Economic value of the pest control service provided by Brazilian free-tailed bats in south-central Texas

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Brazilian free-tailed bats (*Tadarida brasiliensis*) form enormous summer breeding colonies, mostly in caves and under bridges, in south-central Texas and northern Mexico. Their prey includes several species of adult insects whose larvae are known to be important agricultural pests, including the corn earworm or cotton bollworm (*Helicoverpa zea*). We estimate the bats' value as pest control for cotton production in an eight-county region in south-central Texas. Our calculations show an annual value of $741 000 per year, with a range of $121 000–$1 725 000, compared to a $4.6–$6.4 million per year annual cotton harvest.

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Throughout the world, humans compete with a multitude of pest species for food, fiber, and timber, although natural predators greatly reduce the densities of many of these pests. Loss of natural pest control services could have important economic, environmental, and human health consequences (Daily 1997). The Brazilian free-tailed bat (*Tadarida brasiliensis*; Figure 1) provides a continental-scale, natural pest control service in North America. This species overwinters in south and central Mexico and migrates north each spring to form large breeding colonies in northern Mexico and the southwestern United States (Davis *et al*. 1962). Historic records of some summer cave colonies of this species reportedly exceed 20 million individuals. Over 100 million bats may disperse nightly from caves and bridges in south-central Texas to feed. These bats consume enormous quantities of insects throughout the warm months; lactating females, in particular, may ingest up to two-thirds of their body mass each night (Kunz *et al*. 1995).

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The prey of these bats includes adults of several Lepidopteran species in the family Noctuidae (Lee and McCracken 2002, 2005), whose larvae are known agricultural pests, such as fall armyworm (*Spodoptera frugiperda*), cabbage looper (*Trichoplusia ni*), tobacco budworm (*Heliothis virescens*), and corn earworm or cotton bollworm (*Helicoverpa zea*). The cotton bollworm is among the most destructive agricultural pests in the Americas. Here we evaluate the magnitude of this previously unaccounted pest control service in cotton.

The study area

The study area covered an eight-county region (Uvalde, Medina, Zavala, Frio, Dimmitt, LaSalle, McMullen, and Atascosa Counties) in southwest Texas, including the four-county Winter Garden region located southwest of San Antonio (Figure 2). This area has agricultural production capable of supporting insect prey upon which *T brasiliensis* feeds. In recent years, about 10 000 acres of cotton have been harvested in this region, with a market value of between $4.6 and $6.4 million. The region is characterized by a high-input, high-yield system, with extensive use of irrigation water, fertilizer, pesticides, and other inputs. Cotton is planted in February or March and harvested in August and September, with typical yields of 680 kg (600 lb) to 1250 kg (1100 lb) of lint per ha. The price of cotton ranges from $0.50 to $0.70 per pound and the price of seed from $80 to $120 per ton.

There are several colonies of Brazilian free-tailed bats in the San Antonio–Uvalde region (Figure 2), and evidence strongly suggests that individual bats from these colonies feed in and above the agricultural fields in the Winter Garden region at the time of major emergences of insect pests from those fields. First, agricultural production in the area supports large populations of insect pests, most notably the corn earworm or cotton bollworm, initially in wildflowers and corn, which serve as a nursery crop (Kennedy and Margolies 1985). Second, high levels of foraging activity and consumption of insects by bats have been documented in the midst of large moth populations at altitudes of 200–1200 m (Wolf *et al.* 1994). Third, dietary and DNA analysis of bat feces indicate that *H zea* and other agricultural pests constitute a significant fraction of the diet of *T brasiliensis* (Kunz *et al.* 1995; Whitaker *et al.* 1996; Lee and McCracken 2002, 2005; McCracken *et al.* 2005). Fourth, our NEXRAD Doppler radar data (Figure 2) clearly show that the nightly dispersal of bats from their cave and bridge roosts, spreading out over the Winter Garden region, is closely associated in time and space with major emergences of bollworm moths (Beerwinkle *et al.* 1994). Finally, our ground-based visual observations of nocturnal activity over these cotton fields reveal a great deal of foraging behavior by *T brasiliensis* at the time that bollworm moths are emerging.

While there is strong evidence that Brazilian free-tailed bats feed on *H zea*, we are less certain about the number of bats that forage over the Winter Garden cotton crop. *T brasiliensis* has an average flight speed of 40 km hr^{-1} and a nightly flight range of over 100 km (Williams *et al.* 1973), placing a number of large colonies of this species well within reach of the Winter Garden crops. At least three cave colonies, one sinkhole colony, and five bridge colonies are adjacent to cropland that supports corn and cotton production (Figure 2). Using a combination of historic estimates (McCracken 2004) and recent census data from these sites (M Betke *et al.* unpublished), we make a conservative estimate that at least 1.5 million bats feed nightly over the agricultural fields in the Winter Garden region.

Valuing pest control services

We use an avoided-cost approach that places a value on pest control by assessing the costs or expenditures that society avoids as a result of the availability of these services as an input to production. This cost has two components: the value of the cotton crop that would have been lost in the absence of the bats and the reduced cost of pesticide use – private and social – attributable to the presence of bats. These methods have been applied to services provided by wetland ecosystems (Woodward and Wui 2001), but so far have not been used to assess pest control services.

The unit for our analysis is the individual female bat, because relatively few males roost in these large maternity colonies. Because damage to the crop occurs in the larval stage of *H zea*, our goal was to estimate 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 our population estimates of bat colonies in the study area. The model we develop is a

Figure 1. *The Brazilian free-tailed bat (*Tadarida brasiliensis*).*

generalized case, based on the most recent and authoritative data available.

Two principal sources of variability are 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 can be bounded and our results can be tested by their sensitivity to our assumptions of this uncertainty. The second and more interesting source of variation stems from the relation between pest control services supplied by the bats at the adult stage of the pest and (1) pest control supplied by other natural enemies and environmental stresses at earlier stages in the life cycle of *H zea*, and (2) control supplied by farmers through the application of pesticides. We elaborate on this point below. Although the temporal scale of our study was 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 g of adult insects each night (Kunz *et al.* 1995). Fecal analysis indicates that about 31% of the bat's diet is composed of insects of the order Lepidoptera (Lee and McCracken 2002, 2005). The fraction of eaten Lepidoptera that are bollworms is less certain. Because dietary analysis shows that moth consumption increases two- to three-fold during peak bollworm availability (Lee and McCracken 2005), we assume that this increased moth consumption consists largely of bollworms. This translates to 30–60% of the bats' diet, or 10–20 adult bollworms eaten by a single bat each night. The mass of a moth abdomen, the part consumed by bats, is about 0.07 g. We also assume that approximately half of the moths consumed by a bat are

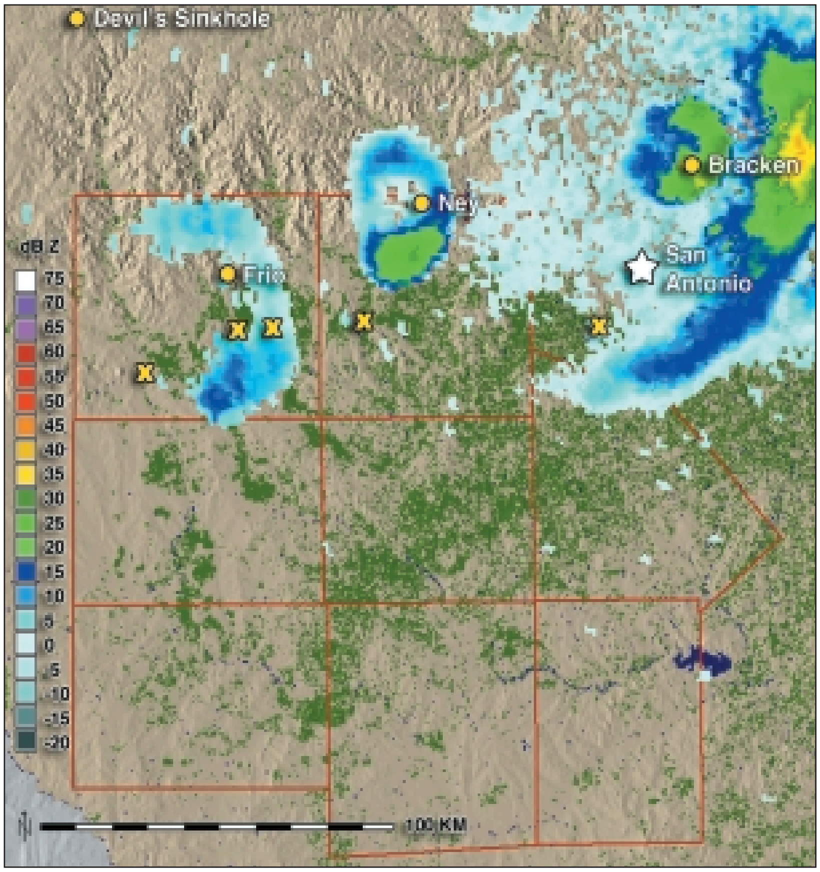

Figure 2. *The 8-county study area (red outline) lies to the southwest of San Antonio Texas and includes colonies of T brasiliensis located in caves (circles) and concrete highway bridges (crosses). Areas of agricultural production are shown in dark green. Also shown is NEXRAD Doppler RADAR imagery of bats returning from nightly foraging over agricultural land. 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.*

female and not all would have infested crops in the Winter Garden area; some may move to other hosts, while others will migrate out of the region. We further assume that 10–20% 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 otherwise have laid eggs on a single host plant within the study area.

The next set of calculations is based on the population dynamics and life history of *H zea* (Sansone *et al.* 2002). A single female will lay 600–1000 eggs in her lifetime. Natural enemies such as ants, beetles, and parasites reduce survivorship to 2–5% through all stages of development (Sansone and Smith 2001), yielding 2% of 600 to 5% of 1000 adult moths. Using the mean value in each range of these survival estimates, a single bat consuming 1.5 adult moths per night will, in effect, prevent about five larvae from damaging crop plants nightly.

The next step is to translate the larvae "prevented" by a bat to the economic value of the damage that these larvae would have inflicted. A single larva will destroy two to three bolls of cotton in its lifetime. However, we correct for the fact that 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 (Sansone *et al.* 2002). That is, fruiting branches set later in the season contribute far less to actual lint yield compared to branches set early in the season. The first third of the fruiting branches set generate about half of the ultimate lint production; the final third accounts for just 7% (Sansone *et al.* 2002).

As a result, a single bat consuming 1.5 adult moths per night could 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 per boll, this means a single Brazilian free-tailed bat provides a service of \$0.02 per night in mid-June, declining to close to zero by August.

The role of pesticides

Economics drive farmers' decisions 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 8000–10 000 larvae per acre, although treatments to control *H zea* in cotton production in the study area vary substantially across farms and time. Such densities generally do not occur until early July, when corn is no longer a viable host for the larvae. Thus, the first week in July is typically when the pesticides are initially applied, which might be followed by as many as three additional applications, spaced about 7 days apart, the last one occurring in the final week of 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 increases from almost zero to 80%, several times higher than what it was prior to pesticide applications.

Pesticides have both private and social costs. The private component is the cost to the farmers of purchasing and applying the chemicals. In the Winter Garden region, a typical single application of synthetic pyrethroid insecticide to control *H zea* costs about \$25 ha^{-1}, with application rates of about 0.03 lb (0.014 kg) of active ingredient used per acre. Social and environmental costs

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

Cost or value	*Low egg/larvae survival*	*Reference case*	*High egg/larvae survival*
Avoided crop damage	\$121	\$638	\$1519
Avoided pesticide cost (private)	\$0	\$100	\$200
Avoided pesticide cost (social)	\$0	\$3	\$6
Total annual value	\$121	\$741	\$1725

Units are thousands of \$US unless otherwise noted.

include public health costs, the loss of natural enemies, the loss of pollination services, losses to fish and birds, and groundwater contamination, as well as others, which we estimate at \$24.38 kg^{-1} (11.06 lb^{-1}) of active ingredient of pesticide (Kovach 2003). This value is based on Pimentel *et al*.'s (1991) estimate of the social and environmental cost of pesticide use in the US at \$8.1 billion dollars, and Gianessi and Anderson's (1995) estimate of 332 million kg (732 million lb) of active ingredients of pesticide use in the US in 1992.

Results

Our results in the case where we assume no use of pesticides are presented in Figure 3a. The reference case places the key demographic variables for *H zea* (survivorship rates for eggs and larvae) at the mean values of their observed ranges. The high and low cases use values at their observed extremes. The annual value has two components. The first is the cumulative value of the avoided damage provided by *T brasiliensis* 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 the reference case, the cumulative annual value of this first component is \$638 000 (Table 1).

The second component of this service is the avoided cost of pesticides. In our reference case, from mid-June to early July, a population of 1 million bats will "prevent" the development of about 5 million larvae per night. If we assume that these larvae would have been distributed evenly across the 4000 ha of cotton, then the economic threshold of 20 000–25 000 larvae ha^{-1} (8000–10 000 $acre^{-1}$) 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 prevent one, and perhaps two, 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 *T brasiliensis*, but the magnitude of consumption by these bats suggests that their loss would be considerable. At about \$25 ha^{-1} per pesticide application, one avoided pesticide application across all 4000 ha would be 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 avoided costs range from zero to \$6000.

Our results in the case where we assume farmers do use pesticides to control *H zea* is presented in Figure 3b. Again, the reference case places the key demographic variables for *H zea* (survivorship rates for eggs and larvae) at the mean values of their observed ranges. The high and low cases use values at their observed extremes. Figure 3b 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.

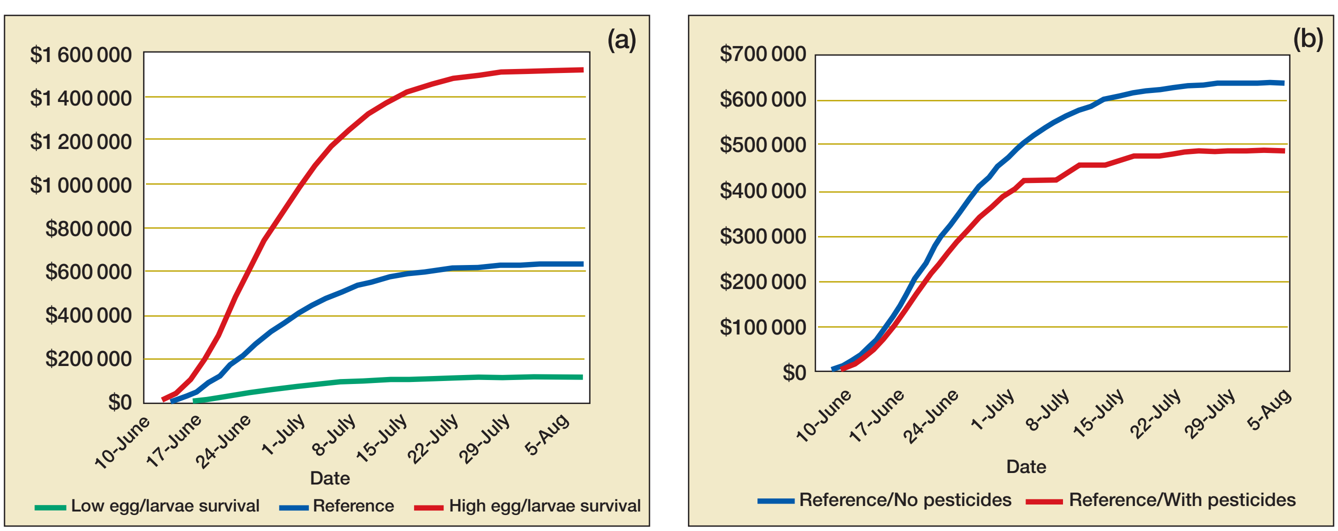

Figure 3. *Estimated annual value of insect pest control provided by the Brazilian free-tailed bat (*T brasiliensis*) to the cotton crop in the Winter Garden region of south-central Texas. (a) Results assume no use of pesticides. (b) The blue line shows the reference case without pesticides, while the red line assumes the use of pesticides.*

Discussion

Our estimate of the value of the pest control service provided by Brazilian free-tailed bats to agriculture ranges from 2–29% of the $6 million value of the cotton crop in the Winter Garden region; the reference case value is about 12%. This suggests that the bats do indeed play a vital role in protecting this crop from damage, and in reducing the costs of pesticide use to farmers and society. One of the distinctive features of this service is that it accrues largely in the early part of the growing season (Figure 3a). Eighty percent of the annual value of the pest control service in the study area accumulates before the end of the first week of July, which in practice is 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 (Wiedenmann and Smith 1997). Because cotton fields are 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. The magnitude of the consumption of moths strongly suggests that *T brasiliensis* reduces crop damage, eliminates at least one application of pesticide, and possibly delays the time when 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 mortality 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.

The use of pesticides to control *H zea* in this region does not significantly reduce the value of the pest control by *T brasiliensis* (Figure 3b). This is due to two factors. First, pest control by bats is concentrated 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 lasts 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 the bats.

Brazilian free-tailed bats clearly play an important role in food production in the Winter Garden region of south-central Texas. Our results suggest that conservation of bat habitat in this region is desirable on economic cost–benefit grounds alone. In other regions of the world, bats also provide key services, such as seed dispersal and pollination of plants (Allen-Wardell *et al.* 1998). Yet the US Fish and Wildlife Service Threatened and Endangered Species Database lists only nine of the 45 bat species of the US as endangered. 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 (Medellín 2003). Our ongoing research will extend this analysis to include all major bat colonies in the region, and to crops other than cotton in Mexico, Texas, and other states in the midwestern US that are beneficiaries of pest control by Brazilian free-tailed bats.

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