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Genetic improvements in major US crops: the size and distribution of benefits

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Abstract

The distribution of welfare gains of genetic improvements in major US crops is estimated using a world agricultural trade model. Multi-market welfare estimates were 75% larger than estimates based on the price-exogenous ‘change in revenue’ method frequently used by plant breeders. Annual benefits of these genetic improvements range from US\$ 400–600 million depending on the supply shift specification. Of this, 44–60% accrues to the US, 24–34% accrues to other developed countries. Developing and transitional economies capture 16–22% of the welfare gain. The global benefits of a one-time permanent increase in US yields are US\$ 8.1 billion (discounted at 10%) and US\$ 15.4 billion (discounted at 5%). Gains to consumers in developing and transitional economies range from US\$ 6.1 billion (10% discount rate) to US\$ 11.6 billion (5% discount rate). © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Since 1960, yield growth has accounted for 92% of the growth of world cereal production (World Bank, 1992). Genetic improvements have accounted for roughly half the yield growth of US field crops (Duvick, 1984; Huffman and Evenson, 1993; Thirtle, 1985). The contribution of genetic improvements to yield growth in other countries has been similarly impressive (Anderson and Hazell, 1989; Byerlee, 1996; Byerlee and Traxler, 1995; Dalrymple, 1977; Evenson

and Gollin, 1997; ICRISAT, 1990; Kuhr et al., 1985; Silvey, 1986).

Yield gains from genetic improvements are the product of public and private investments in plant breeding and the collection, exchange and conservation of plant genetic resources (PGRs). In the latter half of this century, an extensive international system of PGR collection, exchange and research, publicly funded by multilateral donations, developed alongside national plant breeding programs (Ruttan, 1982). Breakthroughs in corn hybridisation in the 1930s spurred the development of the private seed industry. Increased intellectual property protection for commercial seed varieties has contributed to the rapid growth of private investment in plant breeding (Fuglie et al., 1996).

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Despite its success, the system of PGR exchange has been controversial (Frisvold and Condon, 1998; Kloppenburg, 1988; Knudson, 1999; Mooney, 1983). Many developing countries and non-governmental organisations (NGOs) have criticised the system as biased against developing countries (The Ecologist/GRAIN/RAFI, 1996). Because farmers in developing countries have spent thousands of years selecting and saving landraces, developing countries have made essential contributions to plant breeding (Altieri and Masera, 1993; Brush, 1992; Mooney, 1983). Plant breeders today still rely on genetic materials native to developing countries to instil resistance to ever-evolving plant pests and pathogens (Cox et al., 1988; Goodman and Castillo-Gonzalez, 1991; Knudson, 1999; UN FAO, 1997). Yet, while commercial seed varieties have been afforded increasing intellectual property protection, germplasm and landraces continue to be treated as public goods. Kloppenburg summarises the basic argument:

It is no exaggeration to say that the plant genetic resources received as free goods from the Third World have been worth untold billions of dollars to the advanced capitalist nations. (Kloppenburg, 1988 p. 169)

The distribution of gains of PGR exchange has been the source of heated north-south debates in meetings of the UN FAO and the UN Convention on Biological Diversity. Developing country delegates and NGOs have argued that developing countries should be compensated for their historical and current contributions to developing and maintaining landraces and wild plant varieties.

Both critics and advocates of the system of PGR exchange cite dollar estimates of gains to US producers or consumers from yield increases in US crops attributable to the introduction of germplasm from developing countries (Kloppenburg, 1988; Mooney, 1983; Pardey et al., 1996). But where do these figures come from and what do they really say about the distribution of benefits from US yield increases?

Let us address the first question. Plant scientists and economists often estimate the benefits of yield increases using the 'change in revenue method', deriving the gross benefits of a yield increase by multiplying the percent yield increase by total crop revenues. Yet, the change in revenues is not a true measure of

economic welfare change. Moreover, while it can be a reasonable approximation under certain assumptions, this paper demonstrates that the change in economic surplus from US yield gains can differ substantially from estimates calculated using the change in revenue method.¹ While economists also compute economic surplus measures, plant scientists rely almost exclusively on the change in revenue method.

Now consider the question of who receives benefits from yield increases. Changes in gross revenue say nothing about the distribution of benefits between producers and consumers or between regions. Nor do they account for multi-market effects that arise because agricultural commodity markets are vertically and horizontally linked.

A main objective of this study is to estimate the size and distribution of welfare impacts of genetic improvements of major US field crops. Based on surveys of the literature, we obtained estimates of average annual yield gains attributable to genetic improvements for US corn, soybean, wheat, cotton and coarse grain crops. These crops account for over two-thirds of US cropland. We introduced yield gains as supply shocks into USDA's Static World Policy Simulation (SWOPSIM) model of world agricultural trade. Besides reporting the distribution of gains between developed and developing countries, we also compare the multi-market welfare estimates with benefit estimates using the change in revenue method.

2. Model structure

Like OECD's MTM model (Huff and Moreddu, 1989–1990), SWOPSIM is a multi-region, multi-commodity model with log-linear supply and demand equations and government market interventions modelled as producer and consumer price wedges. Researchers have used the model extensively to analyse trade policies (Dixit and Roningen, 1989; Haley et al., 1991; Krissoff et al., 1989; Roningen and Dixit, 1991; Webb et al., 1989) and effects of climate change (Reilly and Hohmann, 1993; Tobey et al., 1992).

¹ As will be discussed later in the text, the change in revenue method can reasonably approximate economic surplus if, for example, demand is highly elastic, supply is highly inelastic, and the yield change is small. For more in-depth discussion of approximation measures, see Norton and Davis (1981).

Table 1
Regional and commodity aggregation used in model simulation

Regional aggregation	Commodity aggregation	
	Crops	Animal products
(1) United States		
(2) Canada		
(3) European Union (EU)	Wheat	Beef
(4) Other western Europe	Corn	Pork
(5) Japan	Coarse grains	Mutton/lamb
(6) Australia	Rice	Poultry meat
(7) New Zealand	Soybeans	Poultry eggs
(8) China and transitional economies (China, FSU, eastern Europe)	Soy meal	Dairy, fluid milk
	Soy oil	Dairy, butter
(9) Developing agricultural exporters (Argentina, Brazil, Indonesia, Philippines, Thailand)	Other oilseeds	Dairy, cheese
	Other meals	Dairy, milk powder
	Other oils	
(10) Developing Asian importers (Hong Kong, Macao, South Korea, Taiwan)	Cotton	
	Sugar	
(11) Rest of world	Tobacco	

Roningen (1986) and Sullivan et al. (1992) provide detailed descriptions of the model. We summarise its basic features. The quantity of commodity j supplied by region i , Q_{ij}^S is

$$Q_{ij}^S = \begin{cases} a_{ij}(1 + h_{ij})PP_{ij}^{\alpha_{ij}} \prod_{k=1}^{n-1} PP_{ik}^{\alpha_{ik}}, & PP_{ij} \geq M_{ij}(1 - v_{ij}) \\ 0, & PP_{ij} < M_{ij}(1 - v_{ij}) \end{cases}$$

where PP_{ij} is the domestic producer price for commodity j in region i and the PP_{ik} terms are domestic producer prices of all other commodities. The own-price supply elasticity is α_{ij} while the α_{ik} terms are cross-price elasticities. The a_{ij} term is a constant and the h_{ij} term is a supply shift parameter, with a base value of 0. The M_{ij} term is the shutdown price for commodity j in region i , while the v_{ij} term is a supply shift parameter, with a base value of 0.

The quantity of commodity j demanded in region i , Q_{ij}^D is

$$Q_{ij}^D = b_{ij}CP_{ij}^{\beta_{ij}} \prod_{k=1}^{n-1} CP_{ik}^{\beta_{ik}}$$

where CP_{ij} is the domestic consumer price for commodity j in region i and CP_{ik} terms are domestic producer prices of other commodities. The own-price demand elasticity is β_{ij} , the β_{ik} terms are cross-price elasticities, and b_{ij} is a constant. Domestic producer and consumer prices can deviate from world prices. Domestic incentive prices depend on the level

of producer and consumer support wedges PSW_{ij} and CSW_{ij} and world prices denominated in local currency:

$$CP_{ij} = CSW_{ij} + f(E_i \times WP_j)$$

$$PP_{ij} = PSW_{ij} + g(E_i \times WP_j)$$

where PSW_{ij} and CSW_{ij} measure levels of government support. E_i is the exchange rate for region i and WP_j is the world price of commodity j . The functions $f(\cdot)$ and $g(\cdot)$ allow for imperfect transmission of world price changes to domestic price changes resulting from subsidies or taxes.

The model is calibrated to 1989 data for agricultural production, consumption, trade and prices. Supply and demand elasticities were developed from comprehensive surveys of the literature (Roningen, 1986; Sullivan et al., 1992). These elasticities are consistent with those used in other world agricultural trade models (e.g. Huff and Moreddu, 1989–1990; Parikh et al., 1988). The version of the SWOPSIM model used in simulation experiments is disaggregated into 11 regions and 22 commodities (Table 1).

3. Modelling supply shocks

A number of studies have modelled the impacts of technological change in agriculture using a log-linear supply and demand specification (Ahmed et al.,

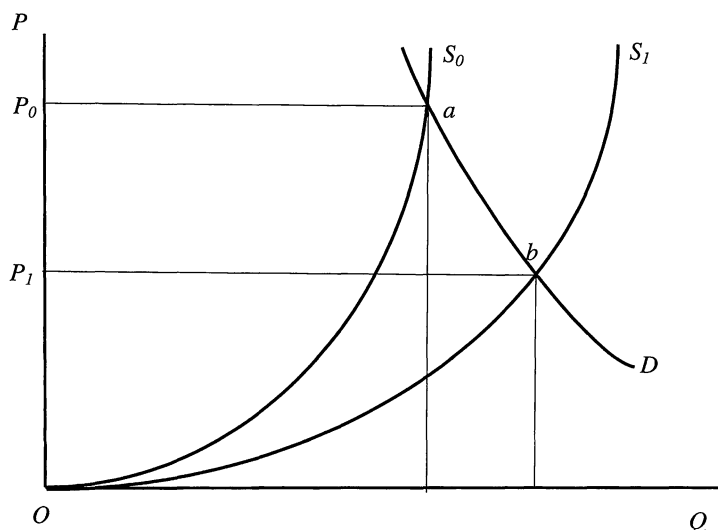


Fig. 1. Pivotal supply shift with log-linear supply and demand.

1995; Akino and Hayami, 1975; Ayer and Schuh, 1972; Oehmke, 1988). Though convenient to use, the log-linear form presents problems in representing producer behaviour and estimating producer surplus. Previous studies have implicitly assumed that the shutdown price equals 0 ($M_{ij} = 0$ in the first equation) so that the supply curve passes through the origin. This implies that positive amounts of the good will be supplied at any positive price, an unrealistic assumption. Technological change is then modelled as an increase in the h_{ij} parameter in the first equation, inducing a pivotal shift of a supply curve with a zero intercept. Fig. 1 illustrates the welfare impact of such a pivotal supply curve shift from S_0 to S_1 . The area Oab equals the increase in economic surplus, the area P_0abP_1 equals the change in consumer surplus and the change in producer surplus equals $OP_1b - OP_0a$. Yet, the welfare impacts of supply shifts are sensitive to assumptions about the nature of the supply curve shift (Alston et al., 1995; Hamilton and Sunding, 1998; Lindner and Jarrett, 1978; Miller et al., 1988; Norton and Davis, 1981; Rose, 1980). If demand is inelastic, this type of pivotal shift predetermines that producers are made worse off by technological change. For example, in Fig. 1 $OP_1b < OP_0a$ so that technological change reduces producer surplus.

We use a more general, truncated log-linear specification that does not predetermine the sign of producer

surplus impacts, is more consistent with theory, and makes better use of available data to represent supply response. These features are highlighted in the first equation. First, a more realistic specification of supply response would allow for some positive minimum price ($M_{ij} > 0$) below which no production would occur. We follow a procedure similar to Rose (1980) and Pachico et al. (1987) truncating the supply curve and giving it a positive intercept. USDA's *Farm Cost and Returns Survey* reports data on average variable cost disaggregated by commodity, region and other characteristics. The shutdown prices M_{ij} were set equal to the minimum average variable costs of the lowest cost producers of the crops experiencing technological change and for US livestock and animal commodities. Because of data limitations, the M_{ij} terms were set at 0

Table 2

Yield increases attributable to genetic improvements assumed in simulations

Crop	Actual annual growth in crop yield (1975–1992) (%)	Yield shock used in simulation experiments (%)
Corn	1.33	0.665
Soybeans	1.23	0.615
Wheat	1.13	0.565
Cotton	2.23	1.115
Coarse grains	1.54	0.770

Source for actual yield growth: Fuglie et al. (1996).

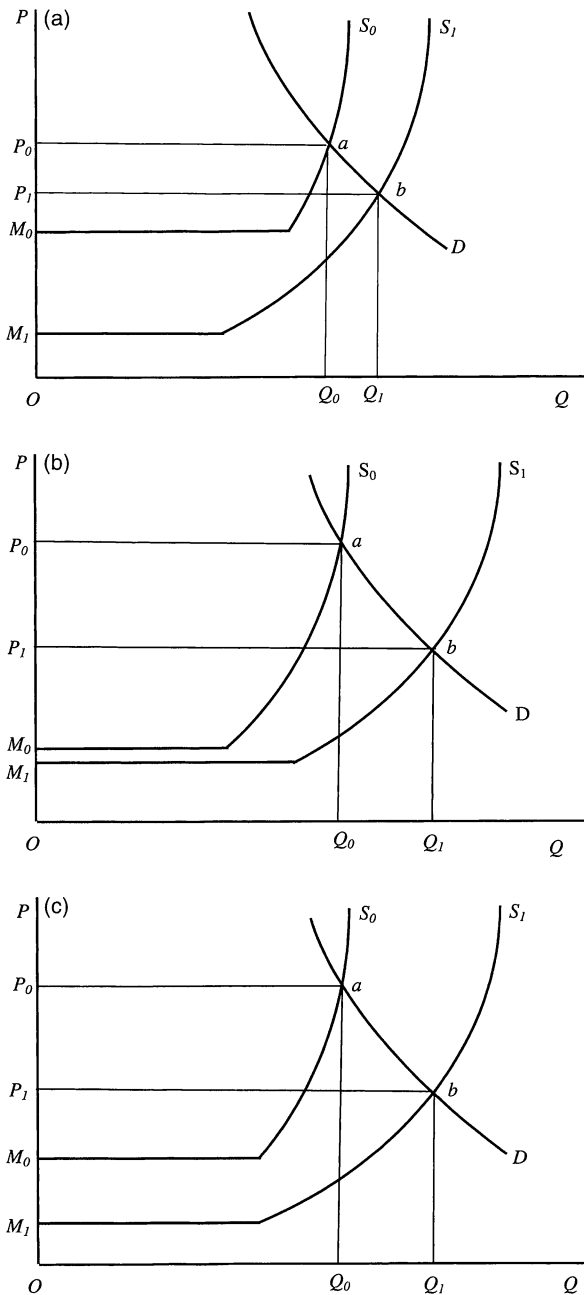


Fig. 2. (a) Truncated log-linear supply curve with convergent supply shift. (b) Truncated log-linear supply curve with divergent supply shift. (c) Truncated log-linear supply curve with proportional supply shift.

for the remaining commodities and regions. We use two supply shift parameters, the h_{ij} and v_{ij} terms. The supply curve has two components: a perfectly elastic portion that v_{ij} shifts vertically and an upward-sloping portion that h_{ij} shifts horizontally. By specifying different percentage changes in h_{ij} and v_{ij} , one can simulate convergent, divergent or proportional supply shifts. The changes in the v_{ij} terms have no impact on production, prices, trade or consumer surplus, but do affect producer surplus. The truncated log-linear specification allows for more flexibility in modelling supply curve shifts. Shifts may be either convergent (h_{ij}/v_{ij} small) as shown in Fig. 2a or divergent (h_{ij}/v_{ij} large) as shown in Fig. 2b. Fig. 2c shows an intermediate specification of a proportional reduction in marginal cost throughout the supply schedule. If supply shifts are more convergent, then producer gains from technological change will be larger. If supply shifts are more divergent then producer gains will be reduced.

In the simulations, we assumed that genetic improvements accounted for half the average annual yield gain of the crops considered (Table 2, column 2). Several empirical studies have reported values around this 50% level, while others report even higher values (Duvick, 1984, 1986; Huffman and Evenson, 1993; Meredith and Bridge, 1984; Miller and Kebebe, 1984; Ramey, 1972; Specht and Williams, 1984; Thirtle, 1985). To simulate the single-year impact of yield improvements, we follow previous studies by taking the supply curve with the genetic improvements as the baseline and comparing it with the supply curve that would have existed in the absence of those improvements (Griliches, 1958; Ayer and Schuh, 1972; Akino and Hayami, 1975). To implement this simulation, the h_{ij} terms for US corn, soybeans, wheat, cotton and coarse grains were decreased by the values shown in Table 2 (column 2). Further we assume a proportional supply shift (Fig. 2c). The v_{ij} parameter shifts upward so that the supply curve shifts up by the same proportion throughout the entire supply schedule.

4. Results

First, we consider the size and distribution of the gross annual benefits of a one-time shift in the supply parameters for major US field crops (Table 3). Net welfare change (ΔW) can be decomposed into changes

Table 3

Welfare effects of genetic improvements in major US crops (single-year impacts measured in 1989, US\$ million)

Region	Change in				
	Producer surplus	Consumer surplus	Government payments	Quota rents	Net welfare
Developed countries	9	511	25	1	496
United States	162	223	33	0	352
Canada	–17	18	–1	0	2
EU	–103	180	–7	0	84
Other western Europe	–10	16	0	0	6
Japan	–9	66	0	1	58
Australia/New Zealand	–14	8	0	0	–6
Developing and transitional economies	–356	443	7	14	94
China/transitional economies	–171	210	2	8	45
Developing agricultural exporters	–61	62	2	–17	–18
Developing Asian importers	–5	14	0	11	20
Rest of world	–119	157	3	12	47
World total	–347	954	32	15	590

Simulation experiment: yield increases for US wheat (0.57%), corn (0.67%), coarse grains (0.77%), soybeans (0.62%) and cotton (1.12%).

in consumer surplus (ΔCS), producer surplus (ΔPS), government payments (ΔGP) and quota rents (ΔQR) such that $\Delta W = \Delta CS + \Delta PS + \Delta QR - \Delta GP$. Government market interventions such as commodity programs or trade restrictions influence overall welfare impacts of technological change (Alston et al., 1988; Oehmke, 1988).

4.1. Distributional impacts

The global welfare benefits of a one-time, single-year yield increase in the US crops were US\$ 590 million (1989 constant). The yield increases lead to modest declines in world commodity prices. This benefits consumers world-wide by US\$ 954 million, while foreign producer surplus declined by US\$ 509 million. In the US, higher yields and lower prices increase commodity program payments and dampen the overall gains in US welfare.

Table 3 shows some distributional impacts of US yield increases. The US captures 60% (US\$ 352 million) of this welfare gain. Other developed countries captured one-quarter of the benefits, with other regions capturing 16%.² Results are similar to Frisvold

(1997) who, using a CGE model of the world economy, estimated that the Canada and US captured only 57% of the benefits from domestic crop productivity increases. Consumers in transitional economies, China and other developing countries are major beneficiaries of US yield gains. Consumer surplus in these regions increases by US\$ 443 million while producer surplus falls by US\$ 356 million.

To examine the sensitivity of these results to the nature of the supply shift, we also experimented with a more divergent shift. In this alternative specification, the h -shifts were maintained as before, but the v -shifts were reduced such that the change in US producer surplus fell to 0 (i.e. consumers capture all the gains of technological change). Equilibrium price and quantity changes remained exactly the same as in the first simulation. With this more divergent shift, US welfare increased by US\$ 190 million instead of US\$ 352. The United States captures just 44% of the gains of genetic improvements, other developed countries capture 34% and developing and transitional economies capture 22%.

But what can we say about the distributional impacts within developing countries? The SWOPSIM model is too aggregate and sector specific to answer this question directly. Yet it does illustrate that developing countries are affected mainly through falling world agricultural prices. The urban poor of developing countries will benefit relatively more than the

² The size of US benefits and their share of global benefits are sensitive to the assumption of proportional supply curve shifts. If supply shifts are more divergent, then US gains and their share of the gains will be less. If the shifts are more convergent, then the opposite will be true.

urban rich because they spend a higher proportion of their income on food. Matters are more complex in rural areas, because agricultural producers both buy and sell commodities. However, the rural poor in developing countries tend to be net purchasers of food. So, one would expect falling world prices to benefit the rural, poor, net-food purchasers and hurt larger-scale producers who are net-sellers of agricultural commodities. Within developing countries, rising US crop yields and falling world prices are

likely to have generally progressive distributional consequences.

The results have interesting implications for the debate over the distribution of benefits of PGR use. Critics of the current system of PGR exchange may focus on the result that developing and transitional economies capture only 16–22% of the welfare benefits. Yet the results also suggest that the poor in those countries are major beneficiaries of US yield gains. While developing countries do not receive direct

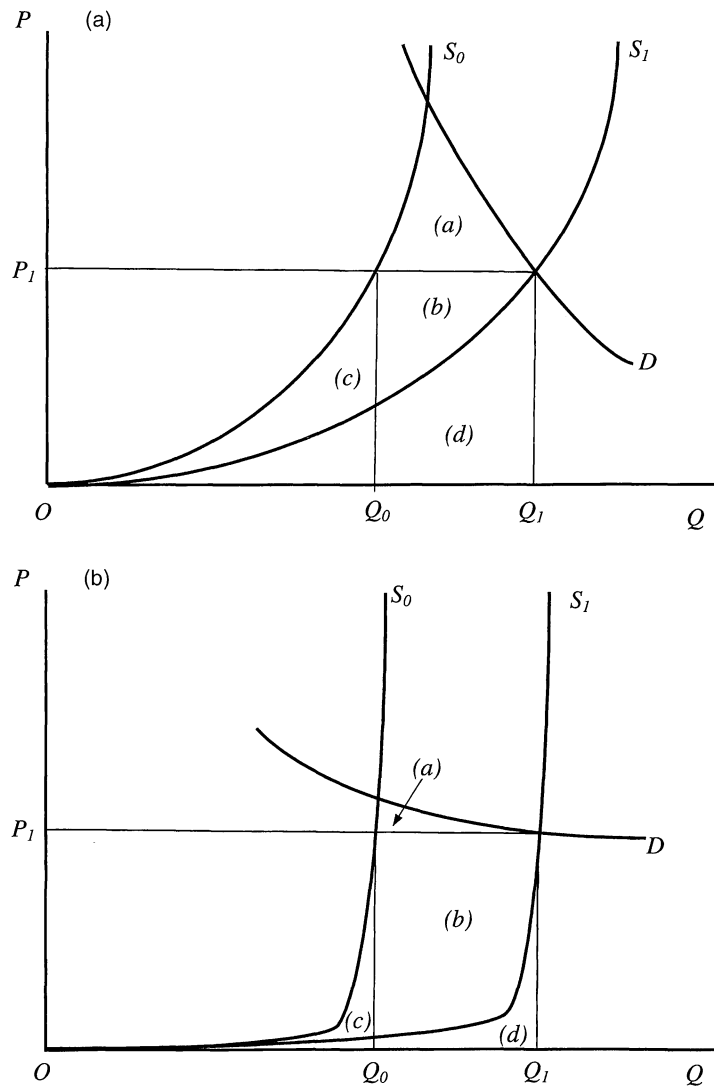


Fig. 3. (a) Change in revenue and economic surplus with a pivotal supply shift. (b) Change in revenue and economic surplus with a pivotal supply shift when demand is highly elastic and supply is highly inelastic.

Table 4
Comparison of change in revenue and multi-market economic surplus measures of the benefits of genetic improvements in selected US crops

Benefit measure	Estimated benefits (1989, US\$ million)	Benefits as a percent of global benefits	Percent difference from change in revenue method
Change in revenue method	338	57.3	0.0
US multi-market economic surplus	352	59.7	4.1
World multi-market economic surplus	590	100	74.6

monetary payments from the use of their germplasm, they do receive benefits as consumer surplus.³ Also, these are measures of the *gross* benefits of yield growth. They do not include the research costs incurred in the US to achieve yield gains.

4.2. Comparison of research benefit measures

For constant-elasticity supply and demand functions, the change in total welfare from a pivotal supply shift (with a 0 shutdown price) can be expressed as:⁴

$$\Delta W = KP_1Q_1 \left(\frac{1}{1 + \alpha_{ij}} + \frac{1}{2} \frac{K}{\alpha_{ij} + |\beta_{ij}|} \right)$$

where P_1 and Q_1 are the equilibrium price and quantity after the supply shift, α_{ij} is the own-price elasticity of supply in region j , and β_{ij} is the own-price elasticity of demand. The term K is proportional to the horizontal shift in the supply curve. The expression KP_1Q_1 would then be the estimated benefit from genetic improvements using the change in revenue method. As noted earlier, it is common for plant breeders to use this method to estimate the economic benefits of yield gains. The change in revenue method will closely approximate ΔW if the term in brackets is approximately 0. This occurs, for example, when supply is highly inelastic ($\alpha_{ij} \approx 0$) and when the yield shock, K , is small relative to $\alpha_{ij} + |\beta_{ij}|$. Fig. 3a and b compare change in revenue estimates with ΔW under alternative elasticity assumptions. The area $a + b + c$ represents the change in ΔW , while $b + d$ represents the change in revenue approximation, KP_1Q_1 . In Fig. 3b, where supply is highly inelastic and demand highly elastic,

KP_1Q_1 is quite close to ΔW . Thus, the change in revenue method may reasonably approximate ΔW for a commodity with highly inelastic supply in a ‘small country’ (i.e. a country whose production has negligible effect on world prices). In such a case, the country would be a price taker with $|\beta_{ij}|$ infinitely large. The calculation for ΔW , however, also depends on the assumptions that the supply shift has no effect on prices of other commodities and that there are no government interventions in the market in question. For our particular case of yield shocks in major US export crops, these, as well as the small country assumption, are violated.

Table 4 compares the estimated benefits of yield increases using the change in revenue method with the multi-market welfare method. While the change in revenue estimate approximates US domestic benefits from genetic improvements, it significantly understates the gain in global economic surplus. The multi-market estimates of US benefits of yield increases are within 5% of benefit estimates derived using the change in revenue method. Global multi-market welfare benefits, however, were about 75% greater than the change in revenue estimates. Plant breeders may not be giving themselves enough credit when estimating the returns to their work.

5. Long-term impacts

The simulation estimated the impacts in single year of a one-time increase in US crop yields from genetic improvements. Yield increases from genetic improvements are not single-year events. Annual yield gains achieved in a given year have been maintained after that. It is appropriate to think of the benefits as an income stream (Evenson and Gollin, 1997). One may then calculate the present value of an annual *permanent* increase in yields from genetic

³ Our simulations systematically *overstate* producer surplus losses in developing/transitional economies because in the model falling feed grain prices induce pivotal supply curve shifts in animal product markets.

⁴ This derivation comes from Norton and Davis (1981).

Table 5
Impact of one-time, permanent yield increase from genetic improvements in selected US crops (present value in 1997 constant, US\$ billion)

Discount rate (r , %)	Change in			
	Global welfare	US welfare	Developing and transitional economies welfare	Developing and transitional economies consumer surplus
10	8.1	4.8	1.2	6.1
7	11.2	6.7	1.7	8.5
5	15.4	9.2	2.5	11.6

Note: crops include corn, wheat, soybeans, cotton and coarse grains.

improvements. The basic results presented below would not change qualitatively if one assumed increases were less than permanent, but long-lived, lasting for say, 30 years.

The simulation estimated the gross annual benefits of yield increases in single year. A conservative first approximation of the value of a permanent increase in yields would be to assume that the single-year benefits are received in each subsequent year. This estimate is conservative because the benefit of an outward supply shift is the area between the old and new supply curves and underneath the demand curve. As income and population grow, this area would grow as demand shifted outward.

Table 5 shows the present value of a permanent increase in US crop yields at different discount rates. No matter the discount rate, the benefits of permanent yield increases are substantial. US benefits range from US\$ 4.8 billion ($r = 10\%$) to US\$ 9.2 billion ($r = 5\%$) in constant 1997 dollars. Global benefits range from US\$ 8.1 billion to US\$ 15.4 billion constant in 1997. Net benefits to developing and transitional economies range from US\$ 1.2 billion to US\$ 2.5 billion. Benefits to consumers in developing and transitional economies range from US\$ 6.1 billion to US\$ 11.6 billion.

Plant breeding and genetic improvements have not merely generated one-time permanent increases in yields, but rather an annual stream of permanent yield improvements. Every year there is a new incremental permanent increase in yields. The problem is equivalent to receiving a new annuity (of varying value) every year. One may properly think of the long-term benefits of genetic improvements as a 'stream of income streams'. It is beyond the scope of our static modelling approach to calculate this stream of streams of benefits. This would require a comparison of

dynamic paths of supply and demand with and without genetic improvements. However, the discounted value of the long-term process of genetic improvements is much larger than benefit of a one-time permanent increase in yields.⁵

6. Conclusions

This study used a world agricultural trade model to estimate the size and distribution of welfare impacts of genetic improvements of major US field crops. We conclude by summarising three major findings. First, global multi-market welfare benefits of genetic improvements in US field crops were 75% larger than benefit estimates from the change in revenue method frequently used by plant scientists. Second, simulation results suggest that 44–60% of the gains accrue to the US, 24–34% to other developed countries and 16–22% to developing/transitional economies. Because of systematic biases in the model used, however, the absolute and relative gains to other countries are likely underestimated. Third, consumers in developing and transitional economies are major beneficiaries of US yield gains. In developing countries, the urban and rural poor are net-food purchasers. Within developing countries, rising US yields and falling world prices will generally have progressive distributional consequences.

⁵ To illustrate, suppose you were to receive an annuity paying US\$ 100 per year for 20 years. At a 5% discount rate, its present value is over US\$ 1300. Now, what if you received a new annuity paying US\$ 100 per year for 19 years in year 2, a new annuity paying US\$ 100 per year for 18 years in year 3 and so on for 20 years? The present value of this stream of annuities would be about US\$ 11,650 or nearly nine times larger than the single one-time annuity.

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