Appendix A

The simulation assumed that demographic entries in the life table for the insect reflect individual probabilities for the event. For example, mortality was the probability that an individual in that stage would die per day. The total number of survivors of a group is the sum of successful Bernouli trials over all individuals in the group. A successful Bernouli trial is a drawing of a random number greater than the mortality rate (Kalos & Whitlock 1986). Thus:

$$N_{f,a+1,g,s} = \sum_{1}^{N_{f,a,g,s}} r(0,1) > M_{f,a,g}$$

where: N is the number in group, M is the mortality rate of group, f is the field, a is the age of group (given by stage and numbers of days in the stage), g is the genotype, s is the sex, and $r(0,1)$ is a uniform random number between 0 and 1. $[r(0,1) > M_{f,a,g}]$ evaluates to 1 if true, otherwise 0.

The resultant binomial distribution was simulated using a normal approximation to the binomial with an algorithm given by Kinderman & Ramage (1976). When the expected number of successes or failures was <10, a Poisson approximation was used, using an algorithm given by Knuth (1969). A 32-bit random number generator (Dudewicz et al. 1985) was used for the simulations.

FORUM

Estimating the Economic Value of Honey Bees (Hymenoptera: Apidae) as Agricultural Pollinators in the United States

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ABSTRACT The economic gains due to honey bee (*Apis mellifera* L.) agricultural pollination are evaluated. The method of analysis focuses on the gains to consumers through lower prices for crops that are benefited by honey bees. Economic demand functions for the major agricultural crops that are pollinated by bees are estimated. The amounts by which the yields of pollinated crops are increased are estimated from a variety of sources. In the final step, the surplus realized by consumers of these crops that would be lost if honey bees were depleted is determined. The annual social gains are estimated to range between $1.6 and $5.7 billion.

KEY WORDS Insecta, *Apis mellifera*, pollination, economics

IN NORTH AMERICA, there are well over five million honey bee (*Apis mellifera* L.) colonies managed by >200,000 hobby, sideline, and commercial beekeepers, and in the United States, over one million honey bee colonies are rented yearly for pollination services in agricultural crops (Free 1970; McDowell 1984; Robinson et al. 1989a, b). There are ≈2.2 million U.S. farms, with about 0.5 billion ha (one billion acres) under management, which gross $167 billion annually (in 1985 dollars) (USDA 1987). Demand for pollination services is greatest in monoculture and where hybrid seed is required. In most crops that are pollinated by insects, bees carry pollen from one plant to another, effecting cross pollination, and are the most numerous pollinating group. This is important for the production of various crops including vegetables, fruits, clovers, oilseeds, alfalfa seeds, nuts, and flower seeds. Pollinators are also required for seed production of many other crops such as soybeans, hay, and forage crops (McGregor 1976, Crane & Walker 1984). Most managed pollination services use honey bees because detailed management systems have been well developed, and the honey bee survives well in many natural habitats and managed environments. Further, of course, the honey bees produce a crop of honey and beeswax as well. There are also ≈3,500 native species of bees (Hymenoptera, Apoidea) in North America, and some of these have been developed as effective, managed pollinators (e.g., species of *Nomia*, *Osmia*, and *Megachile*) (Parker et al. 1976, 1987; Torchio 1987).

Hundreds of species of agricultural plants in 40 plant families, including ≈400 agricultural crops worldwide and about 130 crops in the United States, are pollinated, at least in part, by honey bees and other bees (McGregor 1976, Crane & Walker 1984). The economic value of honey bees as pollinators of crops has never been definitively established (Cheung 1973, Southwick & Southwick 1989). Levin (1983) estimated that the annual value of bee-pollinated crops approached $18 billion, but no estimate was made of the contribution to pollination actually performed exclusively by honey bees. Based on this publication, numerous authors of scientific and popular publications have subsequently stated that the annual value of agricultural crops that benefited by honey bee pollination is ≈$20 billion in this country, and that the yields of fruit, seed, and nut crops would decrease by >90% without the pollination services of honey bees (e.g., Morse 1987, O'Grady 1987, Olmstead & Wooten 1987, Applebome 1988, Camazine & Morse 1988). More recent studies (Robinson et al. 1989a, b) also generate large estimates for this value (≈$10 billion), although at about half of the earlier estimates.

It is clear that honey bees have often been credited with pollination services that are actually performed by other bee species (Duncan 1940, Parker et al. 1987). It has been known for decades that many other types of bees as well as other insects pollinate crops, but their economic value remains unknown, and they are little appreciated (Salt 1940, Peck & Bolton 1946, Butler et al. 1966, Klug & Buenemann 1983, Kevan 1987, Parker et al. 1987).

It is especially important to know the value of the honey bee at this time because of several factors which are affecting, or will soon signifi-

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cantly affect, their populations and their effectiveness in pollination. The importance of these factors cannot be estimated until we have a reasonable grasp of the economic value of the system they are likely to affect. These damaging factors include at least the following four:

(1) Mites that have been recently introduced in the U.S. are internal and external parasites of honey bees and are spreading rapidly (Needham et al. 1988).

(2) A number of diseases affect honey bees, the most significant of which are American foulbrood (AFB), caused by the bacterium *Bacillus larvae;* chalkbrood, caused by the fungus *Ascosphaera apis;* and nosema, caused by the protozoan *Nosema apis* (Shimanuki 1976).

(3) The northward-migrating populations of Africanized honey bees (hybrids and back-crosses between European races of *Apis mellifera* and the African *Apis mellifera scutellata* Ruttner) will directly affect honey bees managed for agricultural pollination and cause a negative public perception of all bees (Nogueira-Neto 1964, Roubik & Boreham 1990).

(4) Finally, there is increasing loss of both native and managed bees because of the increased use of pesticides (Johansen 1977, Erickson et al. 1983).

All of these factors together could create a formidable impact on our honey bee populations and their pollination activities.

Benefits to Society

If there were no honey bees, farmers who produce crops requiring or benefiting from honey bee pollination would soon experience decreased yields. To produce the same output of a given crop, it would be necessary to increase the use of other inputs such as land, fertilizer, labor, etc. This, of course, would raise the cost of producing the same level of output.

In addition to pollinating crops, honey bees produce valuable honey and beeswax. If there were no honey bees, these products would not be available domestically, and their losses could not be made up at a higher cost by adding more of other factors. Substitutes such as plant sugars and other waxes would have to be used. Possibly these losses could be made up by imports from other countries. Costs then would be borne by the consumers who would pay a higher price, and by the beekeepers who would lose profits.

Finally, bees pollinate vegetation which enhances property values in wilderness, urban, and watershed areas. We are unable to estimate how much of this is due to honey bees or its value to U.S. society.

To ascertain the benefits received by the producers and consumers of the affected agricultural products, the effects on the demand and supply curves for the various commodities must first be determined. The long-run aggregate supply curve for an agricultural commodity is likely to be almost perfectly elastic (horizontal) (shown in Fig. 1 as $Supply_0$). This is true because more fields or more farmers can switch to growing a particular crop at approximately the same cost as those who currently produce that crop. If costs fall more than prices drop for a specific crop, enough additional farmers will switch to that crop to reduce prices by the cost decrease. If costs fall by less than prices fall for a particular crop, enough farmers will switch from that crop to cause the prices to fall as much as costs fall. (Of course, as prices rise for these crops, there will be some increase in their consumption and, therefore, more farmers will be needed for those crops. There may be some switching from non-honey bee-pollinated crops, both by the consumers and consequently by farmers.) It should be noted that honey bee-pollinated crops are a relatively small proportion of all agricultural commodities, so the assumption of a very elastic supply (long run) has validity. There is enough supply of uncultivated arable land to add substantially to the amount used for these crops.

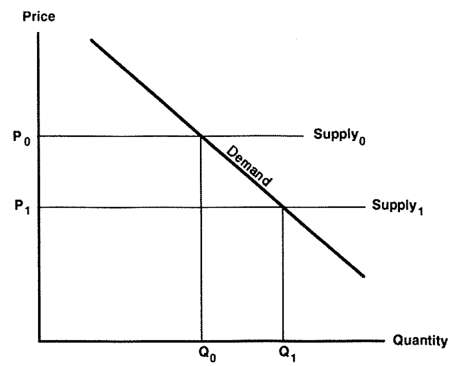

Fig. 1. Societal gain due to lower costs for agricultural crops pollinated by honey bees.

The use of honey bees causes a field to produce $X\%$ more than it would have produced without the honey bees. All other costs for that field (not including any pollination charges) may be assumed to remain the same. The result is that costs for that farmer to produce a unit of that crop will fall by $100\,X\,/\,(100 + X)\%$. If all farmers are subject to this cost decrease, in the long run it follows that prices for this crop will fall by the same percentage. Enough farmers will stop producing this crop or will enter the business of producing this crop to ensure that, in the long run, the price drop just equals the cost decrease. The demand curve will then determine the change in the aggregate output. This is shown in Fig. 1, where $Supply_1$ is below $Supply_0$ by $100\,X\,/\,(100 + X)\%$ because of the $X\%$ increase in productivity, which is due to the presence of the honey bees. Because of the given demand curve, the aggregate quantity demanded rises from Q_0 to Q_1.

The information is now adequate to calculate the long-term societal gain due to honey bees. The farmers have gained nothing because they are still producing at a zero economic profit. The consumers, however, are paying a lower price for the product and are consuming more of it. Their gain can be divided into two parts. First, consider those consumers who are still buying Q_0 of the product. For them, the price has fallen from P_0 to P_1, so they are gaining an amount equal to $Q_0\,(P_0 - P_1)$ (Fig. 1).

The second part of the gain is to those new consumers who now buy the product but did not previously. They now receive a consumers' surplus in that they are able to pay less for the product than its value to them. The value to these consumers is represented by the demand curve while they pay a price of P_1. The consumers' surplus (CS) that is gained is given by;

$$CS = \int_{Q_0}^{Q_1} [P(\text{demand}) - P_1]dQ \qquad (1)$$

The two gains added together represent the societal gain and are equivalent to the area in Fig. 1 between P_0 and P_1 to the left of the demand curve. Because the demand curve is based on annual data, it is an annual societal gain which is calculated. To a small extent, this misstates the value of consumers' surplus. Actually, the demand curve should be income compensated. Because the crops in question involve only a small part of the aggregate consumer budget, the error is sufficiently small to be ignored.

Fig. 1 shows one general case. There is another in which P_0 is above the intersection of the demand curve with the price axis. In that case, because the price without bees would be too high, none of the commodity would initially be consumed. The result is that the gain to the continuing consumers is nonexistent, and all of the gain is in the new consumers' surplus.

Were the demand curve to be perfectly inelastic, the gain would be equal to the amount $Q_1\,(P_0 - P_1)$. Because $P_0 = P_1\,(100 + X)/100$, $P_0 - P_1 = P_1\,X/100$. The gain, which is the largest possible, is then equal to $P_1Q_1\,X/100$. That is, the maximum gain is equal to the current revenue times the proportion that productivity increased when honey bees are present. The actual gain will generally be less than that.

In the general case, the aggregate gain is given by;

$$Gain = Q_0(P_0 - P_1) + \int_{Q_0}^{Q_1} [P(\text{demand}) - P_1]dQ \qquad (2)$$

This aggregate gain can be rewritten after some algebraic manipulation as

$$Gain = (P_0Q_0 - P_1Q_1) + \int_{Q_0}^{Q_1} [P(\text{demand})]dQ \qquad (3)$$

The first term of equation (3) is the difference in revenues to the farmers without honey bees and the revenues with honey bees. The second term is the value placed on the product by those consumers who will buy at the lower price resulting from honey bee pollination and who would have been priced out of the market at the higher price if there were no honey bees.

We would like to compare this gain to that calculated by an incorrect procedure in previous papers on the subject (e.g., Robinson et al. 1989a, b). Generally, those authors have taken the current level of output (using honey bees) and have asked what the loss would be if honey bees were to be no longer used. The calculated difference between the gain and the loss is more than semantics, because a 25% gain using the no-bee base would be equivalent to a 20% loss using the current bee base. Thus, it is appropriate to restate the loss figure in terms of the gains from the no-bee base.

Let Y be the output loss percentage if bees are removed. This translates to a gain percentage X equal to $100\,Y/(100 - Y)$. The previous papers generally calculate this gain using the current (with bees) revenue, along with the anticipated reduction Y in output for each farmer. Their bee value was thus

$$Value = P_1Q_1\left(\frac{X}{100 + X}\right) \qquad (4)$$

This is somewhat less than the correct value if demand is highly inelastic, but it may well be greater than the correct value if demand is more elastic. Only by chance could they equal the correct value as given in equations (2) and (3). In two recent papers, Robinson et al. (1989a, b) made this error. Using their values, we commented on the result but did not develop precise estimates (Southwick & Southwick 1989). Note that a reduction in output will *increase* the crop value if demand is inelastic. We cannot infer social gains or losses simply from the gains or losses to farmers.

At this point, the gains can be calculated according to equation (2) or (3) for those crops that are directly benefited in yield by honey bees.

Table 1. Tables numbers (USDA 1974, 1980, 1987) used for demand data

Crop	1987	1980	1974
Fruits and nuts	Table	Table	Table
Almond	339	385	—
Apple	254	207	292
Apricot	260	302	299
Avocado	266	308	304
Bushberry	—	311	—
Cherry	269	313	305
Cranberry	286	331	320
Grape	206	335	324
Grapefruit	275	319	310
Lemon	275	319	310
Lime	275	319	310
Macadamia	343	389	—
Nectarine	296	341	328
Orange	275	319	310
Peach	299	344	330
Pear	306	351	336
Pomegranate	314	360	—
Plum (Calif.)	313	363	345
Plum–prune (other)	315	361	343
Prune (Calif.)	317	364	346
Strawberry	323	369	351
Tangelo	275	319	310
Tangerine	275	319	310
Temple	275	319	310
Seed crops			
Cottonseed*	139	150	158
Flax*	145	156	164
Peppermint*	181	192	432
Soybean*	166	178	186
Spearmint*	182	193	432
Sunflower*	176	188	—
Other crops			
Carnation*	358	404	381
Gladioli*	358	404	381
Roses*	358	404	381
Chrysanthemum*	358	404	381
Pompon chrysanthemum*	358	404	381
Tea rose*	358	404	381
Mini carnation*	358	404	381
Vegetables	Table	Table	Table
Artichoke*	—	216	219
Asparagus*	—	217	220
Beans, snap	201	221	224
Beans, dry	372	425	404
Beans, lima	—	220	223
Beet*	—	223	226
Broccoli*	203	225	228
Brussels sprouts*	—	227	230
Cabbage*	—	228	231
Cantaloupe	—	230	233
Carrot*	206	232	235
Cauliflower*	207	235	238
Cucumber	213	241	244
Honeydew	215	246	249
Lettuce*	218	249	252
Onion*	219	253	255
Sweet potato	233	270	269
Watermelon	—	278	275
Ladino clover*	—	417	—
Lespedeza*	—	417	393
Red clover*	—	417	393
Sweet clover*	—	—	393
Forage			
Alfalfa*	—	417	393
Crimson clover*	—	417	—
Hairyvetch*	—	417	—

*, pollination needed for seed only.

Some crops, such as alfalfa, are not increased in yield directly but have only their seed production increased. In those cases, the costs of seed will fall as a result of the increased yield of seed, and the price of seed will fall accordingly.

To calculate the gain due to the increase in seed, we need to find out how much the price of the final crop will fall. Where the yield of the crop was increased by X%, we found earlier that the price of the crop would fall by $100X/(100 + X)$%. If the seed comprises W% of the cost of producing the crop, an increase of X% in the yield of seed will, in a corresponding fashion, lower the costs of the crop and the price by $XW/(100 + X)$%. For example, suppose seed is 5% of the cost and seed output increases by 25%. Then the crop price will fall by 1.00%. In some cases, of course, the seed either is itself, or is included in, the entire product. The major fruits and cottonseed are examples. Because the seed is the crop, the cost of the seed is the cost of the crop.

Estimating Demand Functions

A large number of agricultural commodities are pollinated at least partially by honey bees. This section is devoted to estimating the demand functions for the most important ones.

The first step is to recognize that the price of these commodities is determined by the amounts produced. Whatever amount is planted, the later harvest is affected by weather and many other factors. At harvest time, a price results from the quantities that are marketed interacting with the demand curve. Thus, the price is the dependent variable with the quantity as the independent variable. Further, the time when the size of the crop is determined precedes the time when the price is determined. Therefore, unlike most commodities, the price and quantity are not determined simultaneously. It follows that there is no need for a multiequation model, and we can estimate a single demand equation. (We have tried a simultaneous equation model with expected quantity supplied as a function of price and costs for a few crops. The results differed little from the single equation model.)

Table 2. Years of data used to estimate demand functions

Crop	Years
Fruits and nuts	
Almond	1965–1986
Apple	1959–1986
Apricot	1959–1986
Avocado	1959–1986
Bushberry	1965–1977
Cherry	1959–1986
Cranberry	1959–1986
Grape	1959–1986
Grapefruit	1962–1985
Lemon	1962–1985
Macadamia	1965–1986
Nectarine	1959–1986
Orange	1962–1985
Peach	1959–1986
Pear	1959–1986
Pomegranate	1965–1986
Plum (Calif.)	1959–1986
Plum–Prune (other)	1959–1986
Prune (Calif.)	1959–1986
Strawberry	1959–1986
Tangelo	1962–1985
Tangerine	1962–1985
Temple	1962–1985
Vegetables	
Artichoke	1959–1979
Asparagus	1959–1979
Bean, dry	1959–1986
Bean, snap	1959–1986
Bean, lima	1959–1979
Beet	1959–1979
Broccoli	1959–1986
Brussels sprouts	1959–1979
Cabbage	1959–1978
Cantaloupe	1959–1979
Carrot	1959–1986
Cauliflower	1959–1986
Celery	1959–1986
Cucumber	1959–1979
Eggplant	1959–1979
Honeydew	1959–1986
Lettuce	1959–1986
Onion	1959–1986
Sweet potato	1959–1986
Watermelon	1959–1979
Forage crops	
Alfalfa	1959–1979
Crimson clover	1963–1979
Hairyvetch	1965–1979
Ladino clover	1965–1979
Lespedeza	1959–1979
Red clover	1959–1979
Sweet clover	1959–1971
Seed crops	
Cottonseed	1959–1986
Flax	1959–1986
Mint	1959–1986
Soybean	1959–1986
Sunflower	1962–1986
Other Crops	
Carnation	1968–1986*
Chrysanthemum	1966–1986*
Gladioli	1971–1986*
Mini carnation	1968–1986*
Pompon chrysanthemum	1966–1986*
Rose, sweetheart	1968–1986*
Tea rose	1968–1986*

*, except 1982–1983.

Because the best form of the demand equation to choose is unknown, a Box and Cox form is used to let the data pick it (Judge et al. 1980). This form is given generally as

$$P^b = a_0 + a_1Q^b + a_2Y^b \qquad (5)$$

where P is price, Q is quantity, Y is income, and b and a_i are parameters.

The use of the parameter b allows for a variety of forms. At values close to zero, the equation approaches a log-linear function. At larger positive values for b, the demand curve becomes more elastic at higher prices; at larger negative values for b, the demand curve becomes more inelastic at higher prices. Despite this, the final loss results do not exhibit a great deal of sensitivity to the value chosen for b. A value was estimated for b for each crop by a sequential approximation method to find the best-fitting equation.

The data for income are in 1982 dollars (Council of Economic Advisors 1989). The data for Consumers' Price Index are from the same source and are based on 1967 dollars (Council of Economic Advisors 1988). The data for the relevant crops are from the U.S. Department of Agriculture (USDA 1974, 1980, 1987). Table 1 lists the crops and the relevant tables for the particular years. The crops are divided into the categories fruits and nuts, vegetables, forage, seed crops, and other. The years of annual data available for each of the crops are listed in Table 2.

It is also the case for many crops that part of the harvest in one year may be held over and may therefore affect the price in the following year as well as the price in the current year. Accordingly, a generalized least squares procedure (Judge et al. 1980) was used to check on the first-order serial correlation. If there was significant serial correlation, the value of that correlation was computed as s. The results of these regressions are given in Table 3. In addition to the Box and Cox b, the coefficients $a_0 - a_2$ are given. The value of s, the serial correlation, is given if it is significant. The proportion of the variance explained is given as r^2_A which is adjusted for the degrees of freedom used up in the regression. Finally, the average demand elasticity is given for each crop.

An important caveat is that each of these demand functions has been estimated independently. As a result, for example, the effect that production of oranges has on the price of apples is unknown. Any attempt at a more complex estimation with all of the necessary interaction terms would have encountered insufficient available data, so this has not been done. The result may be that demand curves have been estimated

Table 3. Demand function coefficient estimates for equation of form $P^b = a_0 + a_1 Q^b + a_2 Y^b$

Crop	b	a_0	a_1	a_2	s	r^2_A	Elasticity
Fruits and nuts							
Almond	−0.2	0.2448	−0.8089**	+2.2703	+0.49	0.475	−1.69
Apple	(ln)	11.2477**	−1.6978**	+0.6956**	+0.58	0.692	−0.59
Apricot	+1.1	410.45**	−1.685e−4*	−3.283e−2*	+0.37	0.321	−2.34
Avocado	+0.3	−7.419e−2	−1.6097**	+1.2788**	+0.66	0.951	−0.84
Bushberry	+0.4	0.9820**	−8.562e−2*	—	—	0.359	−1.10
Cherry, sweet	+0.5	29.679**	−0.7192**	−0.1025	+0.49	0.780	−2.14
Cherry, tart	−0.3	1.0869**	−2.9401**	—	—	0.520	−0.86
Cranberry	+5.0	4.1911e+5*	8.364e−13	—	+0.74	0.657	NA
Grape	+0.8	31.771*	−3.583e−2**	+7.104e−2*	+0.75	0.694	−1.19
Grapefruit	+1.6	4.3862*	−2.066e−3	−6.743e−6*	—	0.235	−4.72
Lemon	+0.5	2.669**	−9.265e−3**	—	+0.62	0.816	−1.96
Lime	+0.5	1.4687*	−5.527e−2**	+4.399e−2*	+0.66	0.661	−2.00
Macadamia	+7.2	4.944e+9	−1.010e−23	−7.973e−15	+0.68	0.580	−34.11
Nectarine	+1.3	2.531e+2*	−0.963**	+4.234e−2**	+0.32	0.544	−1.21
Orange	−0.1	1.520**	−1.966**	—	+0.44	0.689	−1.52
Peach	+3.5	7.054e+2**	−1.745e−10**	−4.214e−10*	+0.56	0.650	−1.44
Pear	+0.7	54.309**	−0.3080**	—	+0.56	0.762	−0.80
Pomegranate	+1.4	3.411e+2	−5.830e−4*	+1.405e−2	—	0.074	−2.70
Plum (Calif.)	+1.0	210.798**	−1.4507**	+7.935e−2**	+0.47	0.705	−0.96
Plum–Prune (other)	+1.7	6.877e+3**	−1.712**	−7.024e−3**	+0.27	0.455	−1.09
Prune (Calif.)	−0.2	0.6213**	−0.3885**	−0.6839*	+0.59	0.647	−2.24
Strawberry	−0.3	0.6402**	−3.0196**	—	—	0.854	−1.88
Tangelo	−0.5	0.3711*	−7.765**	+22.101*	—	0.757	−3.19
Tangerine	+0.5	2.544**	−1.719e−2**	—	—	0.377	−2.79
Temple	+0.9	4.763**	−1.008e−3*	−1.441e−3*	—	0.332	−2.05
Vegetables							
Artichoke	+11.5	1.558e+11	−1.097e−21**	+4.105e-26**	−0.19	0.753	−2.31
Asparagus	+1.6	1.656e+2**	−1.849e−4**	—	+0.26	0.799	−1.49
Beans, dry	−1.3	0.1215**	−1.938e+4**	—	+0.63	0.477	−1.14
Beans, snap	+0.6	19.458**	−1.794e−3	—	+0.67	0.649	−2.75
Beans, lima	−9.4	9.31e−22**	+2.376e+23	+4.798e+7*	+0.39	0.199	NA
Beet	+2.75	3.133e+3**	+5.346e−4*	—	+0.40	0.183	NA
Broccoli	+2.7	341.89**	−4.146e−9**	+9.834e−8**	—	0.793	−9.76
Brussels sprouts	+10.9	3.134e+11**	−7.451e−22	—	+0.15	−0.019	−34.42
Cabbage	+8.8	4.008e+4*	−3.614e−8*	+8.636e−25**	−0.49	0.617	−0.28
Cantaloupe	+3.0	340.71**	−8.565e−2**	—	+0.32	0.647	−1.18
Carrot	−0.9	0.5205**	−1463.8**	—	+0.23	0.417	−1.57
Cauliflower	+0.7	3.5295**	−3.420e−3**	+1.040e−2**	+0.63	0.774	−4.25
Cucumber	+9.0	2.151e+7**	−6.272e−27*	+4.025e−23*	+0.31	0.237	−1.96
Honeydew	+0.4	2.0803**	−4.227e−2*	−4.125e−2**	—	0.696	−2.05
Lettuce	−2.4	4.760e−2**	−5.963e+9**	+8.749e+5*	—	0.284	−0.90
Onion	+0.2	2.4491**	−0.4509**	+0.5298**	—	0.504	−0.37
Sweet potato	(ln)	18.9266**	−1.4541**	−0.4847**	+0.37	0.559	−0.69
Watermelon	+0.2	2.2821**	−0.2248**	—	—	0.773	−0.66
Forage							
Alfalfa	−0.7	0.2084**	−4.3267**	—	+0.29	0.754	−0.52
Crimson clover	+0.3	8.0962**	−0.15013**	−0.3713**	+0.43	0.785	−1.20
Hairyvetch	+1.0	17.865**	−0.3777*	—	+0.66	0.601	−2.83
Ladino clover	−2.0	5.685e−4**	−9.368e+3**	—	+0.50	0.790	−0.80
Lespedeza	−0.8	0.30176**	−0.9994**	−47.663*	—	0.801	−1.51
Red clover	−1.4	1.416e−2**	−1.4466**	—	—	0.633	−1.56
Sweet clover	+1.3	52.777**	−0.1455	−2.465e−3*	+0.38	0.470	−2.69
Seed crops							
Cottonseed	−1.4	1.2378e−2**	−421.41*	−123.43	+0.52	0.437	−1.48
Flax	−0.1	2.1873**	−0.7497*	−2.0938*	+0.67	0.564	−3.19
Peppermint	−0.9	+0.3436**	−1.104e+2	—	+0.82	0.577	−3.46
Soybean	+0.46	1.5554*	−1.550e−2*	+1.498e−2	+0.69	0.409	−1.57
Spearmint	+1.65	16.635**	−1.797e−5*	—	+0.74	0.565	−3.48
Sunflower	−0.8	0.3318**	−1.794e+2	—	+0.59	0.431	−159.3
Flowers							
Carnation	−0.7	0.7858**	−613.19	−82.245**	—	0.767	−4.83
Chrysanthemum	+1.9	4.5095e+2**	−1.520e−8*	−1.179e−4**	+0.40	0.828	−2.35
Gladioli	−2.0	6.543e−2**	−2.248e+8*	−1.080e+5**	—	0.580	−4.89
Mini carnation	+0.6	1.128**	−1.883e−3**	—	+0.28	0.926	−2.60
Pompon chrysanthemum	+0.7	1.692**	−2.668e−5	−4.799e−3**	+0.29	0.945	−17.28
Rose, sweetheart	+2.6	3.560e+2	−5.550e−12*	−1.455e−7**	—	0.547	−2.73
Tea rose	−0.8	0.2226	−9.699e+2	−17.682**	+0.21	0.709	−3.74

*, significant at 10% level (one-tailed t test); **, significant at 1% level (one-tailed t test).

Table 4. Societal losses at various production cuts

Crop	1986 value	% Seed cost[c]	Cut in output				
			0.1	0.3	0.5	0.7	0.9
Fruits and nuts							
Almond	461.6	—	47.0	149.0	271.3	444.2	847.0
Apple	1,068.3	—	115.0	410.4	856.7	1,664.1	4,097.6
Apricot	22.0	—	1.5	1.5	1.5	1.5	1.5
Avocado	153.5	—	16.5	58.9	121.2	223.0	403.6
Bushberry	111.1[a]	—	11.5	36.9	63.2	80.4	81.3
Cherry, sweet	112.8	—	11.3	32.2	44.2	44.8	44.8
Cherry, tart	50.1	—	5.3	18.5	37.8	72.6	192.2
Cranberry	194.6	—	21.6	83.4	194.6	454.1	1,751.4
Grape	1,170.1	—	122.2	390.9	615.9	632.7	632.7
Grapefruit	335.1	—	27.4	30.5	30.5	30.5	30.5
Lemon	218.1	—	21.1	54.6	64.7	64.7	64.7
Lime	21.0	—	2.1	6.1	8.7	8.9	8.9
Macadamia	35.2	—	3.8	5.6	5.6	5.6	5.6
Nectarine	75.7	—	8.0	25.9	35.5	35.5	35.5
Orange	1,074.1	—	110.4	353.9	647.3	1,047.9	1,850.2
Peach	326.8	—	28.2	28.2	28.2	28.2	28.2
Pear	199.4	—	21.3	73.5	139.5	193.6	194.1
Pomegranate	8.6	—	0.9	3.0	4.1	4.1	4.1
Plum (Calif.)	99.9	—	10.5	34.5	54.5	55.0	55.0
Plum–Prune (other)	11.3	—	1.2	3.2	3.2	3.2	3.2
Prune (Calif.)	78.4	—	7.8	23.7	41.0	63.2	108.7
Strawberry	503.6	—	49.6	147.7	254.6	397.6	737.5
Tangelo	19.0	—	1.8	5.2	8.8	14.0	29.3
Tangerine	48.3	—	4.4	9.6	10.1	10.1	10.1
Temple	15.9	—	1.6	3.7	3.8	3.8	3.8
Forage seed							
Alfalfa	170.5[a]	—	18.5	67.5	147.3	315.4	1,058.8
Crimson clover	3.5[a]	—	0.4	1.2	2.1	3.0	3.3
Hairyvetch	2.9[a]	—	0.2	0.2	0.2	0.2	0.2
Ladino clover	7.1[a]	—	0.8	2.7	6.0	13.2	48.2
Lespedeza	6.7[a]	—	0.7	2.5	5.2	10.6	33.6
Red clover	25.2[a]	—	2.7	9.5	20.4	43.5	151.8
Sweet clover	2.4[b]	—	0.2	0.4	0.4	0.4	0.4
Seed crops							
Cottonseed	298.4	—	30.8	104.6	216.9	449.0	1512.3
Flax seed	41.0	—	3.9	10.4	15.6	20.0	24.6
Peppermint	46.0	20	1.0	3.3	6.6	12.0	28.6
Soybean seed	9,326.2	—	970.1	3,094.2	5,086.0	5,626.3	5,626.3
Spearmint	28.4	20	0.6	2.3	5.0	8.9	9.0
Sunflower seed	185.2	–	2.0	2.7	3.4	5.0	6.7
Flowers							
Carnation	39.4	5	0.2	0.8	1.8	3.9	10.9
Chrysanthemum	19.5	5	0.1	0.4	0.9	1.9	2.6
Gladioli	26.4	5	0.1	0.5	1.2	2.5	7.6
Mini carnation	16.5	5	0.1	0.3	0.8	1.8	5.7
Pompon chrysanthemum	35.5	5	0.2	0.7	1.3	1.8	1.8
Rose, sweetheart	26.0	5	0.1	0.5	1.2	2.4	2.5
Tea rose	124.7	5	0.7	2.6	5.6	11.8	32.5
Vegetables							
Artichoke	36.6[a]	20	0.8	2.9	3.0	3.0	3.0
Asparagus	143.9[a]	24.3	3.7	11.2	12.6	12.6	12.6
Beans, dry	431.2	—	43.8	144.5	292.2	589.3	1918.5
Beans, snap	97.3	—	9.3	22.5	24.3	24.3	24.3
Beans, lima	46.3[a]	—	5.1	19.8	46.3	108.0	416.7
Beet	16.1[a]	12.6	0.2	0.9	2.0	4.7	18.6
Broccoli	227.2	2.4	0.6	2.3	5.4	12.5	44.9
Brussels sprouts	25.0[a]	20	0.2	0.2	0.2	0.2	0.2
Cabbage	264.7[a]	0.7	0.2	0.8	1.8	4.2	8.1
Cantaloupe	209.0[a]	—	21.5	38.1	38.1	38.1	38.1
Carrot	228.0	2.8	0.7	2.7	6.2	14.0	47.7
Cauliflower	188.5	4.3	0.9	3.4	7.7	16.6	41.7
Cucumber	112.9	—	11.8	13.1	13.1	13.1	13.1
Honeydew	69.5	—	7.2	22.8	38.7	48.3	48.6
Lettuce	719.1	1.0	0.8	3.1	7.1	16.5	59.4
Onion	371.4	8.0	3.3	12.7	29.3	67.2	240.4
Sweet potato	130.8	—	14.0	49.4	101.2	191.2	440.9
Watermelon	167.7[a]	—	17.9	62.8	126.5	226.7	409.9

[a] Value in 1979 multiplied by 1.51058 to adjust for CPI.
[b] Value in 1971 multiplied by 2.70734 to adjust for CPI.
[c] Commercial Seed Catalog, 1989, Rochester, N.Y., 1989. Harris–Moran Seed Company.

Table 5. Estimated fraction of crops lost without honey bees.

Crop	Crop loss estimate: No replacement[a]	Expected[b]	Robinson[c]	References[d]
Fruits and nuts				
Almond	0.9	0.5	1.0	2, 3, 4, 17, 18, 22, 23, 30, 31, 32, 33, 34
Apple	0.8	0.3	0.9	2, 3, 4, 9, 16, 21, 22, 23, 26, 30, 31, 33
Apricot	0.5	0.3	0.6	9
Avocado	0.2	0.1	0.9	2, 3, 4, 9, 30
Bushberry	0.7	0.2	0.8	2, 3, 4, 9, 11, 14, 18, 22, 23, 30, 33
Cherry	0.6	0.3	0.8	2, 3, 4, 9, 11, 18, 21
Cranberry	0.4	0.3	0.8	2, 3, 4, 9
Grape	0.15	0.0	0.0	2, 3, 4, 9, 18, 22, 23, 27, 28, 29, 30, 31
Grapefruit	0.5	0.2	0.7	9
Lemon	0.5	0.3	0.2	9
Lime	0.5	0.3	0.3	18
Macadamia	0.2	0.0	0.8	18
Nectarine	0.3	0.2	0.5	9, 21
Orange	0.3	0.1	0.3	9
Peach	0.2	0.1	0.5	2, 3, 4, 9, 18, 21
Pear	0.5	0.3	0.6	2, 3, 4, 9, 16, 21, 30
Pomegranate	0.1	0.0	NA	17
Plum–prune	0.5	0.3	0.6	2, 3, 4, 18, 21
Strawberry	0.3	0.2	NA	9, 18, 26
Tangelo	0.2	0.1	0.4	9
Tangerine	0.2	0.1	0.5	9
Temple	0.2	0.1	0.3	9
Seed crops				
Cottonseed	0.3	0.2	0.2	2, 3, 4, 9, 13, 35, 36, 37
Flax	0.01	0.0	NA	9
Mint	0.1	0.01	NA	18
Soybean	0.01	0.0	0.1	2, 3, 4, 9, 18
Sunflower	0.8	0.5	0.9	2, 3, 4, 9, 18, 22, 23, 30, 33
Vegetables				
Artichoke	0.1	0.0	NA	18
Asparagus	0.9	0.1	0.9	1, 9, 18
Bean	0.1	0.03	NA	9, 18
Beet	0.1	0.0	NA	9
Broccoli	0.9	0.5	0.9	2, 3, 4, 9, 22, 23, 30, 33
Brussels sprouts	0.9	0.5	NA	2, 3, 4, 8, 9, 18
Cabbage	0.9	0.5	NA	2, 3, 4, 24
Cantaloupe	0.7	0.5	0.7	2, 3, 4, 9, 20
Carrot	0.6	0.1	0.9	2, 3, 4, 9, 10, 18, 30
Cauliflower	0.9	0.5	0.9	2, 3, 4, 9, 18
Cucumber	0.6	0.3	0.8	2, 3, 4, 9, 11
Honeydew	0.8	0.5	0.7	2, 3, 4, 18
Lettuce	0.03	0.0	NA	9, 18
Onion	0.3	0.2	0.9	2, 3, 4, 9, 36
Sweet potato	0.1	0.02	NA	9, 18
Watermelon	0.4	0.1	0.6	7, 9, 11
Forage crops				
Alfalfa	0.7	0.2	0.6	2, 3, 4, 5, 6, 9, 12, 15, 18, 19, 22, 23, 25, 30, 33
Crimson clover	0.5	0.3	NA	2, 3, 4, 9
Hairyvetch	0.1	0.01	NA	9
Ladino clover	0.2	0.1	NA	2, 3, 4, 9, 22, 23, 30, 33
Lespedeza	0.01	0.0	NA	2, 3, 4, 9
Red clover	0.25	0.12	NA	2, 3, 4, 9
Sweet clover	0.1	0.05	NA	2, 3, 4, 9, 22, 23, 30, 33
Other crops				
Cut flowers	0.13	0.1	NA	2, 3, 4

[a] Expected losses without honey bees or any replacement insects, and no change in currently managed and unmanaged alternate pollinators. No loss would be a value of 0; no crop would be a value of 1.0.

[b] Losses under the most realistic scenario with 50% loss of European honey bees in northern states due to mites and diseases, and 100% loss of European honey bees in southern states due to Africanized honey bee population expansion, along with some increased use of alternate pollinators, including feral Africanized honey bees.

[c] Robinson et al. (1989b); NA, not available.

[d] Numbers refer to references as follows: 1. G. S. Ayers, Michigan State University (personal communication). 2. S.W.T. Batra, USDA, Beltsville (personal communication). 3. Batra (1982). 4. Batra (1976). 5. Bohart (1972). 6. Bohart (1958). 7. D. M. Caron, University of Delaware (personal communication). 8. Faulkner (1978). 9. Free (1980). 10. Hawthorne et al. (1956). 11. R. Hoopingarner, Michigan State University (personal communication). 12. Johansen et al. (1982). 13. Kaziev (1977). 14. Kevan (1977). 15. Kevan & LaBerge (1979). 16. Klug & Buenemann (1983). 17. McGregor (1980). 18. McGregor (1976). 19. Menke (1952). 20. Norden (1985). 21. R. Norton, Cornell University (personal communication). 22. Parker et al. (1976). 23. Parker et al. (1987). 24. Radchenko (1966). 25. Richards (1987). 26. Rutledge (1988). 27. Sharples et al. (1965). 28. Southwick & Southwick (1989). 29. Steshenko (1977). 30. P. F. Torchio, USDA-Logan, Utah (personal communication). 31. Torchio (1976). 32. Torchio (1982). 33. Torchio (1987). 34. Torchio et al. (1987). 35. USDA (1974). 36. G. D. Waller, USDA, Tucson, Ariz. (personal communication). 37. Waller et al. (1985).

as more or less elastic than they really are. As it turns out, the social gain results are not very sensitive to this factor. Various forms were tried as well as those used, notably the linear and log linear. The results were not much different than those presented here. Consequently, this problem has not been considered further.

Estimates of Societal Losses with Varied Output Reduction

Because most previous estimates of the impact of bees on crops start with the current level of bee usage and crop output, we also do so in the rest of this paper to be consistent. This assumes the current situation as the starting point and asks what social loss can be expected if bees were entirely removed. The figure is the same as the social benefit of the bees; it is only the way of looking at the question which is altered.

The first step is to calculate the losses that would be incurred for a variety of output reductions. Because authorities disagree on the amounts by which outputs would decrease in the absence of bees, we have chosen to present several levels so that the reader may choose the most acceptable loss levels for each crop. Later, we present our estimates of the actual values.

Table 4 gives the amounts of societal losses that accrue from the removal of bees, assuming that crop reductions vary from 10–90%. (Note that a 90% loss implies that bees increase the yield 9-fold (900%), a 70% loss implies a 233% increase, a 50% loss implies a 100% increase (the bees effectively double the crop), a 30% loss implies a 43% increase, and a 10% loss implies that bees increase the yield by 11%.) Because honey bees are not of equal importance to each crop listed, caution should be taken in using this table for actual loss computation. However, if the reader is able to predict the output reduction that would occur for any particular crop, the social loss which would result can be found from Table 4.

The results in Table 4 are calculated in two parts, as shown in Fig. 1. First is the loss borne by the continuing consumers. The cost increase and consequent price increase is computed based on the loss level assumed. Of course, where the seed is not the whole crop and is the only effect, the price increase is accordingly less. The quantities of commodity reserves are computed before and after price changes. The loss to continuing consumers equals the new quantity multiplied by the price increase.

The other portion of the social loss is calculated using a numerical integration procedure as the difference in the demand curve and the new quantity, integrated over the range of prices from the original to the new price.

In the three cases (lima bean, beet, and cranberry) where the coefficient on quantity was estimated as positive (none was significant), the demand was presumed to be perfectly inelastic. Thus, no quantity reduction followed from the price increase, and the loss is equal to the price increase multiplied by the current quantity.

The sum of these two losses was then adjusted to 1986 dollars using the Consumers' Price Index. The results of these losses are presented in Table 4. In addition to these dollar values (in $ millions annually), the crop value is shown. The loss can exceed the crop value because the loss is in terms of consumers' surplus rather than in terms of expenditures.

Estimates of Crop Reduction

The next step is to estimate the amounts by which the various crops would be reduced if honey bees were absent. This is a controversial and inexact process because we cannot be sure how much of the pollination gap would be filled by native bees and other alternative insect pollinators.

Table 5 provides three estimates of the net fractions of each crop which will be lost in the long run if managed honey bee populations are essentially eliminated in the United States. The first column values (No Replacement) assume that there are no replacement alternative pollinators, either managed or unmanaged. The values in the second column (Expected) assume that some use of alternative pollinators is made, including feral (unmanaged) Africanized or European honey bees, and managed insect pollinators such as the blue orchard bee. (Note that it has been assumed that crop losses in the U.S. are not made up by imports from other countries; such imports would reduce the losses felt by U.S. consumers. In that case, the losses would be partially felt by owners of agricultural land who would see a fall in the value of the land. This fall in price would be sufficient to prevent much of the import substitution.) Values in the third column (Robinson) are those presented by Robinson et al. (1989b).

The almond crop, *Prunus amygdalis* L., serves as an example of the derivation of these estimates. The almond flower is self-incompatible and requires cross-pollination to produce seed (McGregor 1976). Using the literature references cited (Torchio 1982, 1987; Torchio et al. 1987, Torchio personal communication) and after consultation with the Almond Board of California and researchers, it was determined that a maximum of ≈10% of the crop could be harvested without managed honey bees (loss, 0.9). Although it has been noted that the honey bee is "practically" the only commercially available pollinator (McGregor 1976), other native and introduced pollinators have proven effective (Torchio 1982, Parker et al. 1987, Torchio et al. 1987). Some species of *Osmia* emerge in synchrony with almond bloom; these are highly effective

Table 6. Estimates of societal value of honey bees, by crop (all values in $ millions)

Crop	Value, 1986	% Seed cost[d]	No replacement value	Expected value	Robinson (1989b) value[a]
Fruits and nuts					
Almond	461.6	—	847.0	271.3	X
Apple	1,068.3	—	2,437.3	410.4	4,097.6
Apricot	22.0	—	1.5	1.5	1.5
Avocado	153.5	—	35.9	16.5	403.6
Bushberry	111.1[b]	—	80.4	11.5	80.9
Cherry, sweet	112.8	—	44.8	32.2	44.8
Cherry, tart	50.1	—	52.0	18.5	118.1
Cranberry	194.6	—	129.7	83.4	891.8
Grape	1,170.1	—	187.1	0.0	0.0
Grapefruit	335.1	—	30.5	30.5	30.5
Lemon	218.1	—	64.7	54.6	37.9
Lime	21.0	—	8.7	6.1	6.1
Macadamia	35.2	—	5.6	0.0	5.6
Nectarine	75.7	—	25.9	16.8	35.5
Orange	1,074.1	—	353.9	110.4	353.9
Peach	326.8	—	28.2	28.2	28.2
Pear	199.4	—	139.5	73.5	164.3
Pomegranate	8.6	—	0.9	0.0	NA
Plum (Calif.)	99.9	—	54.5	34.5	55.0
Plum–Prune (other)	11.3	—	3.2	3.2	3.2
Prune (Calif.)	78.4	—	41.0	23.7	50.9
Strawberry	503.6	—	147.7	98.4	NA
Tangelo	19.0	—	3.5	1.8	6.8
Tangerine	48.3	—	7.8	4.4	9.6
Temple	15.9	—	2.9	1.6	3.7
Vegetables					
Artichoke	36.6[b]	20	0.8	0.0	NA
Asparagus	143.9[b]	24.3	12.6	2.5	12.6
Beans, dry	431.2	—	43.8	13.0	NA
Beans, snap	97.3	—	9.3	2.9	NA
Beans, lima	46.3[b]	—	5.1	1.4	NA
Beet	16.1[b]	12.6	0.2	0.0	NA
Broccoli	227.2	2.4	44.9	5.4	44.9
Brussels sprouts	25.0[b]	20	0.2	0.2	NA
Cabbage	264.7[b]	0.7	8.1	1.8	NA
Cantaloupe	209.0[b]	—	38.1	38.1	38.1
Carrot	228.0	2.8	9.2	0.7	47.7
Cauliflower	188.5	4.3	41.7	7.7	41.7
Cucumber	112.9	—	13.1	13.1	13.1
Honeydew	69.5	—	48.6	38.7	48.3
Lettuce	719.1	1.0	0.2	0.0	NA
Onion	371.4	8.0	12.7	7.4	240.4
Sweet potato	130.8	—	14.0	2.7	NA
Watermelon	167.7[a]	—	91.6	17.9	169.3
Forage seed					
Alfalfa	170.5[b]	—	315.4	40.5	215.5
Crimson clover	3.5[b]	—	2.0	1.2	NA
Hairyvetch	2.9[b]	—	0.2	0.0	NA
Ladino clover	7.1[b]	—	1.6	1.2	NA
Lespedeza	6.7[b]	—	0.1	0.0	NA
Red clover	25.2[b]	—	12.6	6.0	NA
Sweet clover	2.4[c]	—	0.2	0.1	NA
Seed crops					
Cottonseed	298.4	—	104.6	65.0	56.8
Flax seed	41.0	—	0.4	0.0	NA
Peppermint	46.0	20	1.0	0.1	NA
Soybean seed	9,326.2	—	93.6	0.0	970.1
Spearmint	28.4	20	0.6	0.1	NA
Sunflower seed	185.2	—	6.8	3.4	6.7
Flowers					
Carnation	39.4	5	0.3	0.2	NA
Chrysanthemum	19.5	5	0.2	0.1	NA
Gladioli	26.4	5	0.2	0.1	NA
Mini carnation	16.5	5	0.1	0.1	NA
Pompon chrysanthemum	35.5	5	0.2	0.2	NA
Rose, sweetheart	26.0	5	0.2	0.1	NA
Tea rose	124.7	5	0.9	0.7	NA
Total	20,331.2	—	5,669.6	1,605.6	8,334.7

[a] X, not meaningful; NA, not available.
[b] Value in 1979 multiplied by 1.51058 to adjust for CPI.
[c] Value in 1971 multiplied by 2.70734 to adjust for CPI.
[d] Commercial Seed Catalog, 1989, Rochester, N.Y. Harris–Moran Seed Company.

Table 7. Crops given by McGregor (1976) for which losses were not estimated[a]

Fruit and Nuts	Vegetables	Forage	Oilseed	Other
		Data unavailable		
Acerola	Balsam Pear	Alsike Clover	Safflower	Cacao
Crabapple	Cardoon	Arrowleaf Clover	Tung	Cashew
Feijoa	Casaba Melon	Ball Clover		Chicory
Guava	Celeriac	Berseem Clover		Clove
Jujube	Chayote	Black Medic		Coffee
Kiwifruit	Chervil	Broadbeam		Kola
Litchi	Chive	Cicer Milkvetch		Lupine
Loquat	Coriander	Kenaf		Tea
Passion Fruit	Cowpea	Kidney Vetch		
Quince	Crenshaw	Mung Bean		
	Dill	Persian Clover		
	Endive	Pigeon Pea		
	Fennel	Rose Clover		
	Kale	Sainfoin		
	Leek	Scarlet Runner Bean		
	Mustard	Strawberry Clover		
	Parsley	Sweet Vetch		
	Parsnip	Trefoil		
	Pepper	White Clover		
	Pimento	Zigzag Clover		
	Radish			
	Rutabaga			
	Turnip			
	Veg Sponge			
		Honey bees unimportant		
Chestnut	Celery	Crown Vetch	Peanut	Buckwheat
Coconut	Eggplant	Kudzu		
Olive	Pumpkin			
Papaya	Squash			
Persimmon	Tomato			
		Crop unimportant in United States		
Mamey sapote			Rape	
Mango				
Papaw				

[a] For most of these crops, data were not available, usually because the crop is relatively unimportant in the United States, and losses should be small. Some other crops in this list are pollinated primarily by other bees, insects, or wind; honey bees are relatively unimportant.

pollinators capable of being managed commercially. The most likely situation with the loss of honey bees and some use of alternate pollinators (managed and unmanaged) is a 50% yield (loss, 0.5) (see estimates of yield increases in previous section). Estimates for each of the other crops were made in a similar way. In the absence of accurate quantitative data, the numbers provided in Table 5 represent the most accurate estimates developed to date.

Table 5 must be read with caution, however, because the estimates are by necessity generalized. They do not fit all geographic growing zones. In some regions and under certain conditions, the effect of no honey bees can be devastating. In other areas, honey bees can increase crop quality or yields somewhat, but their absence would not cause a great economic loss. Data on bush berry crops (blueberries, blackberries, and raspberries) in New Brunswick and Ontario (Kevan & LaBerge 1979) illustrate this point. In New Brunswick, honey bees were not needed on blueberries until pesticides devastated native unmanaged pollinators. After effective cleanup of the environment, these natural populations of pollinators recovered. During intervening years, honey bees were required and without them there would have been no harvestable crop. On the other hand, honey bees are not useful on cranberries in Ontario unless native bumble bee populations are very low. Honey bees are needed where the cranberry bogs do not support enough bumble bee habitat. Also, the data in the table do not show differing pollination requirements of cultivars. In tree fruits such as apricots, pears, peaches, and plums, some varieties require cross-pollination and others are self-compatible. We have lumped crop varieties together; this may mask these varietal differences (and in some cases dilute somewhat the impact of honey bee pollination activities).

Estimated Social Value

Finally, the objective is to use the societal loss results from Table 4 along with the crop reduction estimates from Table 5 to calculate the actual societal value of honey bees for individual crops.

Table 6 gives these results for the three crop reduction estimates. It also gives the value of the crop in 1986 dollars. Note that where only the seed crops are affected by pollinators, the loss had to be adjusted to reflect that.

The results give a range of annual benefits from a low of $1.6 billion to a high (using data of Robinson et al. 1989b) of $8.3 billion. Because Robinson et al. (1989b) assume no replacement pollinators, their estimate (which is questionable because their economic methodology was incorrect) should be compared with our estimate of $5.7 billion for the no-replacement case.

Another way of expressing this result is that the annual benefit of honey bees to U.S. agricultural consumers is on the order of $1.6–$8.3 billion. The high value assumes that honey bees have replaced no alternative pollinators, either managed or unmanaged, whereas the lower value assumes that honey bees have replaced other pollinators.

Some crops have not been included in this study, although they are pollinated by honey bees. These are omitted because the data were unavailable or bees are not important, or because the crops are not important in the United States. These are listed in Table 7.

The results of this examination of the value of honey bees suggest that more resources and effort need to be applied in two major areas: (1) finding ways to reduce potential colony losses to the honey bee industry; and (2) improving management of alternate native bee pollinators for various crops. Hedgerows and other "conservation zones" criss-crossing large monoculture agricultural fields, as well as bee shelters and bee beds, may ensure hibernation and nesting sites for several species of bee pollinators (Bohart 1958, 1972; Free 1980; Torchio personal communication).

More information on practical application is needed to use managed alternative pollinators effectively. Some species of *Megachile, Osmia, Bombus*, and other genera can now be supplied for a number of crops in limited regions. Feral colonies of Africanized honey bees will undoubtedly occupy the warmer parts of the United States (Taylor 1985, Southwick et al. 1990), and they may prove to be effective pollinators for large monocultures. This means that some honey bees would remain available for pollination in these areas, but because they are wild, their numbers would fluctuate annually and they would generate no income for beekeepers. Nonagricultural social costs would, of course, also be incurred because of the highly defensive behavior of Africanized bees.

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