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A Preliminary Analysis of the Benefits of Introducing Apomixis into Rice

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Abstract

The objective of this research is to undertake an *ex ante* economic analysis of basic scientific research that aims to identify the gene(s) that control apomictic reproduction, with the ultimate aim of transferring the characteristic into commercially important crops. This paper reports very preliminary results, using the introduction of apomixis into rice as a case study. Apomixis is a natural, asexual method of plant reproduction resulting in offspring that are genetically identical to the mother plant. Apomixis promises to revolutionize plant breeding by providing a system for crop improvement that allows any desired variety, including hybrids, to breed true. This ability will make both breeding and seed production more efficient. It offers the opportunity for plant breeders to more readily develop varieties that are specifically adapted to local conditions, using, and thus conserving, greater genetic diversity. Apomixis will also allow resource-poor farmers to replant the seed they produce from locally bred varieties year after year, a strategy not possible with today's commercial hybrid varieties. Global changes in aggregate welfare, resource allocation, production and price levels are calculated using the global economy-wide computable general equilibrium model known as GTAP. Preliminary modeling results suggest that the overall welfare gains associated apomictic rice could be substantial.

1. Introduction

The word apomixis is derived from Latin: *apo* meaning 'away from' and *mixis*, meaning 'the act of mixing or mingling'. It refers to asexual reproduction through seed (Khush et al, 1994). Plants reproduce either sexually by seed, or by some method of asexual propagation (cloning). In *sexual reproduction*, the combination of pollen and egg during fertilization gives rise to a seed that carries a unique combination of genes derived from both parents. This recombination causes variability in a sexually propagated population. Sexual reproduction and genetic uniqueness have provided most species with evolutionary advantages. In agriculture, however, the variability that arrises from sexual reproduction is often regarded as undesirable, since it can negatively effect production practices and the quality of the harvested and processed product. To mitigate these effects breeding strategies typically involving inbreeding are used to 'fix' characteristics in a 'true breeding' commercial variety. Sch strategies are expensive to conduct and often result in potential yield loss through inbreeding depression.

Asexual reproduction, by contrast, provides the advantages of absolute crop uniformity. The genetic make-up of the parents is identical to the progeny, so a single desirable plant can become the basis of a new variety. The efforts essential for sexually propagated plants to 'fix' characteristics to ensure 'true breeding' are therefore unnecessary. Consequently, cloning makes the development of new varieties more time and cost effective.

Asexual reproduction is not a new concept. It can take place either vegetatively or through clonal seed. Many economically important fruiting plants, such as date palms and grapevines, have been propagated by vegetative means for hundreds, sometimes even thousands of years. Similarly, many root and bulb crops such as cassava, potato and garlic are cloned by natural means. More recently, technologies such as tissue culture and cutting propagation have greatly expanded the number of species that can be cloned. Despite the clear advantages of asexual reproduction, it is not viable for the majority of the worlds important crops such as maize, rice, wheat, millet, sorghum, most pulse species, and the majority of economically important forage, fibre and timber species.

Apomixis is an alternative form of clonal reproduction. One of the advantages of apomixis is that it involves clonal seeds, as opposed to vegetative stock. Seeds are ideal planting stock as they are physiologically robust, naturally primed for growth and adapted for field emergence. Apomixis is widespread in plants, occurring naturally in about 400 plant species distributed over more than forty plant families (Bellagio Apomixis Conference, 1998). Few commercially important crops, however, are apomictic. Of those that are, the majority are either tropical fruit trees, such as citrus and mango, or forage species, such as Kentucky Bluegrass (*P. pratensis)* and Signal Grass (*Brachiaria decumbens).*

2. The benefits of introducing apomixis into rice

Rice is the second largest cereal crop in the world, and it has been estimated that half the world's population subsists wholly or partially on rice. Although rice production has doubled over the past 30 years, current consumption trends mean that much more of this cereal will be needed in the future. In addition, rice is a crop that requires abundant water. Global warming trends may mean that rice will need to be more robust in the face of increasing droughts. As a consequence, it is vitally important that rice yields continue to improve and that rice breeding advances are made as quickly as possible.

The potential value of apomixis for plant breeding has been recognized for many years (Hanna and Bashaw, 1987). The following list of benefits has been adapted from Bicknell and Bicknell (1999), focusing on benefits relating to rice production:

1. *Rapid development of new hybrid varieties*. A hybrid is the product of crossing genetically dissimilar parents. A hybrid breeding programme involves establishing a group of genetically uniform and distinct lines that are inbred by repeated self-pollination, and the identification of those combinations of pure lines that render increased vigour. With apomixis the desirable genetic make-up of any individual plant could be ‘fixed’ immediately without the creation of inbred lines, thereby significantly reducing the costs of a hybrid breeding programme and the time it takes to develop a new variety.
2. *Increased biodiversity*. Perhaps paradoxically, clonal reproduction through seed may actually increase crop biodiversity. It is hoped that access to apomixis will provide an incentive for *National Agricultural Research*

Institutes (NARIs), producer cooperatives and possibly even individual producers in resource poor regions to develop their own varieties. As it will be theoretically possible to cross existing landraces with apomictic varieties, new hybrid varieties could be formed which may potentially be specifically adapted to local environmental conditions and growing practices.

3. *Economic hybrid seed production*. In hybrid seed production, the maintenance of inbred lines is a cost decisive activity, and has been cited as the limiting factor for wide-scale adoption of hybrid rice in the tropics and subtropics (Khush et al 1994). Furthermore, the production of seed by these inbred lines remains complicated by their decreased viability, and the laborious and expensive activities for preventing cross-pollination. With apomixis, the cost of hybrid seed production could be drastically cut. Once a favourable variety is created by hybridisation, that plant and its identical offspring could produce seeds asexually at a higher rate than inbred lines.
4. *Propagation of hybrid seed*. Seed produced by hybrid crops is genetically variable. By contrast, apomictic varieties do not change their genetic make-up and thus 'breed true'. Therefore, instead of purchasing new hybrid seed each planting, farmers could save and sow seed of apomictic hybrid varieties without losing its hybrid vigour.
5. *Increased reproduction efficiency*. Crop losses are often caused by limitations of the 'mechanics' of sexual reproduction itself, such as fertilization or pollination difficulties, caused by incompatible varieties, inadequate pollinator activity, or biotic/abiotic stress.

The above list of potential benefits implies that the introduction of apomixis into rice could substantially increase yields in regions where the production of hybrid varieties is currently uneconomic, and reduce the cost of producing hybrid varieties in regions (most notably China) where hybrid varieties are currently produced with conventional breeding practices. It has been estimated that apomixis could increase rice production from 10 – 20%, and reduce the cost of producing hybrid varieties by approximately 10% (McMeniman and Lubulwa, 1997).

3. Methodology

The literature on estimating the returns from agricultural research is vast. The standard approach to the *ex ante* evaluation of research benefits uses a partial equilibrium framework, and involves the assumption that successful research induces a shift in the aggregate supply of a particular output (Alston, Norton and Pardey, 1998). The gross annual research benefits are therefore modeled as the additional area under the demand curve, and between the two supply curves. Under various assumptions about the shape of the supply and demand curves, as well as the nature of the research-induced supply shift, these benefits can be disaggregated into increases in producer and consumer surplus for the commodity under investigation. McMeniman and Lubulwa (1997) use a partial equilibrium framework to estimate the returns to apomixis in rice. Their results suggest that over a 30 year time horizon, the social benefits of introducing apomixis into rice outweigh the costs by over $8 billion (AUD), resulting in an internal rate of return of nearly 80%.

More recently, *ex ante* evaluations of new technologies have been evaluated within a general equilibrium framework. This approach has at least two advantages (Frisvold, 1997). First it allows for endogenous movements of regional prices and quantities in all markets in response to technological change in the market of interest. Second, it allows the analyst to examine the potential impact of technological spillovers between regions.

Anderson and Yao (2003) use a general equilibrium framework to quantify the economic effects of China either adopting or not adopting GMOs under a variety of assumptions regarding the adoption behaviour and political reactions of various trading partners. They model the adoption of GMOs as a 5% Hicks-neutral technology shift for adopting countries, representing one-off 5% gain in total factor productivity. In addition, they incorporate potential consumer backlash as a refusal to grant market access to counties that adopt GMO technology. Their results suggest that the potential gains to China from adopting GMO technology are substantial, and that these gains are reduced only slightly if Western Europe were to ban food imports from China. However, if consumer backlash extended to Northeast Asia, the welfare loss to China would be significant.

In a subsequent paper Anderson, Jackson and Nielsen (2003) use a general equilibrium framework to compare the adoption of 'traditional' productivity enhancing GM technology with the adoption of GM technology that has well defined consumer benefits. Productivity enhancing GM technology was modelled as factor-biased technical change, increasing labour productivity by 8%, land productivity by 6% and chemical input productivity by 5%. Golden rice was used as example of GM technology with consumer benefits. Golden Rice had no direct yield advantage, but it was assumed to increase unskilled labour productivity by 2%. Their results suggest that the potential gains from adopting GM technology are large, and that the gain from adopting Golden Rice are more profound than the gains from traditional GM technology. Furthermore, these gains were robust to trade sanctions. This results was particularly true for rice, which is not a widely traded commodity.

Huang, et al (2004) use a similar general equilibrium framework to conduct a cost benefit analysis of biotechnology adoption in China under various assumptions regarding the crops that are affected and the political stance of China's trading partners. In their study the adoption of GM technology is assumed to augment output and reduce labour and pesticide costs, but increase the cost of seed. They extend the existing literature by using a two-step updating procedure that allows them to capture the dynamics of technology adoption. Their results suggest that the returns to the adoption of a hypothetical productivity-enhancing GM technology for rice are substantial, and significantly greater than the adoption of Bt Cotton even though the forward-linkages are much stronger for cotton. Because so little rice is traded internationally, the trade impacts surrounding this crop are minimal. In addition, the domestic demand conditions in China are such that a supply-induced reduction in price stimulates demand for other consumer goods rather than increasing the demand for rice.

For this preliminary analysis, the benefits of introducing apomixis into rice were quantified using the computable general equilibrium model of the global economy known as GTAP (Global Trade Analysis Project). Table 1 shows the regional and commodity aggregation. As a base case, the adoption of apomixis was assumed to result in a 15% Hicks neutral gain in productivity. For Australia and China, the 15%

productivity shock was weighted downward by 0.66 based on the adoption ceiling reported in McMeniman and Lubulwa (1999). For ASEAN countries it was weighted by 0.45. So, for the GTAP simulations, the rice sectors in China and Australia received a shock of 15% X 0.66 = 10%, while the rice sector of ASEAN countries received a shock of 15% X 0.45 = 6.75%.

Table 1. Regional and Commodity Aggregation

Regional Aggregation	Commodity Aggregation
Canada	Paddy rice
US	Wheat
Mexico	Other grains
EU	Non-grain crops
China	Livestock (Wool, Other livestock)
ASEAN countries (Thailand, Malaysia, Singapore, Indonesia, and the Philippines)	Food products and Textiles
Australia	Manufacturing (including mining)
Rest of World (ROW)	Services

The simulation is a comparative static one. It increases rice productivity in the base year of the GTAP version 5 model. So, essentially it asks, what would be the impacts if apomoxic rice were available and widely adopted in China, Southeast Asia, and Australia in the contemporary economy? In this respect it is a simpler exercise than the Huang et al (2004) study which used a recursive approach to examine the impacts of adopting GM rice and cotton in China from 1997-2010. This study is more akin to Anderson and Yao (2003), which assumes that GM adopting sectors experience a one-off increase in the total factor productivity (Hicks-neutral shock) of 5%.

4. Results

Preliminary results with the GTAP model indicate that increased productivity in the rice sector frees land and labour (particularly in the adopting countries), which is reallocated to other sectors (Table 2). In China, where the demand for rice is highly inelastic, this reallocation effect is most pronounced. Acreage devoted to rice declines by 6.1%, while labour declines 10.3%. Land is reallocated to production of other crops and to animal products. Labour moves to all other sectors. Labour allocated to processed food and textile production increases 1.8%. In ASEAN countries, where the demand for rice is a bit more elastic, the reallocation is less pronounced. Land allocated to rice declines 3% and labour 5.9%. In ASEAN countries, labour input to food and textiles rises 2%. In Australia, the effect is more muted, with increases in manufacturing and services labour of less than 0.05%. Resources move out of rice production in other regions as a result of the falling supply price of rice (See Table 4 below).

Table 2. Percent change in land and labour allocated to each sector

	Canada	USA	Mexico	EU	China	ASEAN	Australia	ROW
Land								
Rice	-0.1	-0.2		-0.3	-6.1	-3.0	-0.4	
Wheat	0.1				1.3	1.1	0.2	
Other Grain					1.1	1.5	0.1	
Other Crops					1.0	1.1	0.1	
Animal Products					1.4	1.6	-0.1	
Labour								
Rice	-0.3	-0.4	-0.1	-0.5	-10.3	-5.9	-0.8	-0.1
Wheat	0.2	-0.1		0.0	0.8	0.2	0.1	-0.1
Other Grain	-0.1	-0.1		-0.1	0.6	1.0		-0.1
Other Crops	-0.1	-0.1		-0.1	0.5	0.4		-0.1
Animal Products	-0.1	-0.1		-0.1	1.0	1.1	-0.2	-0.1
Food / Textiles	-0.1	-0.1		-0.1	1.8	2.0	-0.1	-0.1
Manufacturing					0.2	-0.3		
Services					0.6	0.1		

Blanks indicate a change of less than 0.05%.

Despite the large productivity gains associated with apomixis, rice production increases only 0.05% globally. While production increases in ASEAN countries and Australia, it declines elsewhere. Rice production actually declines in China, albeit by only 0.05%. The effect of apomixis adoption in China is to free up resources to increase production in other sectors with the greatest increase (1.6%) in processed food and textiles. These results are consistent with Huang *et al*. (2004), who found only modest changes in production, despite large productivity shocks. Their study differed from the present research, in that technological change occurred only in China. In our study, incentives for domestic Chinese production are further reduced by increased production in ASEAN countries and Australia.

Table 3. Percent change in production

	Canada	USA	Mexico	EU	China	ASEAN	Australia	ROW
Rice	-0.2	-0.4	0.0	-0.4	-0.1	1.5	9.3	-0.1
Wheat	0.2	0.0	0.0	0.0	0.9	0.5	0.1	0.0
Other Grain	-0.1	-0.1	0.0	-0.1	0.7	1.2	0.0	-0.1
Other Crops	-0.1	-0.1	0.0	-0.1	0.6	0.7	0.0	0.0
Animal Products	-0.1	-0.1	0.0	-0.1	1.1	1.3	-0.2	-0.1
Food / Textiles	-0.1	-0.1	0.0	-0.1	1.6	2.0	-0.1	-0.1
Manufacturing	0.0	0.0	0.0	0.0	0.0	-0.4	0.0	0.0
Services	0.0	0.0	0.0	0.0	0.4	0.1	0.0	0.0

Even though the changes in Chinese, ASEAN and global rice production were only modest, domestic supply price changes are quite significant in the adopting regions (Table 4). The magnitude of these price changes is greater than those in Anderson and Yao (2003), who report price changes of between -1.8% and -4.6% for adopting nations. Much of the discrepancy can be explained, of course, by the relative sizes of the productivity shocks between the two studies.

Table 4 Percent change in supply prices

	China	ASEAN	Australia
Rice	-11.6	-7.9	-9.6
Wheat	0.0	-0.1	0.0
Other Grain	0.0	0.0	-0.1
Other Crops	-0.2	-0.1	-0.1
Animal Products	-1.0	-0.5	-0.1
Food / Textiles	-0.8	-1.1	-0.1
Manufacturing	0.1	0.1	0.0
Services	0.2	0.2	0.0

In dollar terms, changes in rice trade balances are quite modest. For China and ASEAN countries, the trade balance for wheat decreases, while it increases for animal products. In China, the trade balance for other crops (such as cotton) increases. Also for China and ASEAN countries, the trade balance increases for processed food and textiles, while it decreases for manufacturing and services. Overall, the largest trade balance impacts are in the processed food and textiles, with China and ASEAN countries improving their trade balance relative to other regions. The CGE model suggests that, although, the large productivity shock is concentrated in the rice sector, the largest dollar impacts are in processed food and textiles and manufacturing.

Table 5 Change in trade balance in $US million (positive figure indicates increase in exports exceeds increase in imports)

	Canada	USA	Mexico	EU	China	ASEAN	Australia	ROW
Rice	0	-6	0	-1	2	7	8	-11
Wheat	7	3	0	1	-18	-11	3	14
Other Grain	0	-8	0	0	0	-4	0	12
Other Crops	0	-4	-1	8	10	-25	2	7
Animal Products	-4	-11	-1	-15	71	6	-14	-36
Food / Textiles	-54	-312	-18	-504	845	1125	-44	-1092
Manufacturing	40	255	14	361	-748	-735	29	788
Services	6	73	3	109	-54	-262	12	172

The single-year increase in global welfare from the adoption of apomictic rice in China, ASEAN countries, and Australia is over $4.1 billion (Table 6). China and ASEAN countries capture the bulk of these gains. The EU as a whole gains by $94 million even though the trade position of its processed food and textile sectors declines, as does its overall trade balance. Welfare declines in ROW, a net importer of agricultural products that, in the simulation, does not adopt apomictic rice. The real price of land falls in all regions, while real wages increase by 1.04% in China and 0.55% in ASEAN countries.

Table 6. Aggregate welfare effects of the introduction of apomixis into rice

	Change in welfare (equivalent variation)	Change in aggregate trade balance	Change in returns to primary factors adjusted for change in consumer price index		
			Real land rental rate	Real wage	Real capital rental rare
	$US millions	*$US millions*	*Percent*	*Percent*	*Percent*
Canada	6.0	-5.4	-0.12	0.00	0.00
USA	44.5	-9.7	-0.15	0.00	0.00
Mexico	1.5	-2.2	-0.05	0.00	0.00
EU	94.3	-41.6	-0.13	0.00	0.00
China	2892.0	106.9	-0.97	1.04	1.37
ASEAN	1152.4	100.6	-1.94	0.55	0.57
Australia	3.1	-3.5	-0.2	0.01	0.01
ROW	-40.3	-145.1	-0.14	0.01	0.01
World Total	4153.5	0.0			

Sensitivity analysis reveals that improvements in global welfare and trade balance are roughly proportional to the size of the productivity shock that is assumed (Table 7). Global equivalent variation, for example, improves by $4.15 billion annually assuming that the introduction of apomixis into rice is associated with a 15% productivity increase. Changes in the productivity shock of approximately 33% in either direction result in similar percent changes in equivalent variation.

Table 7. Sensitivity Analysis – Welfare and Trade Balance Impacts of Different Productivity Shocks to Rice Sectors of China, ASEAN countries, and Australia

	Equivalent Variation ($US million)			Change in Aggregate Trade Balance ($US million)		
	10% Shock	15% Shock	20% Shock	10% Shock	15% Shock	20% Shock
Canada	4.1	6.0	7.8	-3.7	-5.4	-7.1
USA	30.3	44.5	58.1	-6.6	-9.7	-12.6
Mexico	1.0	1.5	2.0	-1.5	-2.2	-2.8
EU	64.2	94.3	123.3	-28.4	-41.6	-54.3
China	1996.8	2892.0	3727.3	73.4	106.9	138.5
ASEAN	784.9	1152.4	1504.6	68.3	100.6	131.7
Australia	2.1	3.1	4.2	-2.4	-3.5	-4.5
ROW	-27.9	-40.3	-51.9	-99.1	-145.1	-188.9
World Total	2855.5	4153.5	5375.3	0.0	0.0	0.0

5. Discussion

The total welfare benefits calculated in this study are consistent with the annual benefits reported by McMeniman and Lubulwa (1997). Their study, which uses a modified partial equilibrium framework, models the benefit of apomixis research as a parallel shift in the supply curve for rice assuming that all of the major rice producing nations adopt apomixis technology up to a pre-determined ‘adoption ceiling’. Their results suggest total annual gross research benefits of approximately $4 billion (Australian) once the technology has been widely adopted. Most of the benefits are predicted to accrue to China, India, and Indonesia. They do not disaggregate their results to provide information on price, productivity or terms of trade effects.

The results are also broadly consistent with Anderson and Yao (2003), who also use the GTAP framework to model a hypothetical GM-driven growth in productivity in the rice sector. These authors model the impact of GM technology as a one-off 5% Hicks-neutral increase in productivity in China, North America, the Southern Cone of South America and Southeast Asia. Their results suggest a total increase in global economic welfare of approximately $2 billion, with China and Southeast Asia enjoying the majority of the gains. With the exception of North America, there is an increase in rice production in all GM adopting countries. The price of rice declines in all countries, with the largest impact being felt in the adopting countries. China, India, Southeast Asia and Northeast Asia all experience positive changes to their aggregate trade balance in rice, while in the other regions changes in imports outweigh changes in exports.

The results of this study are not so readily compared with Huang et al. (2004), as their analysis focused on the impact of China’s GM policies. Consequently, productivity gains from the hypothetical adoption of GM rice were confined to China, with no subsequent technological spillovers. They also used a two-step recursive approach which allowed them to capture the dynamics of technology adoption from 2001 through to 2010, where our preliminary results are static in nature. With no consumer backlash from trading partners, the adoption of GM rice in China leads to a substantial decline in producer prices a modest increase in output and an improvement in the terms of trade for rice. The overall welfare effects are considerable, with a gain in equivalent variation for the Chinese economy of over $4 billion by 2010. The demand-side effects on the rice sector in China are, however, very similar to our results. Because the demand for rice is not particularly responsive to changes in price or income, the adoption of a technology that enhances rice production ultimately stimulates demand in other sectors of the economy as consumers pend their increased income and money they save on buying rice on other products.

6. Conclusion

This preliminary exercise estimated the impacts in a single year of a one-time increase in rice yields in a limited number of countries from the introduction of apomixis into rice. It can be argued that the resulting welfare effects represent a ‘lower bound’ estimate, because yield increases from apomixis would not be a single year event. It is probably more appropriate to think of the benefits as an income stream (Frisvold, 1997). A first approximation of the total benefits would be to assume that the single-year benefits are received in each subsequent year. This is a conservative assumption, however, because it does not consider subsequent shifts in the demand curve resulting from income and population growth.

A number of tentative conclusions can be drawn from this very preliminary analysis. First, the potential benefits from the adoption of apomixis are substantial. This result supports the consensus of opinion in the scientific community, that the introduction of apomixis technology is probably the most important target of current efforts in plant biotechnology. The main beneficiaries of apomixis technology are, of course, consumers. This result is entirely consistent with predictions based on partial equilibrium analysis. Because the demand for rice is inelastic, particularly in China, the main effect of the adoption of apomixis is to liberate resources from the paddy rice sector and increase the effective income of consumers. Finally, our results suggest that the largest dollar impacts of the proposed technology do not occur in the rice sector, but in the processed food, textiles and manufacturing.

There is tremendous scope for further work on this topic. This preliminary analysis demonstrates the magnitude of the potential benefits from the relatively wide adoption of a new technology that is made freely available. From a distributional perspective, some of the most interesting issues involving apomixis technology surround the potential that it holds for increasing yields in the lesser developed countries. Whether this potential is realised may very well depend on the property rights that ultimately govern the use of the technology. It would be interesting to explore the impact that more restrictive or well-defined property rights would have on the magnitude of the benefits from the technology.

In addition, this case study involved only one crop. The nature of the benefits of apomixis will depend on the crop in question. Not only will the potential yield or cost saving advantages vary among crops, but the market linkages within a global economy will differ as well. As a consequence, it would be interesting to examine a variety of case studies.

There are also important dynamic issues to explore. One of the primary advantages of apomixis is that it hastens the speed of crop improvement. This is particularly advantageous considering the continual pressure that a growing world population places on our food supply.

Finally, because the introduction of apomixis into commercially important crops is likely to involve genetic modification, it would be logical to consider the potential impacts of trade sanctions in a manner similar to the previous general equilibrium analyses cited above.

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