix Table A4. They represent a most-likely or medium case, along with a low-productivity and a high-productivity case. These estimates are intended to depict a range of plausible effects, and can be thought of as the 5^{th} and 95^{th} percentile values in a distribution of potential yield impacts (Hertel, Burke and Lobell 2010).

Several points are worth noting about those shocks. First, there is a wide range of effects between the low and high scenarios for each region. Second, they tend to be positive in all but the low crop productivity scenario for high-income temperate countries except for coarse grains (i.e. maize). Third, they are generally negative for developing countries except in the high productivity scenario. And fourth, those yield shocks are very small over a period as long as 26 years, when compared with the annual productivity growth rates reported in Appendix Table A3. More than that, farm land is projected to account throughout the next two decades for less than one-tenth of GDP in all but the most agrarian of developing economies and to be below 2 percent in high-income countries and globally (Table 13 of Valenzuela and Anderson 2011).[8] Hence the net economic effects of these direct crop yield impacts of climate change will necessarily be small in proportional terms – even though they

[8] Land's share of agricultural GDP is projected to rise by 2030, however. This is in contrast to what T.W. Schultz (1951) anticipated, but is not inconsistent with the developments expected over the coming decades as reviewed, for example, by Hertel (2010).

may have large impacts on very seriously affected regions within some countries, including the hot irrigated horticultural and rice- and cotton-growing regions of Australia and the United States.

The effects of those climate change-induced direct crop productivity impacts on national agricultural self sufficiency for the sector as a whole in 2030, as compared with the baseline in that year, are no more than 2 percentage points except for Australia, New Zealand and Argentina (Table 1). The effects on the production, consumption and trade, summarized in percentage terms in Table 2, are somewhat larger than the effects on self sufficiency, but are still relatively small overall. By 2030 the projected volume of agricultural output would shrink by no more than 2 percent in developing countries in the medium case. In the low-productivity case the adverse effects are larger, ranging down to -5.6 percent for India and -6.5 percent for Sub-Saharan Africa.

Typically the farmgate price of products is projected to move in the opposite direction to farm production in response to these yield shocks though, and to a more amplified extent. For the sector globally, the effect on production would be in the range of -1.3 to 0.6 percent whereas for farmgate prices the range is 6.7 to -2.4 percent (corresponding to low to high productivity shocks, respectively). There is an even more amplified effect on agricultural value added (which also takes account of changes in input prices), at the global level it would change by between -8.6 and 3.6 percent.(last row of Table 2).

The volume of farm products consumed in developing countries would fall in all but the high productivity case. The extent of the change is less than for production though, because incomes earned from non-farm activities would not fall like those from farming.

The difference between the production and consumption effects is the effect on trade. Since most developing countries are reasonably close to self-sufficient in farm products (see Table 1), the effect on their trade would be an amplification of the effect on production or consumption were it not for the fact that in most cases those two latter effects are both negative and so are somewhat offsetting (which is why self sufficiency is projected to change so little in Table 1). Hence agricultural imports of developing countries increase only slightly in the medium case, and even fall slightly in the high productivity case. In the low productivity case, however, some countries would see a sizeable increase in their food imports (final columns of Table 2). In that case it would be high-income countries whose farm exports would be higher (by 10 percent).

The aggregate price of agricultural products in international markets is expected to be higher by 2030 in all but the high productivity case. The most extreme change is for coarse

grains (mostly maize), whose price is projected to be 16 percent higher in the low case and 4 percent higher in the medium case (Table 3). Even higher results are expected from some other studies, however. A recent IFPRI study, for example, projects price effects of climate changes by 2050 of between 20 and 50 percent (Nelson et al. 2010).

The impacts of those price and quantity changes on overall national economic welfare ares summarized in Table 4. For the world as a whole, the negative impact in the medium case is for a tiny fall of 0.03 percent of projected real income by 2030. That aggregate conceals larger proportional changes at the country level, especially for developing countries, but even so they appear to be very minor (0.1 percent of projected real income for that group, and as high as 0.3 percent for India). Those national economic welfare effects come not only from the factor productivity shocks themselves but also from the change in the country's international terms of trade and the impact of producer and consumer responses to them on the resource efficiency costs of distortionary policies such as tariffs and subsidies. The terms of trade effects are non-trivial and for some countries they are larger than (and in some cases the opposite sign to) the direct crop productivity effect.

These projected changes from the assumed crop productivity effects of climate change are but one of the influences expected from temperature and humidity changes over coming decades. We turn now to an additional expected influence, namely via the debilitating impact on unskilled workers in developing countries which van der Mensbrugghe and Roson (2010) indicated could be far more important.

3.2 Effects on unskilled labour productivity

Since temperatures and humidity are expected to rise from already very high levels in most tropical developing countries, the productivity of workers in those countries (especially for those involved in manual farm work activities) is expected to fall in the absence of counter measures (Kjellstrom et al. 2009). By contrast, in high-income countries the temperature rises generally will be from cool or at most moderate rather than from high current levels.

We follow van der Mensbrugghe and Roson (2010) in relying on Kjellstrom et al. (2009) in attempting to simulate the effect of climate change on all unskilled workers in tropical and desertified developing countries, by implementing a shock to unskilled labour productivity in both agricultural and non-farm sectors. Kjellstrom et al. project the magnitude of that shock by the 2020s under the IPCC's A2 scenario to be between 3 and 7.5 percent for Sub-Saharan Africa, 4.9 percent for South Asia, and 7.5 percent for Central America. To err

on the conservative side, we assume a 3 percent decline in unskilled labour productivity by 2030 in all developing countries other than the relatively temperate ones of Argentina, Korea, South Africa and Taiwan and the most affluent ones (Hong Kong and Singapore). To test the linearity of the key effects of such a shock, we also provide results for a 6 percent shock.

It turns out the effects of this shock on agricultural markets are highly linear, which allows the reader to assess the impacts of their own alternative-sized labor shock from climate change simply by factoring up or down the numbers presented below.

For developing countries as a group, the generally negative impact of this shock on the volume of agricultural production is somewhat larger than the effect of the medium crop productivity shock alone. There is an even larger difference in the decline in consumption of farm products (Table 5), so the impact on global agricultural trade is slightly muted. The developing country share of global exports (imports) of farm products would still be lower (higher) by 2030 than in the absence of the two core productivity shocks (the medium crop one and the -3 percent labor one), but the change would be more (less) than if only crop productivity was affected.

The welfare effects are negative and considerably bigger than in the yield shock scenarios, because the shock to unskilled labour is non-trivial and applies to all sectors of developing countries, not just to agriculture. Globally they amount to a loss of $147 billion per year by 2030 for a -3 percent labor shock (and $296 billion, or roughly double, for a -6 percent shock), which compares to a global loss of just $20 billion for the medium crop productivity shock. Almost all of the global welfare loss is felt by developing countries(Table 4).

The self-sufficiency numbers shown in Table 1 refer to all agricultural products, and so do not necessarily relate closely to concerns about staple food import dependence. A better indicator of the latter is grain self-sufficiency, results for which are reported in Table 6. They too seem to be affected very little by the climate change shocks considered here. Even when disaggregated into individual crops such as rice and wheat, the scenarios differ little in their self sufficiency ratios for most developing countries. That does not mean, however, that food security is unaffected. This is because when food production falls in developing countries so too does aggregate income, other things equal; and thus less food can be afforded, so consumption falls as well – as shown in Table 2.

3.3 Combined effects of crop and unskilled labour productivity shocks

When those two sets of shocks are combined, the effects are linear for most but not all indicators. That is, the proportional changes to an indicator can often be simply added. To illustrate that, we show on the right-hand side of Tables 1, 3 and 4-6 the combined effect of the medium crop shock and the -3 percent labor shock.

Perhaps the most important of those combined effects are summarized in Figure 2, which shows the three crop scenarios together with the -3 percent labor scenario. International agricultural prices could rise as much as 4.2 percent, or fall by 1.8 percent, but in the median case would rise only 0.6 percent. That affects countries' terms of trade (and hence incomes) in different ways, depending on their net exports of the various products, The volume of consumption of farm products in developing countries falls in all cases except the high crop productivity case (where the net effect is virtually zero but see Table 5 for national details), which is not good news for food security in those countries. Part of the reason for lower consumption is the fall in net farm incomes in those countries of 1.8 percent in the medium case and 8 percent in the low crop productivity case: only in the high crop productivity case does agricultural value added rise in developing countries as a group (by 3.6 percent).

As for overall economic welfare, it falls for developing countries in all three cases illustrated in Figure 2, by between 0.6 and 1.2 percent of real income (see last columns of Table 4 for national details). By contrast, high-income countries would be affected far less – and would not lose at all in the high crop productivity case. To put those welfare effects in perspective, we ran another simulation in which import tariffs on all goods and all agricultural subsidies were eliminated in 2030 (having left those distortions unchanged in the core simulation from 2004 to 2030): the welfare effects of that extreme policy reform would be roughly enough to offset the effects on developing country welfare of the shocks summarized in Figure 2 (a 1.0 percent gain to developing countries' welfare and a 0.5 percent gain globally).

4. Caveats

The above analysis is very partial in nature, in several respects. First, it examines the effects of just two of the many sets of impacts that climate changes are expected to have on the global economy. The study by van der Mensbrugghe and Roson (2010), for example, also takes into account the effects on energy demand, water availability, tourism and sea level

rise. Not surprisingly, therefore, they get a higher impact of climate change on global economic welfare, of -1.8 percent by 2050. Incidentally, they too compare that with their estimate of the welfare effect of freeing trade policies globally by 2050, which is +0.9 percent according to their global model.

Second, we have analysed the effects only to 2030. The effects of climate change are expected to become more severe in subsequent decades, however, so in the absence of mitigation they could be much larger by the remaining two-thirds of the 21st century than those presented above for 2030. This is supported by the dynamic simulations to 2100 generated by Roson and van der Mensbrugghe (2010).

Third, the nature of each simulated shock obviously determines the size of its effects. The medium crop productivity shocks we model mostly help farm output in higher latitudes over the next two decades and hurt it in many parts of the tropics. The net effect in our case is virtually no aggregate global agricultural output change by 2030: between 0.6 and -1.3 percent. By contrast, van der Mensbrugghe and Roson (2010) assume larger positive shocks in temperate farm regions and smaller negative shocks in the tropics and so project a small net global economic welfare gain from changes in crop productivity. They also adopt a damage function approach to capture the effect of temperature rise on labour productivity (based on such studies as Kjellstrom et al. 2009), in contrast to our simpler homogenous exogenous labour shock for tropical countries. More-sophisticated damage functions with respect to crop productivity also could be adopted, especially now that the GTAP database is being enhanced to enable better modelling of land use changes (see Hertel 2010) and of the impact of changes in water availability in irrigated versus non-irrigated areas (see Calzadilla et al. 2010). Given the great uncertainty associated with the magnitude – and in some cases even the sign of – potential shocks, our results simply show some ranges, and leave it to future analytical work to include likelihood probabilities and explore complementarities in climatic and agent-based modelling.[9] An important feature of the GTAP economic model, however, is that many of the key results of a shock tend to be linear, in the sense that if the shock was 10 percent greater, the effects also would be about one-tenth greater.

Fourth, the standard comparative static version of the GTAP model used in the present study does not capture the complexity of energy markets. In particular, there are no biofuels markets, so the linkage that has recently emerged between biofuel crops and fossil

[9] A forthcoming study by Scealy et al. (2011) draws on that information in an integrated assessment modeling exercise that estimates the range of grain self sufficiency ratios to expect for each country in 2050. Even when projecting out four decades their self-sufficiency ranges are rather narrow, so they would be even narrower in just two decades' time

fuels is not built into the projections. Modellers have certainly begun incorporating elements of that linkage (see, e.g., Golub et al. 2010, Hertel and Beckman 2011), but there is still the challenge of anticipating how governments might alter biofuel subsidies and mandates over the next 20 years (given the newness of many of those policies and the uncertainty still surrounding the net environmental benefits of such supports to biofuel producers).

Fifth, as mentioned at the outset of this paper, the debilitating impact on welfare and food security from extreme weather events is not captured by the comparative static model we have employed. More-frequent extreme weather events such as floods, droughts, frosts, hail and wind can affect all sectors but are especially damaging to farm incomes whenever and wherever they strike – and not linearly, according to a new study of weather-driven maize yield variability in Africa (Lobell et al. 2011). Analysis of the welfare effects of climate change ought to recognise these income distributional consequences, particularly on the poor. Economy-wide modellers are only now beginning to focus on those possible poverty consequences (see, e.g., Hertel, Burke and Lobell 2010; Hertel and Rosch 2010), and to make their models stochastic (e.g. Hertel and Beckman 2011). What also is required is to recognize that if international food price fluctuations increase because of more extreme weather events, so too will the welfare costs of government efforts to use trade measures to insulate their domestic market from those border price gyrations (Martin and Anderson 2012).

And finally, we have assumed throughout that policies are unchanged through the projection period, and in particular that no new mitigation strategies or technologies are adopted to slow climate change, nor are trade, subsidy or tax policies changed. This is an obvious area for extending the analysis. If a carbon tax was gradually phased in by all countries, for example, climate change presumably would eventually slow down. However, it would have little impact before 2030, and meanwhile that set of carbon taxes would alter the international competitiveness of various industries around the world. Carbon-intensive industrial sectors such as China's would be likely to lose comparative advantage, thereby making China's farmers more competitive. And China might not be able to avoid that outcome simply by not adopting a carbon tax, because in that case other countries that have adopted such a tax may impose border tax adjustments on goods imported from China (Mattoo et al. 2009a,b) . One effect of pricing greenhouse gases, however, is that it would provide landowners with mitigation opportunities that would further alter the markets for and national comparative advantages in farm products (Golub et al. 2009). In particular, if that

leads to land being taken out of agriculture for re-forestation to sequester carbon, food prices could potentially become much higher.

5. Implications for food security and farm policies

Given the above caveats, it would of course be premature to draw implications for agricultural, trade and climate change policies from the empirical results presented in this paper. The results are presented simply to illustrate some of the ways in which one or two of the shocks expected from on-going climate change can affect agricultural markets directly or indirectly, and thereby also economic welfare. When those effects are expected by 2030 to be positive in some countries and negative in others, as in the case of farm products, the net impact on world food prices and hence real incomes of both farm and nonfarm households in the decades ahead can only be determined with the use of a global economy-wide model projected forward.

Our findings indicate, in terms of global food security, that the impacts of climate change are less pessimistic than some earlier studies. One of the more widely cited is by Cline (2007), who predicts that by the 2080s, even with carbon fertilization, agricultural output will be 8 percent lower in developing countries, 8 percent higher in high-income countries, and 3 percent lower globally. Those larger magnitudes refer to five decades later than the above projections though, so they may not be inconsistent with our findings for 2030 if indeed it is not until the middle half of the present century that the effects of climate change on agriculture accelerate. A more recent study by Nelson et al. (2010, Table 2.2) suggests that climate change will cause real international prices of grain to be between one-fifth and one-third higher in 2050 than they would be without the climate changes expected in the first half of this century. Again those results for two decades later may not be inconsistent with our findings for 2030.[10] And even if those larger results turn out to be excessive, the policy responses proposed by Nelson et al. (2010), to deal with the possible food security concerns they raise, may well be wise precautionary measures. That is especially the case for expanding agricultural R&D, since there is in any case considerable underinvestment in that

[10] The main reason for the difference in results between the Nelson et al. study and the present one is they assume somewhat larger crop yield declines in developing countries but declines also in high-income countries. by 2050 – in contrast to our study, which assumes some yield improvements up to 2030 in high-income countries, following Hertel, Burke and Lobell (2010) and Reilly et al. (2007). It may well be that the latter improvement in yields by 2030 would reverse with further climate change in subsequent decades.

activity in most developing countries (Alston, Babcock and Pardey 2010), If such investments reduce the perceived need by governments to alter their border measures to retain food self sufficiency or avoid transmitting fluctuations in international prices to their domestic market, it will be doubly beneficial to food security in the rest of the world.

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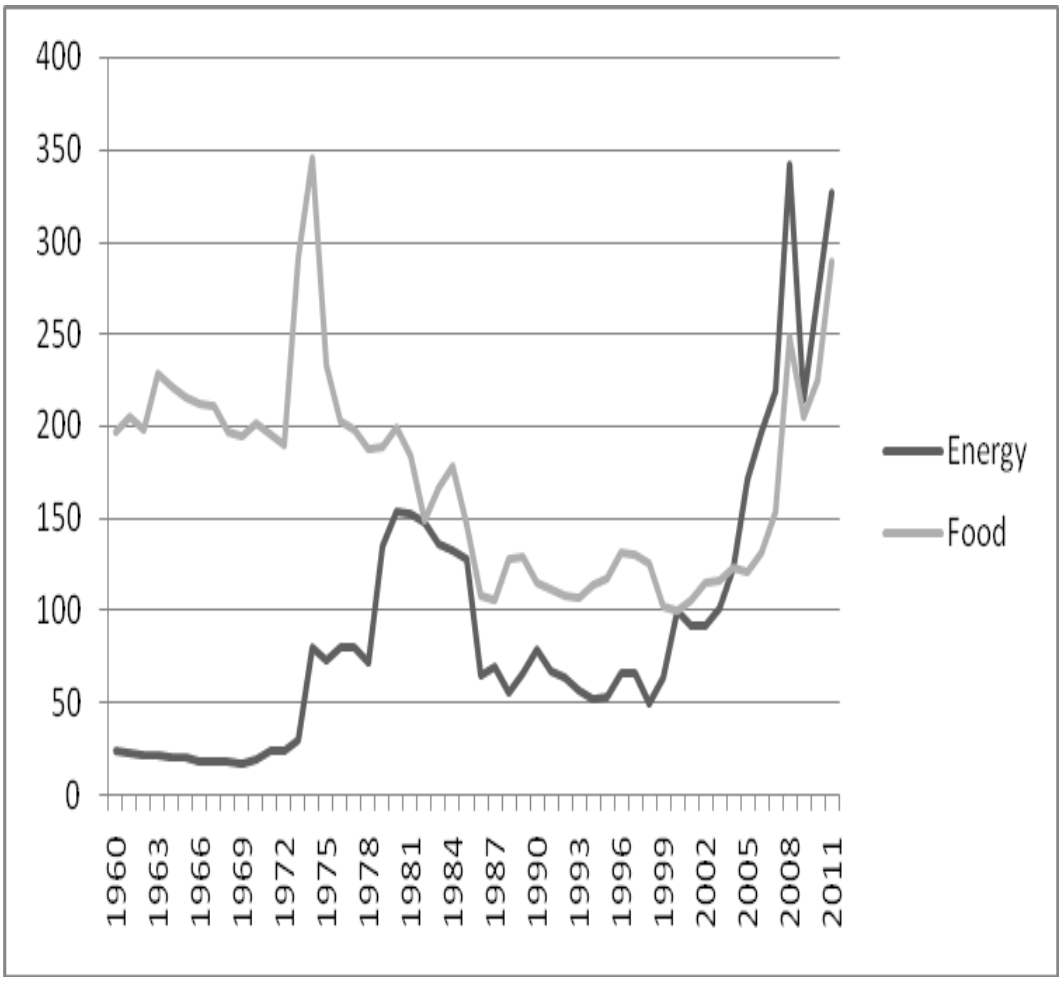
Figure 1: International price indexes for food and fossil fuel energy raw materials, 1960 to 2011[a]

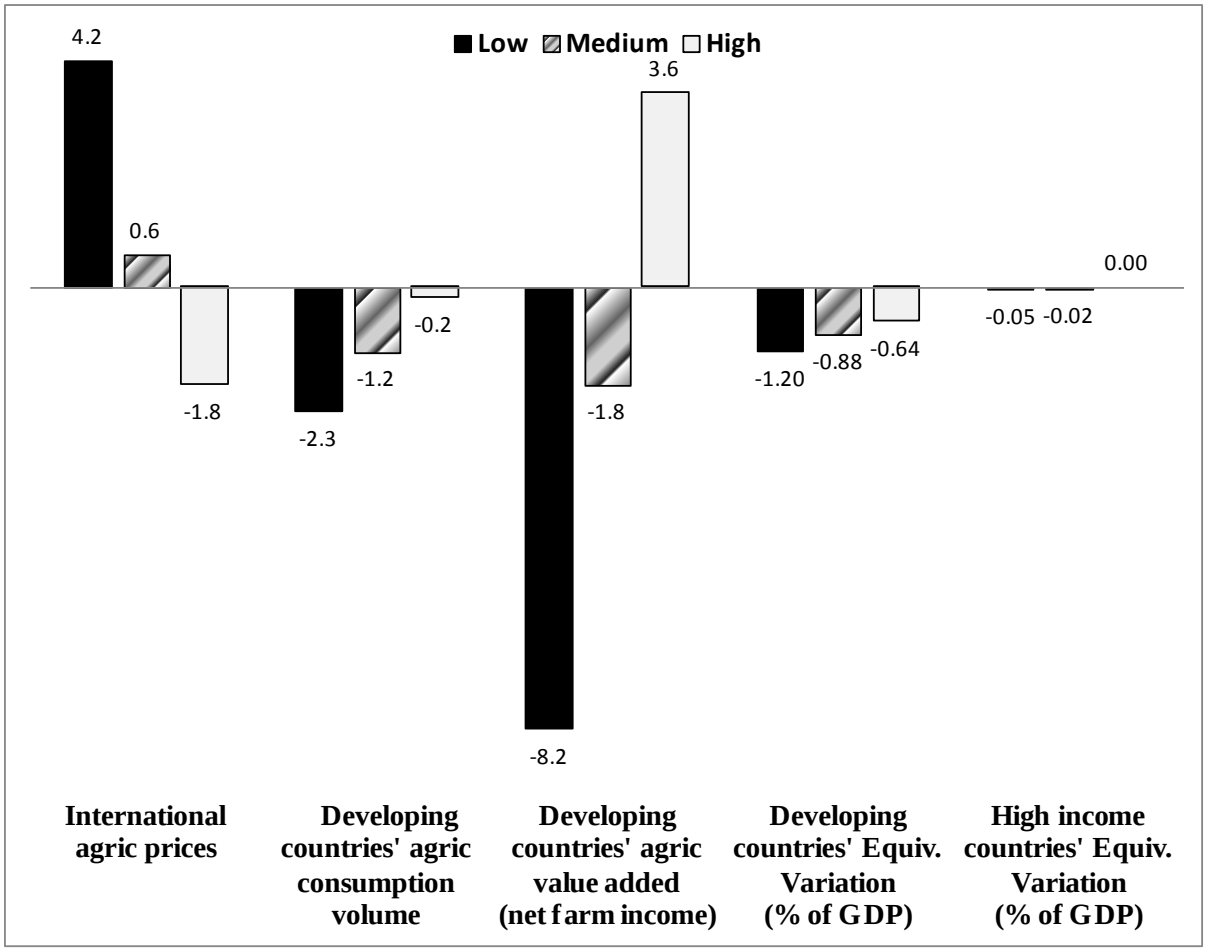
(2000 = 100)



[a] The 2011 data refer only to the first 2 months (January and February).

Source: World Bank, Commodity Price Data (Pink Sheets, see http://go.worldbank.org/5AT3JHWYU0)

Figure 2: Some effects of a 3% decrease in unskilled labor productivity and low, medium and high crop yield productivity shocks on international agricultural prices, consumption of farm products, net farm incomes, and national economic welfare, 2030



Source: Authors' simulations

Table 1: Effects of economic growth, crop yield and labor productivity changes due to climate change, on agricultural self sufficiency, from 2004 to 2030.

(percent)

Regions	Base 2004	Base 2030	Crop productivity shock			Unskilled labor productivity shock		Medium Crop and -3% unskilled labor productivity shock
			Low	Med	High	-3%	-6%	
USA	103	112	111	112	112	112	112	112
Canada	108	119	121	120	119	119	119	120
EU27 and EFTA	94	101	104	102	100	101	101	102
Russia	89	90	89	90	91	90	90	90
Rest of EE/C Asia	100	100	102	101	101	100	100	101
Australia	138	152	159	154	151	153	152	154
New Zealand	161	172	179	174	169	173	172	174
Japan	83	83	84	84	83	83	83	84
Korea	81	80	80	82	83	79	79	82
HK/Sing/Taiwan	66	65	66	66	66	65	65	65
China	97	90	88	89	90	90	90	89
Indonesia	95	84	84	84	88	84	84	84
Malaysia	60	45	42	45	47	46	45	45
Thailand	112	98	95	97	98	97	98	97
Rest of East Asia	100	90	87	89	90	89	90	89
India	101	95	93	94	96	95	95	94
Rest of S. Asia	96	86	84	85	86	86	86	85
Argentina	142	146	155	145	141	145	146	145
Brazil	123	132	134	132	130	133	132	132
Rest of L America	102	95	93	94	95	95	95	94
M. East/N. Africa	84	83	83	83	83	82	82	83
South Africa	107	115	117	115	112	116	115	115
Rest of SS Africa	102	97	93	96	98	97	97	96
High-income countries	**103**	**112**	**114**	**112**	**111**	**112**	**112**	**112**
Developing countries	**98**	**93**	**91**	**92**	**93**	**92**	**92**	**92**
World	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Source: Authors' simulations

Table 2: Effects of crop productivity shocks due to climate change on agricultural prices, production, consumption, value added and trade, 2030 (percent deviation from baseline in projected year)

Regions	Farmer price			Agricultural production volume			Agricultural consumption volume			Agricultural value added			Agricultural value of exports			Agricultural value of imports		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
USA	5.7	0.9	-2.0	-2.6	-0.3	0.9	-2.2	-0.4	0.8	-8.5	-1.6	3.9	0.8	0.8	-0.9	14.2	0.9	-6.8
Canada	4.2	0.3	-2.2	0.3	1.3	1.5	-1.5	0.2	1.4	-9.4	-2.3	3.8	8.6	3.9	-0.3	7.1	0.5	-3.6
EU27 and EFTA	1.7	-0.2	-1.3	3.9	1.2	-1.2	0.4	0.3	0.0	-9.2	-0.8	5.3	18.3	3.9	-6.8	0.9	-0.8	-1.0
Russia	4.2	-0.2	-3.1	-1.5	0.8	2.4	-0.9	0.2	1.0	-4.6	-0.7	2.1	11.1	10.2	10.0	5.9	-1.5	-6.4
Rest of Europe/C. Asia	4.2	-0.5	-3.5	0.8	1.6	1.9	-1.2	0.3	1.2	-7.6	-0.9	4.2	28.7	13.0	0.1	7.3	-1.8	-7.3
Australia	4.1	0.6	-2.2	2.3	0.9	0.9	-2.1	-0.2	1.6	-9.2	-2.1	3.1	10.5	2.8	-0.8	7.2	1.2	-5.8
New Zealand	1.9	0.2	-0.9	5.4	1.5	-1.7	1.0	0.6	-0.2	-9.0	-2.0	3.8	11.2	2.7	-3.8	3.3	-0.3	-1.9
Japan	1.1	-0.4	-1.3	2.7	0.7	-0.8	1.4	0.4	-0.4	-6.6	-0.1	4.5	87.0	14.9	-24.7	0.4	-0.5	0.0
Korea	1.4	-3.4	-7.0	2.9	4.3	5.5	1.8	1.5	1.5	-6.7	0.0	5.6	58.9	44.1	33.8	2.0	-5.4	-10.8
HongKong/Sing/Taiwan	2.2	0.3	-2.5	3.6	1.2	1.7	2.1	0.5	-0.2	-9.0	-2.1	3.8	31.8	11.5	-1.3	3.8	0.9	-3.4
China	12.7	4.3	-1.5	-4.1	-1.7	0.1	-1.7	-0.8	0.0	-12.1	-4.5	1.8	-24.0	-20.2	-18.8	18.0	6.1	-2.4
Indonesia	4.7	1.4	-9.7	0.1	-0.6	6.4	0.4	-0.2	2.1	-5.8	-0.8	5.7	41.9	8.6	66.4	3.0	1.8	-18.5
Malaysia	5.8	1.1	-2.7	-3.5	-1.1	1.3	3.5	0.5	-1.6	-4.0	-0.3	2.8	1.9	-0.7	-3.4	9.1	1.8	-4.0
Thailand	9.0	2.3	-3.2	-4.0	-1.4	0.9	-1.6	-0.7	0.4	-8.3	-2.0	4.1	-1.4	-1.3	-1.2	15.4	3.8	-4.9
Rest of East Asia	7.0	1.7	-2.6	-3.7	-1.3	0.8	-1.4	-0.5	0.4	-5.1	-0.8	3.0	3.4	-2.6	-6.8	13.2	3.4	-4.3
India	12.9	3.3	-4.2	-5.6	-1.7	1.6	-3.0	-0.9	1.1	-8.4	-2.1	3.7	-6.0	-5.9	-4.1	40.8	12.6	-9.5
Rest of South Asia	6.0	1.3	-2.3	-3.4	-1.1	0.8	-1.1	-0.3	0.3	-4.2	-0.5	2.5	4.2	-3.3	-8.8	12.6	4.1	-3.2
Argentina	6.1	1.2	-3.2	-2.1	-1.7	1.8	-8.1	-1.1	4.9	-8.4	-0.1	4.9	11.0	-2.8	-5.0	6.7	1.8	-2.5
Brazil	5.2	0.6	-2.5	-1.4	-0.6	-0.1	-3.1	-0.4	1.4	-7.3	-0.3	5.1	4.1	-1.2	-4.7	6.7	0.7	-3.3
Rest of Latin America	6.5	1.1	-1.7	-2.7	-0.9	-0.2	-1.2	-0.3	0.1	-7.2	-0.8	3.4	-0.7	-4.3	-7.9	10.9	2.2	-1.8
Middle East/Nth Africa	4.1	0.0	-2.9	-0.2	0.6	1.2	-0.1	0.2	0.4	-6.1	-0.6	3.4	18.9	5.4	-3.3	4.5	-0.2	-3.5
South Africa	5.0	0.9	-1.0	-0.5	-1.0	-3.3	-2.1	-0.4	0.0	-14.5	-1.5	8.9	8.8	-2.5	-15.4	6.3	1.7	0.6
Rest S.S. Africa	13.3	2.6	-4.2	-6.5	-1.7	2.1	-2.5	-0.6	1.1	-8.2	-1.5	3.5	-17.4	-6.2	2.5	13.9	2.6	-4.8
High-income countries	**3.4**	**0.1**	**-1.8**	**1.1**	**0.7**	**0.1**	**-0.8**	**0.2**	**0.8**	**-8.4**	**-1.1**	**4.3**	**9.9**	**2.0**	**-3.9**	**3.4**	**-0.6**	**-2.4**
Developing countries	**9.4**	**2.4**	**-3.0**	**-3.4**	**-1.1**	**1.0**	**-1.6**	**-0.5**	**0.6**	**-8.7**	**-2.2**	**3.2**	**2.3**	**-2.2**	**-4.5**	**13.3**	**3.4**	**-4.8**
World	**6.7**	**1.3**	**-2.4**	**-1.3**	**-0.3**	**0.6**	**-1.3**	**-0.2**	**0.7**	**-8.6**	**-1.8**	**3.6**	**8.3**	**1.1**	**-4.0**	**8.9**	**1.6**	**-3.7**

Table 3: Effects on agricultural prices in international markets of crop and labor productivity changes due to climate change, 2030

(percent deviation from baseline in projected year)

Sectors	Crop productivity shock			Unskilled labor productivity shock		Medium Crop and -3% unskilled labor productivity shock
	Low	Med	High	-3%	-6%	
Rice	4.5	1.0	-1.9	0.4	0.8	1.4
Wheat	6.6	-0.3	-4.9	0.1	0.2	-0.2
Coarse grains	15.9	4.3	-2.3	0.1	0.3	4.4
Fruit & veg	6.8	0.4	-3.7	0.2	0.4	0.6
Oilseeds	7.4	0.2	-4.7	0.1	0.2	0.3
Sugar	0.8	0.1	-0.5	0.3	0.7	0.4
Cotton	9.3	1.1	-4.4	0.0	0.0	1.1
Other crops	6.7	0.2	-4.3	0.2	0.4	0.3
Beef/sheep	1.7	0.2	-0.8	0.2	0.5	0.5
Pork/chicken	1.6	0.1	-0.9	0.2	0.5	0.3
Dairy	0.8	0.1	-0.5	0.2	0.4	0.3
All agriculture & food	**4.1**	**0.4**	**-2.0**	**0.2**	**0.4**	**0.6**
Forestry	-1.0	-0.2	0.3	-0.3	-0.6	-0.5
Coal	0.5	0.2	0.1	-3.1	-6.1	-2.9
Oil	-0.5	-0.1	0.1	-0.8	-1.6	-0.9
Gas	-0.5	-0.2	0.0	0.6	1.2	0.4
Minerals nec	-0.2	0.1	0.1	-0.7	-1.4	-0.7
Fish and processed food	1.2	0.2	-0.5	0.3	0.6	0.4
Light manufacturing	-0.1	0.0	0.0	0.3	0.7	0.3
Heavy manufacturing	-0.3	-0.1	0.1	0.1	0.2	0.1
Utilities & construction	-0.1	0.0	0.1	0.3	0.6	0.3
Electricity, gas distrib.	-0.2	0.0	0.1	0.0	0.1	0.0
Transport	-0.3	0.0	0.1	0.3	0.6	0.2
Other services	-0.4	-0.1	0.2	0.3	0.6	0.2

Source: Authors' simulations

Table 4: Effects on national economic welfare of crop yield and labor productivity changes

(2004 US$ million, equivalent variation of income from baseline in 2030)

Regions	Crop productivity shock			Unskilled labor productivity shock		Medium crop and -3% unskilled labor productivity shock,	
	Low	Med	High	-3%	-6%	in US $m	as % of GDP
USA	195	647	371	-1642	-3239	-1019	-0.01
Canada	431	58	-193	-404	-799	-351	-0.03
EU27 and EFTA	-7002	-555	5054	-3426	-6846	-3948	-0.03
Russia	-1643	-100	925	-2208	-4401	-2302	-0.23
Rest of EE/C Asia	351	897	1213	-645	-1291	236	0.02
Australia	1612	375	-260	-1528	-2994	-1170	-0.11
New Zealand	436	85	-137	-4	-6	80	0.05
Japan	-3574	-464	1709	110	200	-340	-0.01
Korea	-1074	7	823	-11829	-23907	-11827	-0.80
HK/Sing/Taiwan	-788	-27	661	-8254	-16699	-8282	-0.70
China	-30524	-9825	4921	-37424	-76113	-46932	-1.03
Indonesia	-1182	-311	3927	-5070	-10232	-5373	-0.91
Malaysia	-487	-85	273	-2724	-5503	-2806	-0.92
Thailand	-1261	-277	455	290	582	12	0.00
Rest of East Asia	-1869	-484	577	-3179	-6428	-3653	-0.93
India	-22411	-5812	7094	-11972	-24330	-17653	-1.05
Rest of S. Asia	-5172	-1060	2033	-3460	-7005	-4500	-1.05
Argentina	1072	-27	-531	-88	-175	-118	-0.05
Brazil	1061	-11	-641	-10189	-20562	-10204	-0.97
Rest of L America	-5331	-1057	1367	-22026	-44464	-23057	-0.91
M. East/N. Africa	-3560	-253	2019	-14258	-28798	-14503	-0.74
South Africa	221	22	-60	-392	-761	-374	-0.11
Rest of SS Africa	-6447	-1398	1688	-6226	-12591	-7576	-1.17
High-income countries	**-9194**	**943**	**8682**	**-9748**	**-19377**	**-8814**	**-0.02**
Developing countries	**-77751**	**-20598**	**24606**	**-136802**	**-276986**	**-156846**	**-0.88**
World	**-86945**	**-19657**	**33289**	**-146550**	**-296363**	**-165659**	**-0.28**

Source: Authors' simulations

Table 5: Effects of labor productivity and crop yield changes due to climate change on agricultural consumption and agricultural value added, 2030 (percent)

Regions	Unskilled labor productivity shock				Effects of crop yield shocks and a 3% decrease in unskilled labor productivity					
	3% decrease		6% decrease		a) Low Productivity		b) Medium Productivity		c) High Productivity	
	Agricultural consumption volume	Agricultural value added	Agricultural consumption volume	Agricultural value added	Agricultural consumption volume	Agricultural value added	Agricultural consumption volume	Agricultural value added	Agricultural consumption volume	Agricultural value added
USA	0.1	-0.1	0.0	-0.2	-2.2	-8.5	-0.4	-1.7	0.9	3.8
Canada	-0.1	-0.1	0.0	-0.2	-1.5	-9.3	0.2	-2.3	1.4	3.6
EU27 and EFTA	0.0	-0.2	0.0	-0.5	0.4	-9.2	0.3	-0.9	0.0	5.0
Russia	-0.2	-0.1	-0.1	-0.3	-1.0	-4.6	0.1	-0.8	0.9	1.9
Rest of Europe/C. Asia	-0.1	-0.1	0.0	-0.2	-1.2	-7.5	0.3	-1.0	1.2	4.0
Australia	0.1	-0.3	0.0	-0.6	-2.0	-9.3	-0.1	-2.4	1.7	2.7
New Zealand	-0.2	-0.3	-0.1	-0.7	0.9	-9.1	0.4	-2.2	-0.3	3.4
Japan	0.1	-0.2	0.0	-0.4	1.4	-6.6	0.4	-0.3	-0.3	4.2
Korea	-1.2	0.1	-0.6	0.3	1.1	-6.4	0.9	0.2	0.8	5.8
HongKong/Sing/Taiwan	-1.3	0.4	-0.6	0.7	1.5	-8.6	-0.1	-1.7	-0.9	4.2
China	-1.9	0.3	-0.9	0.6	-2.6	-11.6	-1.7	-4.1	-0.9	2.1
Indonesia	-1.5	0.6	-0.7	1.2	-0.3	-5.1	-0.9	-0.2	1.4	6.4
Malaysia	-1.5	0.7	-0.8	1.4	2.6	-3.2	-0.2	0.4	-2.3	3.5
Thailand	0.0	-0.3	0.0	-0.6	-1.6	-8.4	-0.7	-2.2	0.4	3.7
Rest of East Asia	-1.4	0.3	-0.7	0.7	-2.1	-4.7	-1.2	-0.5	-0.3	3.3
India	-1.3	0.5	-0.6	1.0	-3.6	-7.9	-1.5	-1.6	0.4	4.2
Rest of South Asia	-1.4	0.5	-0.7	1.0	-1.8	-3.7	-1.0	0.0	-0.4	3.0
Argentina	0.3	-0.1	0.2	-0.2	-7.9	-8.3	-0.9	-0.2	5.0	4.7
Brazil	-1.5	0.4	-0.7	0.9	-3.8	-6.8	-1.1	0.2	0.7	5.5
Rest of Latin America	-1.5	0.5	-0.8	0.9	-1.9	-6.7	-1.0	-0.4	-0.6	3.8
Middle East/Nth Africa	-1.4	0.4	-0.7	0.8	-0.8	-5.6	-0.5	-0.3	-0.4	3.8
South Africa	0.0	-0.2	0.0	-0.4	-2.1	-14.4	-0.5	-1.6	0.0	8.5
Rest SS Africa	-1.8	0.7	-0.9	1.4	-3.4	-7.5	-1.5	-0.8	0.1	4.2
High-income countries	**0.1**	**-0.2**	**0.1**	**-0.3**	**-0.7**	**-8.4**	**0.3**	**-1.2**	**0.9**	**4.1**
Developing countries	**-1.5**	**0.4**	**-0.8**	**0.8**	**-2.3**	**-8.2**	**-1.2**	**-1.8**	**-0.2**	**3.6**
World	**-0.8**	**0.2**	**-0.4**	**0.4**	**-1.7**	**-8.3**	**-0.6**	**-1.6**	**0.2**	**3.8**

Source: Authors' simulations

Table 6: Grain self sufficiency, 2004 and 2030 baseline and after crop and labour productivity losses from climate change

(production as a percentage of domestic consumption)

Regions	Baseline		With climate change	
	2004	2030	Medium Crop productivity shock	Medium Crop and -3% unskilled labor productivity shock
USA	163	183	178	178
Canada	280	357	360	359
EU27 and EFTA	94	107	109	109
Russia	99	101	102	102
Rest of EE/C Asia	95	94	95	95
Australia	334	401	415	414
New Zealand	75	81	81	81
Japan	83	81	81	81
Korea	83	79	80	80
HK/Sing/Taiwan	64	61	63	63
China	98	95	95	95
Indonesia	94	92	91	91
Malaysia	43	36	36	36
Thailand	131	115	114	114
Rest of East Asia	98	90	90	90
India	103	102	102	102
Rest of South Asia	98	92	92	92
Argentina	378	447	433	429
Brazil	99	100	99	99
Rest of L America	80	77	77	77
M. East/N. Africa	64	62	62	62
South Africa	84	110	111	110
Rest of SS Africa	77	78	79	79
High-income countries	**104**	**118**	**119**	**119**
Developing countries	**93**	**90**	**90**	**90**
WORLD	**100**	**100**	**100**	**100**

Source: Authors' simulations.

Appendix Table A1: Aggregations of regions[a] in the GTAP model

	Regions-Aggregation	Comprising GTAP regions
1	USA	United States of America; Rest of North America
2	Canada	Canada
3	EU27 and EFTA	Austria; Belgium; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Switzerland; Norway; Rest of EFTA; Bulgaria; Romania
4	Russia	Russian Federation
5	Rest of Eastern Europe and Central Asia	Albania; Belarus; Croatia; Ukraine; Rest of Eastern Europe; Rest of Europe; Kazakhstan; Kyrgyztan; Rest of Former Soviet Union; Armenia; Azerbaijan; Georgia; Iran Islamic Republic of; Turkey
6	Australia	Australia
7	New Zealand	New Zealand
8	Japan	Japan
9	Korea	Korea
10	Hong Kong, Singapore, and Taiwan	Hong Kong; Taiwan; Singapore
11	China	China
12	Indonesia	Indonesia
13	Malaysia	Malaysia
14	Thailand	Thailand
15	Rest of East Asia	Cambodia; Lao People's Democratic Republ; Myanmar; Philippines; Viet Nam; Rest of Southeast Asia, Rest of Oceania; Rest of East Asia
16	India	India
17	Rest of South Asia	Bangladesh; Pakistan; Sri Lanka; Rest of South Asia
18	Argentina	Argentina
19	Brazil	Brazil
20	Rest of Latin America	Mexico; Bolivia; Chile; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela; Rest of South America; Costa Rica; Guatemala; Nicaragua; Panama; Rest of Central America; Caribbean
21	Middle East and North Africa	Rest of Western Asia; Egypt; Morocco; Tunisia; Rest of North Africa
22	South Africa	South Africa
23	Rest of Sub-Saharan Africa	Nigeria; Senegal; Rest of Western Africa; Central Africa; South Central Africa; Ethiopia; Madagascar; Malawi; Mauritius; Mozambique; Tanzania; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Rest of Southern African Customs Union

[a] Regions 1 to 8 are categorized in this paper as High-income Countries, the rest (regions 9 to 23) as Developing Countries. Russia and the rest of Eastern Europe and Central Asia are included in the first group because they share a relatively cool climate and have the same expected changes in crop yields as Western Europe to 2030.

Source: Authors' aggregation derived from GTAP database (www.gtap.org).

Appendix Table A2: Aggregations of sectors in the GTAP model

	Sectors-Aggregation	Comprising GTAP sectors
1	Rice	Paddy rice; Processed rice
2	Wheat	Wheat
3	Coarse grains	Cereal grains nec
4	Fruit & veg	Vegetables, fruit, nuts
5	Oilseeds	Oil seeds, Vegetable oils and fats
6	Sugar	Sugar cane, sugar beet; Sugar
7	Cotton	Plant-based fibers
8	Other crops	Crops nec
9	Beef/sheep	Cattle,sheep,goats,horses; Meat of cattle, sheep, goats, horses; Wool, silk-worm cocoons
10	Pork/chicken	Animal products nec; Meat products nec
11	Dairy	Raw milk; Dairy products
12	Forestry	Forestry
13	Coal	Coal
14	Oil	Oil
15	Gas	Gas
16	Minerals nec	Minerals nec
17	Fish and processed food	Fishing; Food products nec; Beverages and tobacco products
18	Light manufacturing	Textiles; Wearing apparel; Leather products, Wood products; Paper products, publishing; Metal products; Motor vehicles and parts; Transport equipment nec; Manufactures nec
19	Heavy manufacturing	Petroleum, coal products; Chemical,rubber,plastic prods; Mineral products nec; Ferrous metals; Metals nec; Electronic equipment; Machinery and equipment nec
20	Utilities and construction	Water; Construction; Trade
21	Electricity and gas distribution	Electricity; Gas manufacture, distribution
22	Transport	Transport nec; Sea transport; Air transport
23	Other services	Communication; Financial services nec; Insurance; Business services nec; Recreation and other services; PubAdmin/Defence/Health/Education; Dwellings

Source: Authors' aggregation derived from GTAP database (www.gtap.org).

Appendix Table A3: Assumed annual rates of growth in factor endowments and real GDP, and implied total factor productivity and real GDP per capita growth rates, from 2004 to 2030[a]

(percent per year)

Regions	Popul-ation	Unskilled labor	Skilled labor	Capital	Real GDP	Implied TFP[a]	Implied realGDP per capita
USA	0.7	0.8	-0.2	3.2	2.6	1.4	1.9
Canada	0.4	0.4	-0.6	3.1	2.6	1.2	2.2
EU27 and EFTA	-0.1	0.0	-0.7	1.9	1.9	1.2	2.0
Russia	-0.6	-0.7	-1.0	3.2	3.2	1.2	3.8
Rest E. Europe/C. Asia	0.6	0.7	1.4	3.9	4.1	1.2	3.5
Australia	0.6	0.8	-0.2	3.7	3.4	1.5	2.8
New Zealand	0.7	1.0	0.0	3.6	3.4	1.2	2.7
Japan	-0.3	-0.7	-1.4	2.3	1.4	1.0	1.7
Korea	0.3	-0.4	2.0	4.9	4.7	1.9	4.4
HongKong/Sing/Taiwan	0.4	0.2	0.6	4.9	4.5	1.8	4.1
China	0.6	0.5	4.5	6.0	6.0	2.2	5.4
Indonesia	1.1	1.3	3.7	4.8	5.1	1.6	4.0
Malaysia	1.3	1.5	5.0	5.7	5.7	1.6	4.3
Thailand	0.5	0.1	2.0	4.0	4.7	1.7	4.2
Rest of East Asia	1.2	1.5	2.9	4.1	4.4	1.2	3.2
India	1.1	1.5	3.0	5.9	5.8	1.8	4.7
Rest of South Asia	1.7	2.2	3.1	5.0	5.1	1.4	3.4
Argentina	0.9	0.3	2.9	2.7	3.4	1.5	2.5
Brazil	1.0	0.9	2.3	3.3	3.7	1.3	2.6
Rest of Latin America	1.3	1.6	2.9	3.5	4.0	1.0	2.6
Middle East/Nth Africa	1.6	2.0	2.4	4.1	4.6	1.0	2.9
South Africa	0.4	0.7	0.5	1.9	3.3	1.8	2.9
Rest Sub-Saharan Africa	2.0	2.5	2.4	3.8	4.6	1.0	2.6
High-income countries	**0.2**	**0.2**	**-0.5**	**2.6**	**2.2**	**1.2**	**2.0**
Developing countries	**1.2**	**1.4**	**2.9**	**4.6**	**4.7**	**1.5**	**3.5**
World	**1.0**	**1.2**	**1.1**	**3.1**	**2.9**	**1.3**	**1.9**

[a] Additional primary sectoral TFP shocks (percent per year) from 2004 to 2030: coal 2.1, oil 1.9, gas 1.3, mineral resources 1.2, agriculture and food 0.9 (except cotton 1.3), forestry 1.2.

Source: Authors' compilation drawing on World Bank and OECD projections.

Appendix Table A4: Exogenous yield shocks attributed to climate change in 2030, by region and sector
(percentage change in land productivity)

Regions	Rice			Wheat			Coarse grains			Fruits & veg			Oil seeds			Cotton			Other crops[a]		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
USA	-10	-3	4	-10	2	14	-32	-15	-3	-10	2	14	-10	2	14	-15	-3	9	-10	2	14
Canada	-10	-3	4	-5	7	19	-17	-10	-3	-10	2	14	0	10	24	-10	-3	4	-10	2	14
EU27 and EFTA	-5	7	19	-5	7	19	-17	-5	7	-5	7	19	-5	7	19	-5	7	19	-5	7	19
Russia	-5	7	19	-5	7	19	-17	-5	7	-5	7	19	-5	7	19	-5	7	19	-5	7	19
Rest of Europe/C. Asia	-5	7	19	-5	7	19	-17	-5	7	-5	7	19	-5	7	19	-5	7	19	-5	7	19
Australia	-15	-3	9	-5	7	19	-17	-5	7	-5	-3	19	-10	2	14	-10	-3	4	-5	7	19
New Zealand	-5	7	19	-5	7	19	-17	-5	7	-5	7	19	-10	2	14	0	7	14	-5	7	19
Japan	2	9	16	-3	4	11	-7	0	7	-3	4	11	2	9	16	2	9	16	-3	4	11
Korea	5	12	19	5	12	19	-2	5	12	5	12	19	5	12	19	5	12	19	5	12	19
HongKong/Sing/Taiwan	5	12	19	5	12	19	-2	5	12	5	-3	19	5	12	19	5	12	19	5	12	19
China	-12	0	12	-10	2	14	-22	-10	2	-15	-8	-1	-12	0	12	-6	0	7	-15	-8	-1
Indonesia	0	-3	14	0	-3	14	-7	-10	7	0	7	14	0	-3	14	0	-3	14	0	-3	14
Malaysia	-10	-3	4	-10	-3	4	-17	-10	-3	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
Thailand	-10	-3	4	-10	-3	4	-17	-10	-3	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
Rest of East Asia	-10	-3	4	-10	-3	4	-17	-10	-3	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
India	-15	-5	4	-10	-3	4	-17	-10	-3	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
Rest of South Asia	-15	-5	4	-10	-3	4	-17	-10	-3	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
Argentina	-10	-3	4	-10	-3	4	-2	-10	22	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
Brazil	-10	-3	4	-10	-3	4	-17	-10	-3	-10	-3	4	-5	2	9	-10	-3	4	-10	-3	4
Rest of Latin America	-10	-3	4	-10	-3	4	-17	-5	-3	-10	-3	4	-10	-3	4	-10	-3	4	-10	-3	4
Middle East/Nth Africa	-5	2	9	-5	2	9	-12	-5	2	-5	2	9	-5	2	9	-5	2	9	-5	2	9
South Africa	-20	-8	4	-20	-8	4	-42	-20	-8	-20	-8	4	-20	-8	4	-20	-8	4	-20	-8	4
Rest SS Africa	-15	-3	9	-15	-3	9	-22	-10	2	-15	-3	9	-15	-3	9	-15	-3	9	-15	-3	9

[a] Except for Sugar crops wherein productivity shock are zero in all cases.

Source: Authors' compilation drawing on Hertel, Burke and Lobell (2010).