Estimation of the Economic Value of the Pest Control Service Provided by the Brazilian Free-tailed Bat in the Winter Garden Region of South-Central Texas

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Abstract
Brazilian free-tailed bats *(Tadarida brasiliensis*) form enormous breeding colonies each summer in large caves in south-central Texas and northern Mexico. Prey of these bats includes several species of adult insects whose larvae are known to be important agricultural pests, including the corn earworm or bollworm (*Helicoverpa zea*). We estimate the value of the bats in controlling this pest in cotton production for an eight county region in south central Texas. We estimate the avoided damage at $741,000 per year, with a range of $121,000 to $1,725,000, compared to a $6 million per year annual cotton harvest.

Introduction

Throughout the world, humans compete with over 70,000 pest species for food, fiber and timber (1). Natural enemies, including predators such as birds, bats, spiders, and ladybeetles, parasites such as wasps and flies, pathogens such as fungi, viruses and bacteria, and other organisms, reduce densities of most pest species. In economic terms this important ecosystem service is a "positive externality" because its value to agricultural production is not reflected in the value of the habitat that generates the service. Without this value-added tag that could signal their degradation, ecosystem services tend to be under-valued and hence overexploited. Their value becomes evident only when they are degraded or eliminated by human activity. Public attention to the value of these benefits is important to provide support for reasonable public policies to protect critical ecosystems (2).

Loss of natural pest control services could have significant economic, environmental and human health consequences (3). Society could suffer the cost of more crops lost to pests. Alternatively, society could attempt to replace the lost service by a technological equivalent such as chemical pest control that has its own set of costs. Pesticides are expensive, and they can have harmful and unintended consequences. For example, more than 500 insect and mite pests have developed resistance to pesticides (4), requiring either higher doses or the development of new chemicals. Because most pesticides are not target specific, many natural enemies of pests are killed by heavy pesticide use. Moreover, exposure to pesticides and herbicides pose health risks to humans and other. Protection and enhancement of natural pest control services would minimize both the need for pesticides and their harmful side effects, and enhance integrated pest management. Identification and measurement of the magnitude and value of natural pest control services is essential in this effort.

The Brazilian free-tailed bat *(Tadarida brasiliensis*) provides a continental-scale natural pest-control service in North America. This species over-winters in south and central Mexico and migrates northward each spring to form enormous breeding colonies in northern Mexico and the southwestern U.S. (5). Historic records of some summer cave populations of this species reportedly exceed 20 million individuals. Over 100 million bats may disperse to feed nightly from caves and bridges in south-central Texas.

Brazilian free-tailed bats consume enormous quantities of insects throughout the summer breeding months, when individuals and especially lactating females may ingest up to two-thirds of their body mass each night (6). The bats' prey include adults of several lepidopteran species in the Family Noctuidae whose larvae are known agricultural pests, such as fall armyworm (*Spodoptera frugiperda* J. E. Smith), cabbage looper [*Trichoplusia ni* (Hubner)], tobacco budworm [*Heliothis virescens* (F.)], and corn earworm or bollworm [*Helicoverpa zea* (Boddie)] (7). The cotton *H. zea* is among the most destructive agricultural pests in the Americas. Here we evaluate the magnitude of this as of yet unaccounted for pest control service.

The Study Area

The study area is defined by the area of agricultural production capable of supporting insect prey populations for *T. brasiliensis*, and the spatial extent of foraging behavior of this species. We select an eight county region located southwest of San Antonio known as the Winter Garden region (Figure 1). In recent years about 10,000 acres of cotton have been harvested, with marketed production worth between $4.6 and $6.4 million. The area is characterized by a high-input, high-yield system with extensive use of irrigation water, fertilizer, pesticides and other inputs. The crops are planted in February or March and harvested in August or September, with typical cotton yields of 680 (600) to 1,250 (1,100) kg (pounds) of lint per ha (acre). The price of cotton ranges from $0.50 to $0.70 per pound and the price of seed from $80 to $120 per ton (8).

The Winter Garden region lies in close proximity to several colonies of Brazilian free-tailed bats in the San Antonio-Uvalde region in south-central Texas (Figure 1). Several lines of evidence strongly suggest that individuals from these colonies feed in and above the agricultural fields in the Winter Garden region at the same time of major emergences of insect pests from those fields. First, agricultural production in the region supports large populations of insect pests, most notably the corn earworm or bollworm, especially on corn, which serves as a nursery crop (9). Plant infestation rates by larvae of corn earworm and other noctuid insect pest species in the Winter Garden typically reach 100% in fruiting corn. Larval densities can exceed 60,000/ha, equivalent to one or more per corn plant (39). Moths (adult stage) emerge in large numbers from corn fields after pupating in the ground in late June and early July (10). These moths either disperse locally into suitable crop habitats, such as rapidly fruiting cotton, where they lay eggs, or they ascend to altitudes where winds assist their migration for up to several hundred kilometers per night (11). These migrants infest crops north of the immediate study area.

Second, high levels of foraging activity and consumption of insects by bats have been documented within the midst of these large moth populations at altitudes of 200 to 1,200 meters. Radiomicrophones that detect the ultrasonic calls of foraging bats have been attached to free-floating weather balloons (12) or to the tether lines of kites (13). Analysis of these calls indicate that the level of bat foraging activity over agricultural fields is often more than an order of magnitude greater than that in habitats outside of agricultural areas (14).

Third, dietary and DNA analysis of bat feces indicate that *H. zea* and other agricultural pests constitute a significant fraction of the diet of the Brazilian free-tailed bat. Examination of stomach contents and feces produced by pregnant and lactating females collected upon their return from nightly foraging bout show that Brazilian free-tailed bats in south-central Texas feed largely on moths (Lepidoptera), beetles (Coleoptera), true bugs (Hemiptera), plant hoppers (Homoptera), and flying ants (Hymenoptera) (15, 40). The presence of moths in the diet is most pronounced in the second nightly feeding bout, corresponding to the nightly dispersal of moths from the source fields. Over longer periods, the volume of moth remains in the bats' feces increases two- to three- fold when bollworms are maximally available in the region (16, 40). DNA sequence fragments attributed to bollworms and tobacco budworms have been amplified from these fecal samples.

Fourth, NEXRAD Doppler radar data clearly document the nightly dispersal of bats from their colonies, spreading out over the Winter Garden region, and their early morning return (Figure 2). The Doppler data are filtered to remove weather activity, and composited to enhance the visibility of biological activity. These data clearly show that the nightly dispersal and feeding activities of Brazilian free-tailed bats are closely associated in time and space with major emergences of bollworm moths (17).

Finally, ground-based visual observations of nighttime activity over cotton fields in the Winter Garden region reveal significant foraging behavior by the Brazilian free-tailed bats over those fields at the time that bollworm moths are emerging (18).

While there is strong evidence that Brazilian free-tailed bats feed on *H. zea,* we are less certain about the number of Brazilian free-tailed bats that forage over the Winter Garden cotton crop. The bats have an average flight speed of 40 km/hr and a nightly flight range of over 100 km (19), placing a number of large colonies of this species well within reach of the Winter Garden region. There are at least 5 cave colonies, 1 sinkhole colony and 6 bridge colonies adjacent to large crop fields (Figure 1). Using a combination of historic estimates (20) and current censuses (21), we make a conservative estimate that at least 1.5 million bats feed nightly over the agricultural fields in the Winter Garden region.

Pest Control by Natural Enemies in Ephemeral Crop Habitats

The timing and nature of foraging behavior by Brazilian free-tailed bats exhibit many attributes common to natural insectivores in ephemeral crop habitats (22). The growth of pest populations in seasonally ephemeral habitats such as a cotton field can exhibit exponential growth over a limited period of time. Because the habitat is ephemeral, extension of the latent phase of population growth—when pest densities are relatively low and slow growing—reduces the time available for the epidemic phase where explosive growth can breach thresholds that cause plant damage and trigger chemical intervention. If the natural control is strong enough and when phenological stages of a pest-susceptible crop are of short duration, the entire window of vulnerability may be passed completely and the herbivore essentially becomes a non-pest (22). However, any disturbance of natural controls can trigger resurgence of pest populations.

By the time that cotton becomes a viable host around the third week of June, the colonies in the region are large and approaching peak numbers. During the third week of June, maturing corn usually ceases to be a viable host for *H. zea*, and the pest switches to cotton as a host. At this juncture the pest control service of the bats switches from corn to cotton. Thus, the bats reduce the initial inoculums in cotton because they target the pest *before* its arrival in the cotton fields. With fewer immigrants, *H. zea* remains in the latent growth phase for a longer period.

Early season insect control by the bats is enhanced by their vagility and polyphagic diet. They can move into areas above corn and cotton fields from a variety of wild and agricultural habitats. Dietary and DNA analysis of feces from Brazilian free-tailed bats indicate a diverse diet that includes both pest and non-pest species (23, 40). Polyphagous natural predators use diverse, alternative sources of nutrition before the target, in this case *H. zea,* is present, and thus do not rely exclusively on agricultural pests to sustain their populations. Finally, the searching ability of a natural enemy is also important because it extends the latent period of pest growth. In particular, the ability to find and attack pests early in the insect eruption cycle is crucial to early season control.

While there is no empirical evidence for this from the field in the case of *H. zea* control by Brazilian free-tailed bats, other insectivorous bats are well known for the acuity of their search and attack capabilities (24), and for their ability to track local insect abundance and quickly recruit into areas as prey becomes available (25).

Valuing Pest Control Services

The consumption of insect pests by Brazilian free-tailed bats can be valued as an input to agricultural production akin to inputs such as tractors, labor, fertilizer and chemical pesticides. However, since this service is not directly observed and a value therefore is not placed on its magnitude, we use indirect methods to estimate its value to farmers and society (26). In the avoided cost approach, one places a value on pest control by assessing the costs or expenditures society avoids due to the availability of these services as an input to production (reference). In the present case this cost has two components. The first is the value of the cotton crop that would have been lost in the absence of the bats. The second is the reduced cost of pesticide use—private and social—attributable to the presence of bats. These methods have been applied to the services provided by wetland ecosystems (27), but heretofore have not been used to assess pest control services.

The unit for our analysis is the individual female bat. Because damage to the crop occurs in the larval stage of *H. Zea*, the goal is to calculate the number of larvae "prevented" from reaching maturity by the presence of a single bat. The overall impact on agriculture is estimated by scaling up population estimates of colonies in the study area.

There are two principal sources of variability in the key parameters in our model. The first is our uncertainty about some aspects of the behavior of the bats and their insect prey. This uncertainty can be bounded and our results can be tested as to their sensitivity to that range. The second and more interesting source of variation stems from the relation between control supplied by the bats at the adult stage of the pest and (i) control supplied by other natural enemies at earlier stages in the life cycle of *H. zea*, and (ii) control supplied by farmers with pesticides. We elaborate on this point below. Although the temporal scale of this study is restricted to a single growing season, the uncertainties of bat population dynamics do not affect this scale.

A single female Brazilian free-tailed bat (at peak lactation) weighing 12.5 g will consume about 8.1 grams of adult insects each night (6,15). Fecal matter analysis indicates that about 31 percent of the bat's diet is insects of the order Lepidoptera (28, 40). Less certain is the fraction of Lepidoptera eaten that is accounted for by bollworms. Because dietary analysis shows that moth consumption increases two- to three-fold during peak bollworm availability (40), we assume that this increased moth consumption is largely due to bollworms. This translates to 30 to 60 percent of the bats' diet, or 10 to 20 adult bollworms eaten by a single bat each night. The mass of a moth abdomen, the part consumed by a bat, is about 0.07 grams. Approximately half of the moths consumed by a bat are female, and not all would have infested crops in the Winter Garden area; some may move to other hosts and will others will migrate out of the region. We assume that between 10 and 20 percent of the moths eaten by a bat would have dispersed into a crop in the region. Thus, in the middle of this range a single bat will eat about 1.5 female moths each night that would have laid eggs on a single host plant in the region.

The next set of calculations is based on the population dynamics and life history of *H. zea*, which are well documented in the agricultural entomological literature (29). A single female will lay between 600-1,000 eggs in its lifetime (30). Of those, from 6 to 30 percent will hatch, and of those hatched, between 2 to 5 percent will survive thorough all stages of development (39). The mortality at the egg and larval stages is caused by a host of other natural enemies including fire ants, flower bugs, big-eyed bugs, convergent lady beetles, spiders, and parasites such as *Trichogramma pretiosum* and *Eucelitoria bryani* (31). In the middle of this range of these survival estimates, a single bat consuming 1.5 adult moths per night will, in effect, prevent about 5 larvae from damaging a crop each night.

The next step is to translate the larvae "prevented" by a bat to the economic value of the damage that larvae would have inflicted. A single larva will destroy 2-3 bolls of cotton in its lifetime. However, the susceptibility of the cotton plant declines over the course of the growing season because the contribution of fruit set earlier in the season is more valuable than fruit set later in the season. Thus, fruit set earlier in the season will contribute more to yield due to availability of adequate resources (light, water and nutrients) and avoidance of high pest populations. Fruit retention declines throughout the boll loading period as the overall nutrient requirements increase. In general, the first ten fruiting branches contribute 85-90 percent of the crop (29). Thus, the potential cost for an insect to remove a boll from the first fruiting branch is higher than the last fruiting branch. As a result, a single bat consuming 1.5 adult moths per night will prevent damage to upwards of 10 bolls per night in mid-June, but close to zero by the end of the growing season in early August. With the price of cotton in 2001 at about $.0017/boll (8), this means a single Brazilian free-tailed bat provides a service of $0.02 per night in mid-June, which declines to close to zero by August.

The Role of Pesticides

Economics drive the farmer's decision regarding the use of pesticides: when does the potential injury from a pest justify the cost of a pesticide application? In the Winter Garden region, the economic threshold for *H. zea* is breached at a density of 8,000-10,000 larvae per acre, although treatments to control *H. zea* in cotton production in the Winter Garden region vary substantially across farms and time.

The pest control provided by Brazilian free-tailed bats, which operate in the background from the farmer's perspective, affects both the potential need for chemical control, and, in turn, is affected once a chemical has been applied. It is plausible to postulate that the bats reduce the need for chemical control by suppressing pest densities below the economic threshold, or by delaying the time until that threshold is attained. Once applied, a pesticide alters the benefits provided by the bats by reducing the abundance of the pest, but also by suppressing the populations of other natural enemies in the field (32). The net effect of chemical control on the mix of pest reduction spread over many natural enemies is complex and difficult to predict *a priori*.

In the Winter Garden region, sufficient pest densities in cotton to warrant the use of pesticide generally do not occur until early July when corn in the region is no longer a viable host for the larvae. Thus, the first week in July typically is the time when the first pesticide application usually occurs, which might be followed by as many as three additional applications spaced about 7 days apart, the last one coming in the final week in July. A pesticide application eliminates close to 100% of *H. zea* eggs and close to 90% of its larvae, however these effects are short-lived. After just 2-3 days, egg survivorship jumps from almost zero to 80%, several times what it was prior to the application of the pesticide.

Pesticides have private and social costs. The private component is the cost to farmers to purchase and apply the chemicals. In the Winter Garden region a typical single application of synthetic pyrethroid insecticide to control *H. zea* costs about $25 (10) per ha (acre), with applications rates of about 0.03 pounds (0.014 kg) of active ingredient used per acre. Pesticides also have social and environmental costs that are not reflected in their market price. These include public health costs, the loss of natural enemies, the loss of pollination services, fishery and bird losses, and groundwater contamination, among others. Kovach (33) estimates the environmental cost to be $24.38 (11.06) per kg (pound) of active ingredient of pesticide. This is based on Pimentel et al.'s (1) estimate of the social and environmental cost of pesticide use in the U.S. at $8.1 billion dollars, and Gianessi and Anderson's (34) estimate of 332 (732) million kg (pounds) of active ingredients of pesticide use in the U.S. in 1992.

Results

Our reference or "most likely" valuation assumes no use of pesticides and assumes that the key demographic variables for *H. zea* (survivorship rates for eggs and larvae) are located at the mid point of their observed ranges (Figure 3). The high and low cases utilize values at their observed extremes. The first component of this total is the cumulative value of the avoided damage provided by Brazilian free-tailed bats from June 10, the approximate date when the transition of *H. zea* from corn to cotton is complete, to August 8, the approximate date when cotton is no longer susceptible to damage from *H. zea*. In this case, the cumulative avoided damage directly due to bat predation is $638,000. The total cumulative avoided damage is $741,000, with a range of $121,000 to $1,725,000 (Table 1).

The second component of this service is the avoided cost of pesticides. This requires an assessment of not only the number of avoided moth larvae, but also how they are dispersed across the total cotton acreage. An order of magnitude analysis suggests that this effect could be significant. In our reference case, from mid-June to early July a population of 1 million bats will "prevent" about 5 million larvae per night. If we assume these would have been distributed evenly across the 4 (10) thousand ha (acres) of cotton, then the economic threshold of 20,000-25,000 (8,000-10,000) larvae per ha (acre) would be reached in about 12 days; in the low egg/larvae mortality case these densities are reached in just a few days. Thus, it is quite plausible that the bats produce one, and perhaps two, avoided applications of pesticides in the early stages of the cotton crops. Of course, there would be other sources of mortality for *H. zea* in the absence of bats, but the magnitude of consumption by the bats suggests that their loss would be considerable. At about $25 (10) per ha (acre) per pesticide application, one avoided pesticide application across all 4,000 (10,000) ha (acres) is worth $100,000. In Table 1 we present the impact of zero, one, and two avoided applications, generating a range of zero to $200,000 for the avoided cost of pesticide use. The associated social and environmental costs avoided range from 0 to $6,000.

We compared these results with a second case where we assume that farmers do apply pesticides to control *H. zea.* Figure 4 compares the reference case with no pesticides to one in which pesticide applications are made on July 7, 14, 21, and 28. The cumulative value in the case with pesticides is just 10% lower than the case with no pesticides.

Discussion

Our estimate of value of the pest-control service provided by Brazilian free-tailed bats to agriculture ranges from about 2 to 29 percent of the $6 million value of the cotton crop in the Winter Garden region; the reference case value is about 12 percent. This suggests that the bats do indeed play a vital role in protecting this crop from damage, and in reducing the costs to farmers and society of pesticide use. One of the distinctive features of this service is that it accrues largely in the early part of the growing season (Figure 3). Eighty percent of the avoided damage in the Winter Garden region accumulates before the end of the first week of July, which in practice is the time when farmers consider their first application of pesticides. This result is consistent with the behavior of an effective natural enemy in ephemeral crop habitats, namely the extension of the latent phase of population growth by a vagile, polyphagic population that is well-established in the area before the pest moves into the target crop. The magnitude of the consumption of moths strongly suggests that Brazilian free-tailed bats reduce crop damage, eliminate at least one application of pesticide, and possibly delay the time at which pesticides are first used. Each of these impacts has positive economic and environmental benefits.

There is a clear tradeoff among different forms of natural enemy control in this agroecosystem. In years when morality rates are high for the egg and larval stages of *H. zea,* the number of larvae prevented from reaching the moth stage by the bats is reduced. Conversely, in years when control by natural enemies at those early stages is relatively low, the impact of the bats is much greater.

There is no significant tradeoff between control by bats and chemical control through pesticides. That is, the use of pesticides to control *H. zea* in this region does not significantly reduce the value of the pest control by Brazilian free-tailed bats (Figure 4). This results from two forces. First, pest control by bats is front-loaded in the early part of the cotton-growing season when pest densities are not high enough to trigger a pesticide application. Second, the reduction in eggs and larvae by a pesticide application is short-lived, lasting just a few days, and the pesticide dramatically reduces densities of many natural enemies along with eggs and larvae of *H. zea.* In effect, this increases the role for insect pest control by Brazilian free-tailed bats.

Brazilian free-tailed bats clearly play an important role in food production in south Central Texas, suggesting that conservation of bat habitat may be desirable on economic cost-benefit grounds alone. Our ongoing research will extend this analysis to include all major colonies in the region, and to crops other than cotton in Mexico, Texas and other states in the midwest that are beneficiaries of pest control by the Brazilian free-tailed bat (21).

In other regions of the World, bats provide essential services such as seed dispersal and pollination of plants that humans depend on directly and indirectly (35). The U.S. Fish and Wildlife Service (36) lists 9 of the 45 bats species of the U.S. as endangered. Brazilian free-tailed bats have unique vulnerabilities as their large maternity colonies in Texas and over-wintering colonies in Mexico make them highly susceptible to disturbance. This species reproduces slowly—only one pup per female per year—so when a colony is severely disturbed it may be slow to recover, if at all. Cave ecosystems in general are under assault from guano mining, land development, pollution, misguided vampire bat control attempts, prescribed burns in land management, vandalism and impact from uninformed recreational cave explorers (37). Many caves in northern Mexico that once supported robust Brazilian free-tailed bat populations have been destroyed. This trend is slowly reversing, and, although local conservation efforts have shown success (38), robust evidence on the economic value of insectivorous bats will provide important foundation for the generalized interest in protection of bats, especially by decision-makers. The combination of bats' role in sustaining ecosystems and economies suggest that protection of bat habitat should be a key conservation priority.

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Table 1. Value of pest control service provided by the Brazilian free-tailed bat (*Tadarida brasiliensis)* in the Winter Garden region of south-central Texas. Units are thousands of $US unless otherwise noted.

Cost or value	Low egg/larvae survival	Reference Case	High egg/larvae survival
Avoided crop damage	$121	$638	$1,519
Avoided pesticide cost (private)	$0	$100	$200
Avoided pesticide cost (social)	$0	$3	$6
Total Annual Value	$121	$741	$1,725

Figure 1 - The 8-county study area (red outline) lies to the southwest of the San Antonio Texas and includes 6 colonies of *T. brasiliensis* located in caves (circles), and 6 that inhabit concrete highway bridges (stars). Areas of agricultural production are shown in green. These 12 colonies among the several dozen in south central Texas likely have the greatest impact on pest insect populations.

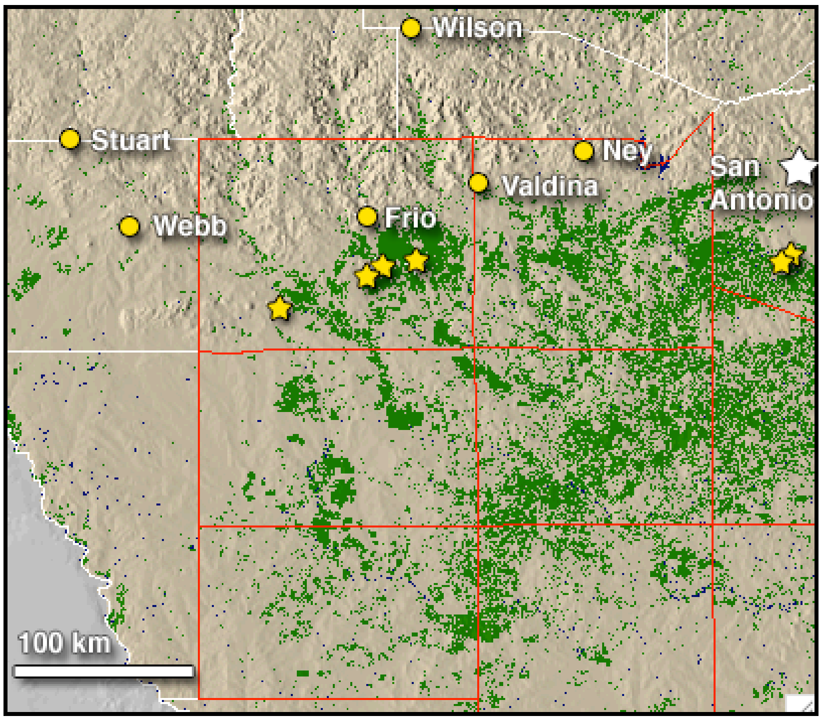

Figure 2 - NEXRAD Doppler RADAR imagery of bats returning from nightly foraging over agricultural land (green) in south central Texas. Each pixel corresponds to approximately 1 km^2 of reflectivity from bats aloft. Darker colors indicate greater reflectivity and hence greater density of bats. Large areas of reflectivity are seen twice nightly - at the time of emergence and again when bats return to their roosts. The timing, directionality and density of the reflectivity suggest that large numbers of bats forage over this area of agricultural production, consuming significant quantities of pest insects.

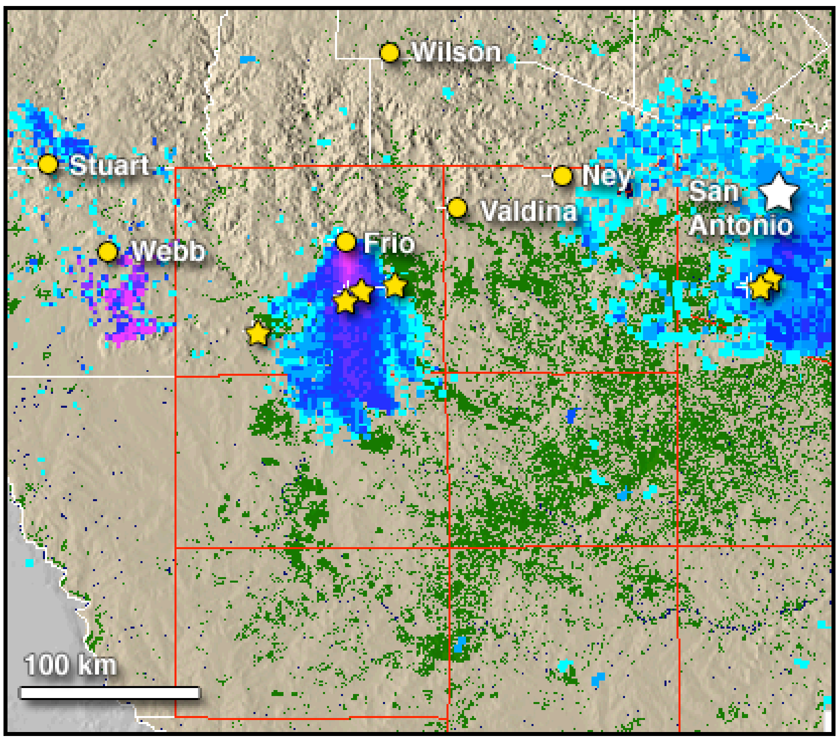

Figure 3. Estimated annual cumulative avoided damage to the cotton crop in the Winter Garden region of south-central Texas due to the insect pest control provided by the Brazilian free-tailed bat (*Tadarida brasiliensis)*. Units are thousands of $US unless otherwise noted.

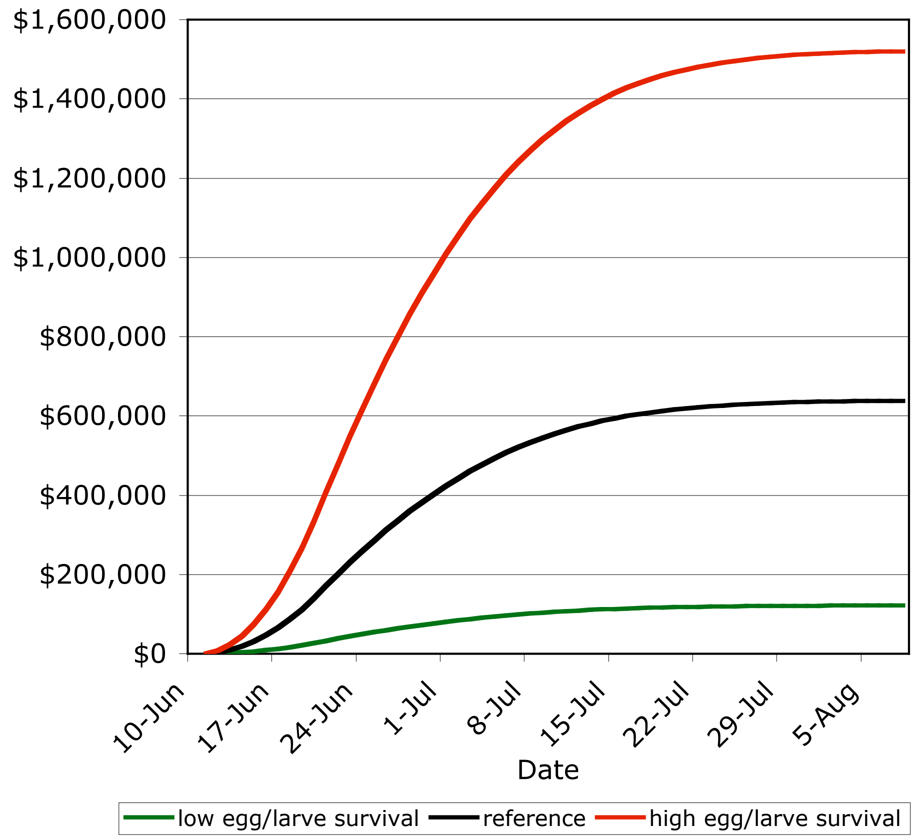

Figure 4. Estimated cumulative avoided damage to the cotton crop in the Winter Garden region of south-central Texas for the reference case with and without pesticide applications. The avoided damage is due to the insect pest control provided by the Brazilian free-tailed bat (*Tadarida brasiliensis)*.