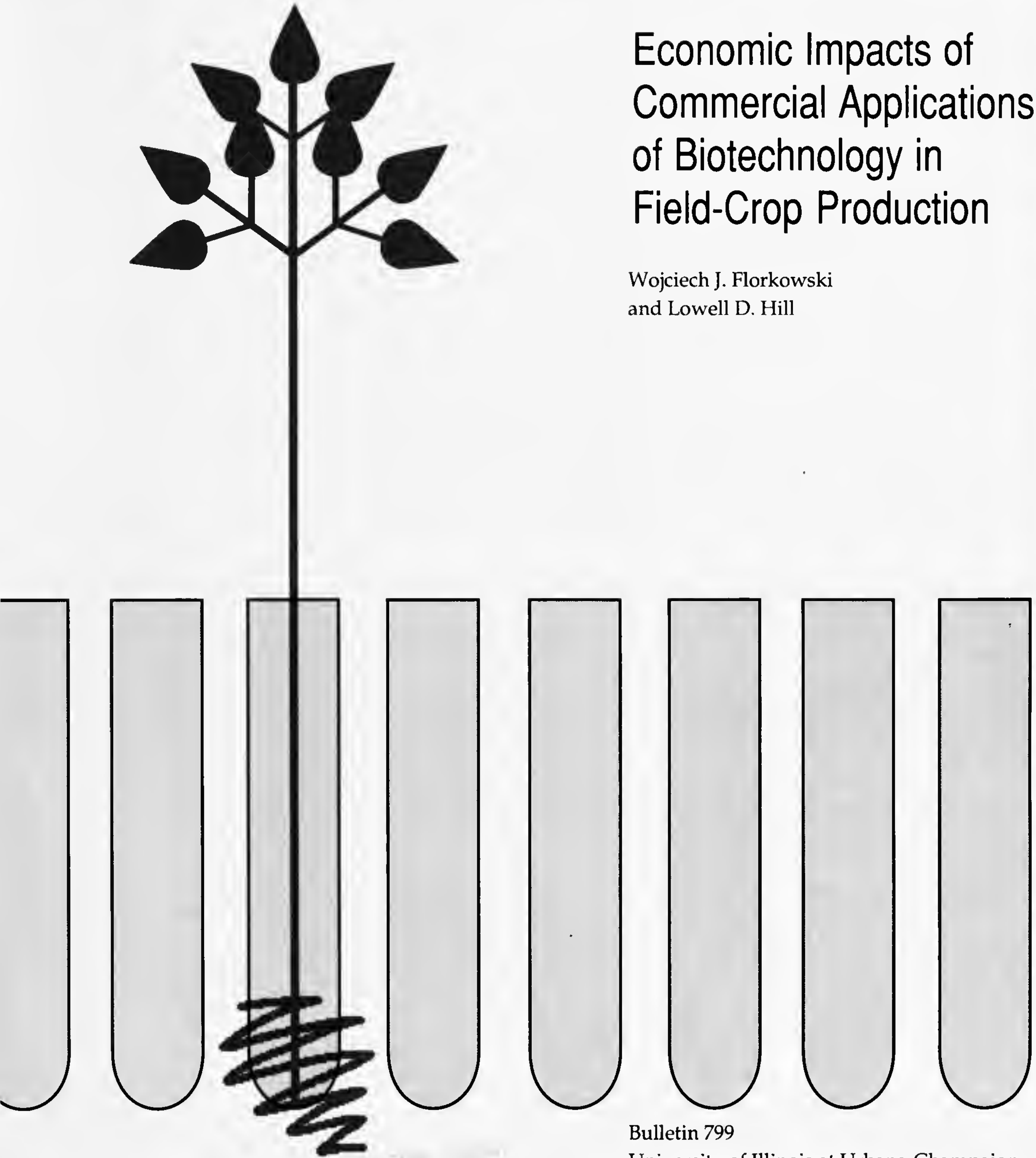

Economic Impacts of Commercial Applications of Biotechnology in Field-Crop Production

Wojciech J. Florkowski
and Lowell D. Hill

Bulletin 799
University of Illinois at Urbana-Champaign
College of Agriculture
Agricultural Experiment Station

AUTHORS: Wojciech J. Florkowski is an assistant professor of agricultural economics at the University of Georgia and Georgia Experiment Station, Griffin, Georgia. Lowell D. Hill is the L.J. Norton Professor of Agricultural Marketing in the Department of Agricultural Economics at the University of Illinois at Urbana-Champaign, Urbana, Illinois.

Editor: Mary E. Theis
Designer: Krista Sunderland

U.S. scientific leaders in the development of agricultural biotechnology can contribute to the economic growth of many countries by commercializing plant cultivars with improved genetic characteristics. In the face of limited resources and the high cost of research, the undesirable effects of past adoptions of technology have made the public and research community more aware of the importance of evaluating economic impacts before adopting a technology. Lack of information about the potential effects of biotechnology has led to a discussion of its environmental hazards (Brill), social issues (like those described by Buttel), and patenting of altered cultivars (Schmid). Biotechnology has also been the focus of several agricultural economists (Butler; Sundquist et al; Lu; Harl; Hill et al; Offut and Kuchler; Kalter and Tauer; Hueth and Just).

The U.S. Department of Agriculture (USDA) and the Office of Technology Assessment of the U.S. Congress have conducted studies on the impacts of agricultural biotechnology as well as other modern technologies. But most of these studies have avoided the issues of distributional welfare effects as the technologies have been commercially adopted.

Analysts of economic and social consequences have often relied on qualitative evaluation without quantifying the results. Any attempt to quantify something so complex as the welfare effects of adopting a technology must incorporate numerous simplifying assumptions and be limited to partial equilibrium analysis. Useful insights into relationships among the important variables can be obtained by quantifying at least first-order consequences of change.

With the use of static analysis, this manuscript provides estimates of the welfare changes associated with commercialization of twelve alternative plant biotechnologies. Welfare is measured by consumer and producer surpluses. The analysis gives information about the potential regional reallocation of agricultural land and about welfare gains to consumers. The models used in the analysis demonstrate long-term, aggregate effects of each new technology, assuming full adoption. Impacts of each technology are examined independently of the other eleven; no simultaneous adoption of two or more technologies was allowed in the model.

Description of Selected Alternative Biotechnologies

Symbiotic Changes. This biotechnological alternative focuses on improving the ability of plants to obtain nitrogen from the soil. Nitrogen fixation technology would enable corn and other plants to fix nitrogen on their roots much as the soybean plant does now. This symbiotic technology would be of great importance to farmers because nitrogen fertilizer represents a significant cost and because the lack of supply in many countries prohibits use of fertilizer at the optimum levels.

New Rhizobia Strains. Genetic changes in rhizobia, bacterial species capable of fixing nitrogen, are also receiving considerable attention. The symbiotic relationship between rhizobia and legume crops is recognized as having significant economic importance in agriculture and the cost of food production. Developing new strains of rhizobia that will be effective on crops other than legumes could extend this beneficial relationship to other crops. These rhizobia may also be altered to increase the amount of nitrogen fixed in the symbiotic relationship currently found in most legume crops.

Altered Protein Content. Biotechnology can alter the chemical composition of grains. Protein content and quality, in terms of amino acid balance, are of special importance. In countries suffering from protein deficiency, increased protein would directly improve nutritional levels. Higher protein grains could also reduce the cost of production for livestock where supplemental protein is now required.

New Resistant Varieties. Besides directly destroying the plant, pests can indirectly cause plant loss by creating an environment conducive to other diseases. Resistant varieties of plants can be developed by directing genetic changes. The southern corn leaf blight is one example of how genetic differences have altered the impact of a disease. Developing corn plants resistant to *aspergillus flavis* is also a high research priority in many countries.

Frost Tolerance. Frost damage to crops frequently lowers the yield or totally destroys crops in many parts of the world. Some plants are highly susceptible, others quite tolerant to cold temperatures including frost. Genetic manipulation could increase the resistance of important crops to the danger of occasional frost.

Herbicide Tolerance. Increased herbicide tolerance would increase crop yields and the value of a crop where treatment for pests, diseases, or weeds harms the protected crop. Genetic changes could neutralize the impact of herbicide residues in the soil. Significant commercial progress has been made on this technology in recent years.

Heat Tolerance. Heat stress significantly lowers the yields of many crops. In some cases, it precludes the cultivation of some feed and food cereals in regions where they are needed. The global warming trend may also increase the interest in heat tolerance for many crops now grown in temperate regions. Developing varieties that are resistant to heat is one of the objectives of genetic manipulation.

Plant Growth Regulators (PGRs). These regulators stimulate or retard plant growth. Some growth regulators are now in commercial operation. For example, wheat may be sprayed to control plant growth and prevent lodging. Future developments in biotechnology may widen the array of uses and plants for which PGRs are effective.

Ice-Retarding Bacteria. Crop production can be influenced not only by genetic changes in the plants but also by genetic changes in the microorganisms associated with the plants. Ice-retarding bacteria, one such example, has been chosen for analysis in this study because it has been developed to the point of experimental application. Presence of these microorganisms prevent damage to crops from low temperatures of surrounding air.

The Model

Assuming that the agricultural sector operates under conditions of perfect competition, by maximizing the sum of consumer and producer surpluses incorporated in an objective function, we can estimate changes in welfare after the use of selected agricultural biotechnologies. This procedure was developed by Samuelson and made operational by Takayama and Judge through application of quadratic programming (QP). As an alternative to QP, Duloy and Norton suggested a linear-programming (LP) algorithm with grid linearization. This method allows an analysis of both separable and nonseparable demand functions and has been recommended for agricultural sector analysis (McCarl and Spreen). Taylor et al. applied this grid linearization to separable demand functions. In case of nonseparable demand functions, the price is expressed as a function of parameters of substitutes' demand functions. An integral incorporated into the objective function of the model used to estimate welfare and distribution effects of technology adoption for a two-commodity, two-market case is:

$$P_c = \left(\frac{Q_{tc}-(a_{cd} + a_{ce}) - (b_{csd} + b_{cse})}{(b_{cd} + b_{ce})}\right)\left(\frac{Q_{ts}-(a_{sd} + a_{se})}{b_{sd} + b_{se}}\right) + \left(\frac{(b_{scd} + b_{sce})\,(b_{sd} + b_{se})}{1 - ((b_{csd} + b_{cse})\,(b_{cd} + b_{ce}))}\right)$$

where subscript c refers to one commodity, for example, corn; subscript s refers to another commodity, for example, sorghum; d indicates the domestic market, e the export market; Q_t is the total quantity of the domestic and export market; P is the price of each commodity. The equation becomes a part of an integral measuring the area under the demand function for commodity c, with Q_{ts} as an argument. A similar derivation procedure was followed in specifying the objective function used in this study (Florkowski).

Future characteristics of agricultural biotechnologies, yield, and the use of fertilizer and pesticides, must be incorporated into a model in order to provide a reliable solution. With information about the direction of changes in input use from an international survey (Florkowski and Hill), we assumed, after consulting agronomists, that the size of increase or decrease in a specific input use would amount to 10 percent of its cost. The international survey also provided estimates of expected yield changes (Table 1). Twelve of the twenty technologies included in the survey were included in the analytical model. The principal criterion for selection was the probability of rapid commercial adoption assigned by survey respondents. Other selection criteria included possible future changes in input use induced by biotechnologies, expected yield changes, goals of plant-breeding programs, and the availability of the necessary data for specifying a model. This study considered only the impact of genetic improvement through biotechnology and the minimum changes in input use. Other factors have been omitted, such as machinery that decreases soil compaction and increased yields from higher concentrations of atmospheric carbon dioxide or improved management.

The formulated benchmark model used statistics published in the final version of the *1982 Federal Enterprise Data System (FEDS) Budgets* on the cost and quantities of inputs applied per acre for nine row crops: barley, corn, cotton, oats, peanuts, rice, sorghum, soybeans, and wheat. In order to arrive at the cost of production at the regional level, the production costs reported for states were weighted by the state's share in acreage planted of a crop in a given region in 1982.

The costs used in the model, which are variable cost categories reported by budget data and fixed costs, include the cost of machinery, tractors, and general farm overhead. The cost of share rent was excluded because it represents a part of the calculated consumer and producer surpluses.

This study uses Soil Conservation Service (SCS) data on yield adjustment for different land classes compiled in 1974 (USDA, 1975) and used in studies by Nicol and by Taylor and Frohberg. Data on the amount of land available in different quality classes were obtained from the USDA Natural Resource Inventory. Yields in the model were calculated as simple averages of yields reported by the SCS and adjusted by land class.

The averages were further adjusted for genetic yield improvement between 1974 and 1982 in order to make the yield data correspond to 1982 cost estimates. The size of the yield increase from genetic gain was obtained through field tests (Miller and Kebede; Meredith and Bridge) or through interviews with experts (Hymowitz; Lambert). In the case of cotton and peanuts, no field test data were available, so we adjusted yields by calculating a percentage increase using the difference between weighted average yields for the early 1970s and 1980s. We calculated weights as a percentage share of the total regional harvested acreage for each state. The yield of rice in the benchmark model remained unchanged because the comparison of averages between the two periods did not show significant differences. We assumed that the yield of oats and barley increased by 0.3 percent annually because of genetic improvement. For crops not explicitly included in the model, an estimate of total land area allocated to these crops was withdrawn from the total land available in the model for crop production.

Table 1. Expected Percentage Changes in Yield from Application of Selected Biotechnologies

Technology	Corn	Rice	Sorghum	Soybeans	Wheat
			percent		
Symbiotic[a]	−4	−3	−8	7	−2
New rhizobia strains[b]	4	1	−2	12	0
Altered protein[c]	−3	−5	−8	1	−4
Virus-resistant[d]	8	9	9	7	9
Bacteria-resistant[d]	8	6	5	10	6
Fungus-resistant[d]	10	12	7	12	7
Insect-resistant[e]	10	10	10	8	11
Frost-tolerant[f]	6	9	8	7	8
Herbicide-tolerant[g]	4	9	5	10	6
Heat-tolerant[h]	5	5	7	12	8
Plant growth regulator[i]	12	13	3	12	5
Ice-retarding bacteria[j]	5	6	6	6	4

[a] Biotechnology altering a plant in order to induce a symbiosis between a plant and nitrogen-fixing bacteria.

[b] Genetically altered rhizobia strains that through symbiotic association with a plant increase the amount of nitrogen available to a plant.

[c] Biotechnology increasing the content of digestible protein in kernels.

[d] Virus-resistant, bacteria-resistant, and fungus-resistant plants developed through biotechnology are plants that are resistant to economically important diseases caused by viruses, bacteria, or fungi.

[e] Plants resistant to insect damage.

[f] Plants tolerating below freezing temperatures through their internal mechanism.

[g] Plants tolerating a high level of herbicide spray.

[h] Plants that have a high tolerance for extreme temperatures during a growing season.

[i] Plants responding to plant growth regulators applied during a growing season by increased yields.

[j] Genetically altered bacteria that when sprayed on frost-sensitive plants delay ice crystal formation, preventing frost damage.

Individual crops, crop mixes (McCarl), and rotations used in the benchmark model were based on USDA agricultural statistics for the last 5 to 10 years, on the graphic summary of the location of crop production from the latest U.S. census of agriculture, on *FEDS Budgets*, and on personal interviews with agricultural experts from a number of states. Crop mixes were fixed for each region, and the share of total acres allocated to each crop in any given mix was based on the historical data provided by various sources. The acreage of each crop within the crop mix was constrained by that crop's share of total acreage and by the total acreage of cropland available. Individual crops not included in a crop mix were constrained only by the available acreage of cropland in the region.

Benchmark Model Solution and Validation

A benchmark model for ten regions of the United States including nonirrigated and irrigated land is presented below.

$$MAX\ S = \sum_{n} D_n - \sum_{k}\sum_{i}\sum_{j} C^k_{ij} A^k_{ij} - \sum_{k}\sum_{m}\sum_{j} C^k_{mj} A^k_{mj}$$

$MAX\ S$ = Maximize the sum of the consumer and producer surpluses, subject to the following constraints:

1. Land constraint

   $\sum_{j} A^k_{mj} \leq L^k_m$ — total nonirrigated land; for all k, m, j

   $\sum_{j} A^k_{ij} \leq L^k_i$ — total irrigated land; for all k, i, j

2. Commodity balance

   $\sum_{m} \sum_{j} \sum_{k} Y^k_{mjn} A^k_{mj} + \sum_{i} \sum_{j} \sum_{k} Y^k_{ijn} A^k_{ij} - \sum_{p} Q^p_n \geq 0$ for all n

3. Constraints on steps for area under the demand function for each commodity

   $\sum_{p} Z^p_n \leq 1.0$ for all n

4. Demand-supply balance

   $\sum_{p} Q^p_n \geq T_n$ for all n

5. Constraints on acreage allocated to each crop

   $\sum_{m} A^k_{mjn} \leq \sum_{m} a^k L^k_m$ for all k, j, n; $0 < a < 1$

   $\sum_{i} A^k_{ijn} \leq \sum_{i} b^k L^k_i$ for all k, j, n; $0 < b < 1$

where

a	is a coefficient allocating a proportion of the total available nonirrigated land class to production of a crop under a given technology;
b	is a coefficient allocating a proportion of the total available irrigated land class to production of a crop under a given technology;
i	subscript denoting the quality class of irrigated land;
j	subscript denoting the cropping pattern, including rotational schemes and mix of crops in the region;
k	subscript denoting the geographical production region;
m	subscript denoting the quality class of nonirrigated land;
n	subscript denoting a commodity;
p	segment of the demand schedule;
A	acres of crops produced;
C	cost of production per acre;
D	area under the demand curve;
L	total acres of cropland;
Q	quantity of a commodity represented by the area under a segment of the demand curve, D;
T	total production of a crop;
Y	yield of each crop under the given technology, crop mix, and land class;
Z	activity representing the pth segment on the demand schedule;
A^k_{ij}	acres of crop production under cropping pattern j on irrigated land class i in region k;
A^k_{ijn}	acres of crop production under cropping pattern j producing commodity n on irrigated land class i in region k;
A^k_{mj}	acres of crop production under cropping pattern j on nonirrigated land class m in region k;
A^k_{mjn}	acres of crop production under cropping pattern j producing commodity n on nonirrigated land class m in region k;
C^k_{ij}	cost per acre of producing crops under cropping pattern j on irrigated land class i in region k;
C^k_{mj}	cost per acre of producing crops under cropping pattern j on nonirrigated land class m in region k;
D_n	area under the demand curve for commodity n;
L^k_i	total acres of irrigated cropland of class i in region k;
L^k_m	total acres of nonirrigated cropland of class m in region k;
Q^p_n	quantity of commodity n corresponding to D^p_n;

T_n	total production of commodity *n* in 1982
Y^k_{ijn}	yield per acre of commodity n produced under production cropping pattern *j* on irrigated land class *i* in the region *k*;
Y^k_{mjn}	yield per acre of commodity *n* produced under production cropping pattern *j* on nonirrigated land class *m* in region *k*;
Z^p_n	activity in the model drawing an amount equal to the area under the demand curve at the *p*th step on the function. This amount is drawn from the demand-supply balance for commodity *n*.

All of the above parameters and variables are assumed to be non-negative. Ranges on the production of crops included among the constraints of the benchmark model were used in order to arrive at a solution that would be comparable to land allocation for actual acreage use in 1982.

The percentage absolute deviation (PAD) was used as a criterion for model evaluation (Norton and Schiefer). The PAD value of 6.74 percent for the benchmark model indicates that model acreage allocation differed by 6.74 percent from the actual acreage allocation of 1982.

Comparisons between the 1982 actual yield and yields in the benchmark solution were used to further validate the benchmark model (Table 2). Yields for irrigated and nonirrigated fields were combined to obtain average yields for each region and crop. Areas where the benchmark model yield did not deviate by more than 10 percent included the Northeast, Delta, Appalachian, and Pacific regions. Yield for the Lake States, the Southeast, and Northern Plains had a deviation larger than 10 percent. These larger deviations included the yield of oats in the Lake States, soybean yield in the Southeast, and sorghum yield in the Northern Plains. The yield of wheat and oats deviated more than 10 percent from the actual average yield in the solution for the Corn Belt. Similarly, the yield of oats and corn in the Mountain region deviated more than 10 percent from the 1982 level. The solution obtained for the Southern Plains showed deviation above 10 percent in the cases of corn, sorghum, and cotton. Some of the discrepancies between average yields and actual yields were the result of inadequate data on crop yield on irrigated land by land class. Comparison of calculated yields with long-term average yields revealed differences with regard to the same crop — differences that, on occasion, were larger than the 1982 averages.

Prices obtained from the model solution reflected the market equilibrium determined by the model. The differences between the actual 10-year average prices and estimated prices were substantial (Table 3). Among the reasons for those differences were the omission of some economically important crops, inaccurate estimates of long-term, own-price and cross-price demand elasticities (Table 4), imperfections in real markets, and forces distorting equilibrium prices. As an example of market imperfections, rice is traded on a thin market (Rastegari-Henneberry). Accuracy in estimating price elasticity is diminished by the fact that the prices of some commodities, such as barley, cotton, or soybeans, are influenced by their dual usage or the demand for a joint product.

Given the objective of the study, that is, the evaluation of a potential change in economic welfare due to the commercial application of an agricultural biotechnology under long-term equilibrium conditions, the set of prices generated by the model was considered satisfactory evidence that the model's specifications were correct.

Results

Impact of Biotechnologies. Solutions of the model provided estimates of land allocation after the application of biotechnologies (Table 5). The commercial planting of cultivars

Table 2. Comparison of Yield Estimates and Actual Yields Per Acre

Region	Yield	Barley	Corn	Oats	Sorghum	Soybeans	Wheat	Cotton	Peanut	Rice
		bushels per acre						pounds per acre		
Northeast	Actual	56.7	97.5	60.3		27.2	39.6			
	Estimated	101.3	62.0				41.2			
	Percent[a]	103.9	101.2				104.1			
Southeast	Actual	50.0	79.4	57.6	42.9	24.6	33.4	754.8	3121.7	
	Estimated		84.5			27.7	33.9	722.6	2974.6	
	Percent[a]	106.5				111.0	101.5	95.7	95.3	
Appalachia	Actual	53.8	99.4	55.4	63.7	27.5	36.8	718.2	2838.9	
	Estimated		105.2			29.9	40.1	723.8	2948.0	
	Percent[a]		105.9		108.7	109.1		99.3	101.6	
Lake State	Actual	57.9	110.9	60.3		34.0	40.2			
	Estimated	58.1	100.4	67.0		35.8	40.9			
	Percent[a]	100.3	90.5	111.0		105.2	101.7			
Corn Belt	Actual		122.8	61.0	76.8	36.1	39.8	648.0		4480.0
	Estimated		111.9	68.4		39.3	44.1			
	Percent[a]		91.1	112.2		108.7	110.6			
Delta	Actual		71.8	70.0	44.5	25.2	38.0	768.8		4233.5
	Estimated					27.5	35.2	720.0		4301.2
	Percent[a]					109.3	92.7	93.7		101.6
Southern Plains	Actual	42.4	104.8	37.2	53.7	23.4	28.7	296.6	1606.8	4686.5
	Estimated		63.3	44.6		26.2	431.3	1469.0	4681.9	
	Percent[a]		60.4	82.9		91.4	145.4	90.5	99.9	
Northern Plains	Actual	50.6	99.4	56.1	64.4	30.2	37.3			
	Estimated	54.6	86.6	55.4	71.2	31.8	37.6			
	Percent[a]	107.8	87.1	98.7	110.4	105.3	100.6			
Mountains	Actual	60.6	126.5	55.4	40.6		57.4		1046.5	
	Estimated	65.8	142.0	63.2	35.3		55.2		1017.5	
	Percent[a]	108.5	112.3	114.1	86.8		96.1		97.2	
Pacific	Actual	61.5		70.2	77.0		54.7		1077.0	6700.0
	Estimated						49.4			
	Percent[a]						90.0			

[a] Estimated yield as a percent of the 1982 actual yield.

Table 3. Estimated Quantities and Prices for Selected Crops

Crop	Price		
	Estimated	Actual	Percent[a]
	dollars per bushel		
Barley	4.04	2.94	137.41
Corn	5.90	3.19	184.95
Cotton	.31[b]	.71[b]	43.66
Oats	2.63	1.82	144.51
Peanut	.2659[b]	.2659[b]	100.00
Rice	.3829[b]	.1257[b]	304.61
Sorghum	8.24	2.92	282.19
Soybeans	8.26	7.89	104.69
Wheat	5.27	4.38	120.32

[a] Estimated price as a percent of the 10-year average price.

[b] Dollars per pound.

Table 4. Price Demand Elasticities Used for Estimating the Benchmark Model

Crop	Demand elasticity	
	Domestic	Export
Barley	−.40	−1.51
Corn	−.70[a]	−1.31[a]
Cotton	−.12	−.80
Oats	−.85	NA[b]
Peanut	−1.60	−3.20
Rice	−.11	−1.30
Sorghum	−2.20[c]	−2.36[c]
Soybeans	−.30	−2.80
Wheat	−.55	−1.82

[a] Cross-price demand elasticity of corn with regard to sorghum is 0.14.

[b] Insufficient export volume to estimate elasticities.

[c] Cross-price demand elasticity of sorghum with regard to corn is 1.79.

with higher protein content, virus- and bacteria-resistant cultivars, and heat-tolerant cultivars will also cause a withdrawal of more than 20 million acres of land. According to solutions of the model, less land will be withdrawn with the introduction of cultivars that can establish symbiotic relationships with nitrogen-fixing bacteria, are resistant to insects, or are tolerant to frost and herbicides.

In general, agricultural production will become limited in areas with soils susceptible to erosion because land capability classes five and six will be withdrawn from production. It also may be that in some southern regions, insect-and-weed pressure may outpace the benefits of biotechnologies that lower pesticide use under the assumed crop mix. The use of new cultivars generally will increase the acreage allocated to row crops in the Corn Belt and the Southern Plains. In the Corn Belt, new cultivars will lead to larger production of commodities under consideration. But the comparative advantage of the Corn Belt will decrease with the introduction of bacteria-resistant and heat-tolerant cultivars elsewhere and the use of improved rhizobia strains. After commercialization of any of these twelve technologies, an increase in acreage planted

Table 5. Land Allocation Following Commercialization of Corn, Soybeans, Wheat, Sorghum, and Rice Cultivars Developed with Selected Biotechnologies

	Regions										
Technology	North-east	South-east	Appala-chia	Lake States	Corn Belt	Delta	Southern Plains	Northern Plains	Moun-tains	Pacific	Total
	thousands of acres										
Symbiotic	−148	−2013	−116	−779	+838	−130	+1922	−1631	0	0	−2057
New rhizobia strains	−5113	−2014	−109	−6188	−531	+55	+1722	−1306	−253	0	−13737
Altered protein	−40	−1551	0	−753	+817	−6430	−6746	−5912	−599	0	−21214
Bacteria-resistant	−20	−6522	−3321	−2504	−1414	−13091	+1722	0	0	0	−25150
Virus-resistant	0	−254	+369	+150	+1053	0	−28920	−5321	−8577	0	−24346
Fungus-resistant	−589	−1551	+9	−282	+817	−7648	+1714	−1231	−901	0	−10062
Insect-resistant	0	−1237	−7	−753	+817	0	−2521	−549	0	0	−4250
Frost-tolerant	0	−2013	0	+702	+838	−6400	+1722	0	0	0	−5151
Heat-tolerant	−5113	−2013	−352	−9717	−531	−6400	+1722	−2180	−648	0	−25232
Herbicide-tolerant	−37	−2013	−116	−839	+21	−6400	+1722	0	−207	0	−9591
Plant growth regulators	−681	−1551	−352	−3431	0	−4239	−2254	−7723	−3575	−5032	−28838
Ice-retarding bacteria	−965	−1551	−7	−1860	+817	−12351	+1722	−5316	−307	0	−19818

in the Southern Plains can be expected. Solutions obtained for the Southern Plains should be evaluated cautiously because of specification problems related to irrigated acreage.

Total Welfare Changes. The process of production and adjustment to a new market equilibrium leads to a change in the welfare of producers and consumers. Predicted changes were based on several simplifying assumptions. In particular, the quantities demanded by domestic and export buyers were expected to increase by no more than 50 percent above 1982 consumption. The domestic demand was assumed to be inelastic. Shifts in crop acreages among regions, changing crop mixes, and altered input use changed the production and price of each crop and determined the size of consumer and producer surpluses. Under these assumptions, an increased supply lowers the price and increases consumer surplus. But the producer surplus can change in either direction because of the interaction of production costs and input use (Tayler et al.).

The change in total welfare, measured as the sum of producer and consumer surpluses, differed with the technology applied (Table 6); but the average gain in the total surplus for all technologies in the model amounted to $13.4 billion. The total surplus — including both producer and consumer surpluses — will be the largest following commercialization of cultivars that contain higher amounts of protein, that are resistant to diseases caused by viruses and bacteria, or that react to PGRs.

According to the solutions of the model, total surplus was increased with the adoption of any of the technologies. Gains from seven of the technologies — symbiotic, fungus-resistant, insect-resistant, herbicide-tolerant, and frost-tolerant cultivars as well as ice-retarding bacteria and new rhizobia strains — were below the average of $13.4 billion. The other five technologies resulted in above-average increases in total surplus relative to the benchmark solution (Table 6).

Distributional Effects Among Sectors. Although adoption of all technologies produced an increase in total welfare, the distribution of welfare among producers and consumers differed with the nature of the new technology. Solutions of the twelve models indicated the largest gain to consumers was from the development and use of cultivars with altered protein content (Table 6). The consumer surplus increased by $51.1 billion. Producer surplus decreased by $835 million after the commercialization of cultivars with altered protein content, but the decrease was less than that for any other technology.

Another technology that resulted in large welfare gains to consumers was the development of virus-resistant cultivars. The gain of $35.2 billion in consumer surplus offset the decrease of $4.8 billion in producer surplus — the second largest of any biotechnology examined. The application of bacteria-resistant cultivars resulted in an increase in consumer surplus of $23.0 billion and a decrease of $3.8 billion in producer surplus.

Disease-resistant cultivars could bring some of the largest gains in consumer surplus. They also may cause some of the most significant decreases in producer surplus, but developing cultivars resistant to bacteria and viruses is not an easy task. The numbers of both viral and bacterial diseases are large, and absolute success is unlikely. Nevertheless, results of this study, stress the economic importance of disease-resistant cultivars.

The technology that resulted in the largest decrease of producer surplus, $5.0 billion, was the application of plant growth regulators. The increase in consumer surplus — a substantial increase, though not the largest one — amounted to $19.3 billion. The use of cultivars with a symbiotic mechanism for fixing nitrogen caused a medium-sized decrease in producer surplus, compared with the effects of other technologies. At the same time, the increase in consumer surplus with this biotechnology was one of the smallest ($4.7 billion).

Table 6. Consumer and Producer Surpluses Generated by the Application of New Technologies

Technology	Total surplus	Increase in total surplus[a]	Producer surplus	Decrease in producer surplus[b]	Consumer surplus	Increase in consumer surplus[b]
	.... *millions of dollars*		....	*percent*	*millions of dollars*	*percent*
Benchmark	156,868		49,064		107,804	
Symbiotic	158,536	1,668	46,023	−6	112,513	4
New rhizobia strains	161,125	4,257	45,421	−7	115,704	7
Altered protein	207,925	51,057	48,229	−2	159,696	48
Virus-resistant	187,241	30,373	44,244	−10	142,997	33
Bacteria-resistant	176,084	19,216	45,257	−8	130,827	21
Fungus-resistant	163,886	7,018	46,288	−6	117,598	9
Insect-resistant	166,798	9,930	44,274	−10	122,524	14
Frost-tolerant	168,611	11,743	46,628	−5	121,983	13
Herbicide-tolerant	158,779	1,911	46,385	−5	112,394	5
Heat-tolerant	161,962	5,094	44,974	−8	116,988	9
Plant growth regulators	171,100	14,232	44,015	−10	127,085	18
Ice-retarding bacteria	160,597	3,729	46,606	−5	113,991	6
Average[c]	170,220	13,352	45,695	−6.8	124,525	15.6

[a] Increase in total surplus when compared to total surplus generated in the benchmark model.

[b] Percentage change in surplus relative to the benchmark solution.

[c] Average was calculated for all technologies, excluding the benchmark model.

Among biotechnologies for stress tolerance, development of frost-tolerant cultivars, herbicide-tolerant cultivars, and ice-retarding bacteria caused relatively small decreases in producer surplus: $2.4 billion for frost-tolerant cultivars, $2.7 billion for herbicide-tolerant cultivars, and $2.5 billion for the development of ice-retarding bacteria. The gain in consumer surplus for the frost-tolerant technology was $14.2 billion; for herbicide-tolerant cultivars, it was $4.6 billion; and for the technology of ice-retarding bacteria, it was $6.2 billion.

Solutions were influenced by the methodological framework, the assumption about future demand, and the regional crop mix. Results indicated the existence of multiple optimal solutions, a natural occurrence in a competitive environment (Paris). Therefore, any future changes in agricultural policy, economic conditions, or technological development could alter the impact of commercial biotechnology used in agricultural production.

Distributional Effects Among Regions. Spatial distribution of aggregate income will vary among technologies. The withdrawal of large portions of acreage from production in the Delta and the Southeast can be expected to decrease the total farm revenue in those regions (Table 3). A similar situation will occur, to a lesser degree, in three other regions: the Appalachians, the Mountains, and the Northern Plains.

The production of major crops is likely to remain concentrated in the Lake States and the Corn Belt. As a result, a larger portion of the aggregate income will be received by midwestern producers. The effects of income concentration in the Corn Belt and the Lake States are strengthened by the cropping pattern that consists primarily of corn and soybeans, and to some extent, wheat. The model reflected the domination of the commodity markets by corn, soybeans, and wheat. Depending on government programs, land may be removed from production in the Delta and Southeast, or alternative crops may be introduced.

Shifts in the spatial distribution of income will generate a second wave of effects. Because new technologies will be neutral with respect to economies of size, benefits from their application will occur in proportion to acreage planted with new cultivars. New technologies may accelerate the trend toward larger farms. Also, if information about new technologies is not made equally available to all farmers, early adopters, who often are large farm operators, will be among the first to identify and use the opportunity for increasing their income.

Environmental Impacts. Application of all new technologies, except for new rhizobia strains and symbiotic nitrogen fixation, according to results of the international survey would lead to increased use of nitrogen, phosphate, and potash fertilizers. Plants can only use a portion of the fertilizer applied at any given time because their nutrient requirements are limited, because their root zone is finite, and because moisture often cannot be controlled. Therefore, increased use of fertilizers, particularly nitrogen, increases the content of undesired chemical substances in the soil. Leaching of nitrogen is particularly harmful because it causes water pollution and leads to additional costs related to upgrading water quality and maintaining drainage. Increased use of fertilizers as a result of some applications of biotechnology may not be welcomed by environmentalists, despite increased commodity supply and lower prices.

Application of cultivars resistant to viruses, bacteria, fungi, and insects would lower pesticide use. A decrease in the use of pesticides would slow down the development of mutant insects. It would also help to eliminate some fears of harmful pesticide residue in agricultural commodities.

Changes in plants will cause researchers to focus on manipulating specific, well-characterized genes (Brill). It seems unlikely that an addition of several genes to a plant could create a weed. In the opinion of experts, weeds require a large number of genetic traits in order to maintain their character. If any negative characteristics do occur, breeders can recognize them in a plant; and "because the genetic alteration in a recombinant plant is well-controlled, the likelihood of a problem is far less than [it is] in standard breeding practices" (Brill), which mix specific and uncharacterized genes of different plants. In addition, the safety of developing biotechnologies and their application has been assessed (Fiskel and Covello) and is regulated.

Conclusion

Model solutions suggest a decrease in total acreage used for the production of nine crops subject to the analysis following the introduction of biotechnology. Irrigated and nonirrigated land withdrawn from production is located in the Delta and Southeast and, to a smaller extent, in the Appalachian, Mountain, and Northern Plains regions. The affected regions represent a range of different climates and growing conditions that offers a potential for developing specialized agricultural production, which could potentially neutralize the negative effects on farm income.

A decrease in agricultural activity will slow the degradation of the environment. Replanting the withdrawn land with perennial or cover crops would lower soil erosion. The technologies presented in this paper that would cause the largest relocation of crops and prove beneficial from the standpoint of soil protection are the use of PGRs, heat-tolerant cultivars, bacteria- and virus-resistant plants, and cultivars with altered protein content.

The four technologies most beneficial to society, as measured by the change in total surplus are cultivars with altered protein content, virus- and bacteria-resistant cultivars, and cultivars responding to PGRs. This ranking was largely influenced by the size of consumer surplus, which was the highest for these technologies. All biotechnologies negatively affected producer surplus — the smallest effect being that from commercialization of cultivars with altered protein content, and the largest being the effect of widespread use of PGRs. Under the assumption of no change in demand, a larger volume of commodities causes lower gross income in the aggregate as a result of a decrease in prices. In the cost data used in this model, the new technologies did not sufficiently reduce the cost of production to compensate for lower prices.

The introduction of new technologies decreases aggregate farm income, as measured by producer surplus. But aggregate income of the agricultural sector in each region will be affected differently. A larger portion of total farm income will go to producers in the Midwest. Individual farm income may decrease or increase, depending on market price and skillful application of the new technologies. The reduction in farm income shown by the models is the direct result of increased supply under the assumed price elasticities. The negative effects on the producer sector can be alleviated by expanding demand, finding new uses, and controlling supply through government action; by transferring income from consumers, processors, and other groups that benefit from lower crop prices; and by lowering costs of production.

The impact of biotechnology as presented here illustrates a polar case of a long-term full adoption of twelve separate technologies applied to a limited number of field crops. The information about potential future land allocation and welfare changes contributes to the constantly expanding pool of knowledge concerning predictions of the impact of agricultural technology. Specifically, this study indicated to agricultural research administrators the perceived probabilities of developing different biotechnologies and economic impact of their commercialization. Allocation of research funds may be determined not only by the short-term success in developing a technology but also by its long-term welfare effects. Welfare effects, in turn, may not be limited to the easily quantifiable changes in total surplus. These may also include the technology on quality and sustainability of natural resources, such as unpolluted water or uneroded soil. Some of the biotechnologies considered in this study will lower pesticide use and withdraw land from agricultural production.

Policymakers may use the information from this study to formulate policy goals that would make the necessary adjustment easier and to fully explore benefits offered by the use of biotechnology in crop production. For example, programs for alternative land use or economic programs that sustain rural community growth may be needed as agriculture diminishes in importance.

For farm groups and checkoff programs, the results of this study suggest paying more attention to the demand for agricultural crops. Traditional food, feed, and fiber use of grains, oil crops, and cotton could be augmented by industrial uses of crops. Industrial use of agricultural crops would change the demand structure and create new markets. Checkoff funds applied toward research on new uses of commodities and on feasibility studies of new markets can make biotechnology work to the benefit of farmers.

References

Brill, W.J. "Safety Issues in Perspective" in *Biotechnology in Agricultural Chemistry.* Eds. H.M. LeBaron, R.O. Mumma, R.C. Honeycutt, and J.H. Duesing. Washington, D.C.: American Chemical Society, 1987.

Butler, L.J. "Current Status of Emerging Agricultural Biotechnologies." Unpublished paper presented at the American Association of Agricultural Economics Annual Meeting, August 1983.

Buttel, F.H. "Biotechnology and Genetic Information: Implications for Rural People and the Institutions That Serve Them." *The Rural Sociologist* 5(2):68-78.

Duloy, J.H., and R.D. Norton. "CHAC. A Programming Model of Mexican Agriculture" *in Multi-Level Planning: Case Studies in Mexico.* Eds. L. Goreux and A. Manne, pp. 291-337. Amsterdam: North Holland Publishing Co., 1973.

Fiksel, J., and V.T. Covello, eds. *Biotechnology Risk Assessment. Issues and Methods for Environmental Introductions.* New York: Pergamon Press, 1986.

Florkowski, W.J. "Economic Impact of Commercial Application of Biotechnology on Selected Crops." Dissertation, University of Illinois at Urbana-Champaign, 1986.

Harl, N.E. "Economic and Environmental Effects of Developments in Biotechnology." Unpublished paper given at the Western Agricultural Economics Association Annual Meeting, San Diego, July 9, 1984.

Hill, L.D., J. Stockdale, H.F. Breimyer, and G.E. Klonglan. *Economic and Social Consequences of Biological Nitrogen Fixation in Corn Production.* AE-4608. Urbana-Champaign: University of Illinois Department of Agricultural Economics and Illinois Agricultural Experiment Station, 1986.

Hueth, O.L., and R.E. Just. "Policy Implications of Agricultural Biotechnology." *American Journal of Agricultural Economics* 69(1987):426-431.

Hymowitz, T. Personal communication. May 12, 1986.

Kalter, R.J., and L.W. Tauer. "Potential Economic Impacts of Agricultural Biotechnology." *American Journal of Agricultural Economics* 69(1987):420-425.

Lambert, R.J. Personal communication. May 12, 1986.

Lu, Yao-chi, ed. *Emerging Technologies in Agricultural Production.* Washington, D.C.: USDA Cooperative State Research Service, 1983.

McCarl, B.A. "Cropping Activities in Agricultural Sector Models: A Methodological Proposal." *American Journal of Agricultural Economics* 64(1982):768-772.

Meredith, Jr., W.R., and R.R. Bridge. "Genetic Contributions to Yield Changes in Upland Cotton." *Genetic Contributions to Yield Gains of Five Major Crop Plants.* Proceedings of a Symposium Sponsored by Division C-1 of the Crop Science Society of America, 2 December 1981 in Atlanta, Georgia. CSSA Special Publication No. 7. Ed. W.R. Fehr. Madison, Wisconsin: Crop Science Society of America, 1984.

Miller, F.R., and Y. Kebede. "Genetic Contributions to Yield Gains in Sorghum, 1950 to 1980." *Genetic Contributions to Yield Gains of Five Major Crop Plants.* Proceedings of a Symposium Sponsored by Division C-1 of the Crop Science Society of America, 2 December 1981 in Atlanta, Georgia. CSSA Special Publication No. 7. Madison, Wisconsin: Crop Science Society of America, 1984.

Nicol, K.J. "A Modeling Approach to the Economic and Regional Impacts of Sediment Loss Control." Dissertation, Iowa State University, 1974.

Norton, R.D., and G.W. Schiefer. "Agricultural Sector Programming Models: A Review." *European Review of Agricultural Economics* 7(1980):229-265.

Rastegari-Henneberry, S. *The World Rice Market.* Giannini Foundation Information Series, No. 85-2. Davis: Giannini Foundation of Agricultural Economics/University of California Division of Agricultural Sciences, 1985

Safety in Biotechnology Working Party of the European Federation of Biotechnology. "Safe Biotechnology. General Considerations." *Applied Microbiology and Biotechnology* 21(1985): 1-6.

Samuelson, P.A. "Spatial Price Equilibrium and Linear Programming." *American Economics Review* 42(1):283-303.

Schmid, A.A. "Biotechnology, Plant Variety Protection, and Changing Property Institution in Agriculture." Unpublished paper presented at the American Association for the Advancement of Science Annual Meeting, New York, May 27, 1984.

Sundquist, W.B., K.M. Menz, and C.F. Neumeyer. *A Technology Assessment of Commercial Corn Production in the United States.* Station Bulletin 546-1982. St. Paul: Minnesota Agricultural Experiment Station, 1982.

Takayama, Takashi, and G.G. Judge. *Spatial and Temporal Price and Allocation Models.* Amsterdam: North-Holland Publishing Co., 1976.

Taylor, C.R., and K.K. Frohberg. "The Welfare Effects of Erosion Controls, Banning Pesticides, and Limiting Fertilizer Application in the Corn Belt." *American Journal of Agricultural Economics* 59(1977):25-26.

Taylor, C.R., P.J. van Blokland, E.R. Swanson, and K.K. Frohberg. *Two National Spatial-Equilibrium Models of Crop Production.* AERR 147, February 1977. Urbana-Champaign: University of Illinois Department of Agricultural Economics and Illinois Agricultural Experiment Station, 1977.

U.S. Congress. Office of Technology Assessment. *Technology, Public Policy, and the Changing Structure of American Agriculture.* March 1986. Washington, D.C.: Office of Technology Assessment, 1986.

U.S. Department of Agriculture. *FEDS Budget 1982.* September 1984. Stillwater, Oklahoma: USDA Economic Research Service — Oklahoma State University, 1984.

U.S. Department of Agriculture Soil Conservation Service. *Basic Statistics — 1977 National Resources Inventory.* Statistical Bulletin Number 686. December 1982. Ames: Iowa State University Statistical Laboratory, 1982.

U.S. Department of Agriculture Soil Conservation Service. Unpublished data on soil loss and yield adjustment for land resource areas and land capability units. 1975.

Allocation of Acreage Among Crops Included in the Benchmark Model

		Percent of land class allocated to specific crops								
Region	Land class[a]	Barley[a]	Corn	Cotton	Oats	Peanut	Rice	Sorghum	Soybeans	Wheat
Northeast	3w, 4s, 4w	0	80	0	20	0	0	0	0	0
	all others	0	73	0	13	0	0	0	0	0
Southeast	3w, 4w	0	20	0	0	0	0	0	80	0
	all others	0	20	5	0	7	0	0	50	23
Appalachia	3w	0	33	2	0	0	0	0	50	15
	all others	0	33	2	0	2	0	0	45	18
Lake States	2c, 6s, 7s	18	48	0	10	0	0	0	24	0
	6e, 7e	0	50	0	25	0	0	0	25	0
	all others	3	49	0	9	0	0	0	24	15
Corn Belt	all	0	50	0	0	0	2	0	40	8
Delta	all	0	0	5	0	0	0	0	70	25
Delta[b]	1, 2e, 2w, 3w	0	0	40	0	0	60	0	0	0
	3e, 3s	0	0	100	0	0	0	0	0	0
	4w	0	0	0	0	0	100	0	0	0
Southern Plains	1, 2w, 3w	0	2	35.5	0	1.5	0	15	0	46
	2e, 3e, 3s	0	4	16	0	0	0	20	0	60
	2s, 3w, 4w	0	2	19.5	0	0	0	19	0	59.5
	3c, 4s	0	0	19.5	0	0	0	19	0	61.5
	4c	0	4	16	0	0	0	20	0	60
Southern Plains[b]	1	0	17	60	0	0	0	20	0	0
	2e, 3e	0	20	35	0	0	0	45	0	0
	2w, 3w	0	0	0	0	0	70	30	0	0
	4w	0	0	0	0	0	100	0	0	0
	2s, 2c, 3s	0	0	53	0	12	0	35	0	0
Northern Plains	2c, 3c, 4w	0	0	0	0	0	0	0	0	0
	5, 6e, 6s, 6w	0	0	0	0	0	0	0	0	100
	all others	6	14	0	8	0	0	0	12	50
Northern Plains[b]	1, 2s	0	80	0	0	0	0	20	0	0
	all others	0	100	0	0	0	0	0	0	0
Mountains	2c, 3c	60	0	0	0	0	0	0	0	40
	all others	25	0	0	5	0	0	7	0	63
Mountains[b]	1, 2e, 2s, 2w	20	23	10	0	0	0	6	0	40
	3e, 4e, 4w, 2c	15	0	5	0	0	0	0	0	80
	3c	30	0	0	0	0	0	0	0	70
	3w	26	24	0	0	0	0	0	0	50
	3s, 4s	30	22	12	0	0	0	6	0	36
Pacific	all	0	0	0	0	0	0	0	0	100

[a] Land classes are those identified by the Soil Conservation Service. Numbers refer to productivity; letters refer to topography and erodibility [USDA, 1982].

[b] Irrigated.

1.5M–3-90–United Graphics–MET