Journal of Insect Conservation **6**: 247–259, 2002.

Insect conservation in an urban biodiversity hotspot: The San Francisco Bay Area

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Received 29 May 2002; accepted 11 March 2003

Key words: biodiversity; endangered species; habitat restoration; introduced species; species richness; San Francisco Bay Area; insects; urbanization

Synopsis

The San Francisco Bay Area hosts a diverse insect fauna and a dense cluster of urban areas. The high diversity of insects in the Bay Area arises for three primary reasons: its location in the California biotic province, the diverse local environment and the entomologist-area effect. The juxtaposition of high insect diversity and an area intensively used by humans led to the first recorded extinction as well as the first efforts to conserve insects in the United States. Habitat loss due to urbanization, agriculture, and invasive species is largely responsible for local extinctions and reduction in abundance of the remaining species. Invasive species such as the Argentine ant and pathogens causing mortality of oaks and pines are poised to have substantial impacts on the insect fauna of the Bay Area in the near future. Understanding which taxa can or cannot persist in remnant habitat patches within an urban or agricultural matrix, and what management practices would encourage persistence should be a focus of future research. Assessments of population status should be focused on insects at risk of extinction because of their restricted geographic ranges, low vagility, interactions with invasive species, or known reduction in their habitat. Assessments that combine examinations of museum collections, literature, and field surveys might enable determination of the status of many species within the Bay Area. Such an approach might better define the scope and magnitude of the problem of conserving insects in an increasingly urbanized region.

Introduction

The San Francisco Bay Area (hereafter as Bay Area) hosts a high diversity of insect species and nearly seven million people (Myers *et al*. 2000; ABAG 2001). Given the coincidence of a biodiversity hotspot and a major urban center, it is not surprising that the Bay Area is also a hotspot for threatened biodiversity. More than 50% of the species of arthropods listed by the U.S. government as endangered occur in the Bay Area (Dobson *et al*. 1997). While the listing of insect species in the Bay Area as endangered may reflect a geographical bias and that the first entomologist in the U.S. Office of Endangered Species, Paul Opler, was trained in the Bay Area, many local taxa have small, restricted distributions and are threatened by urbanization (Bossart & Carlton 2002). In this paper we address the following questions: What is the scope of the problem of conserving insects in the Bay Area? What efforts have and are being made to assess the impact of urbanization on insects, to develop conservation plans for endangered insects, to restore or protect habitat, and to re-establish locally extirpated species? What then are the prospects for insect conservation in the Bay Area?

The San Francisco Bay Area

The Bay Area is a nine county region of approximately 18,000 km^2 that includes San Francisco Bay and surrounding lands (Figure 1). We define our region as the Bay Area standard metropolitan statistical area (SMSA) because information on human demography, economic conditions, and land use and land cover changes are reported for this area. We conceive of an

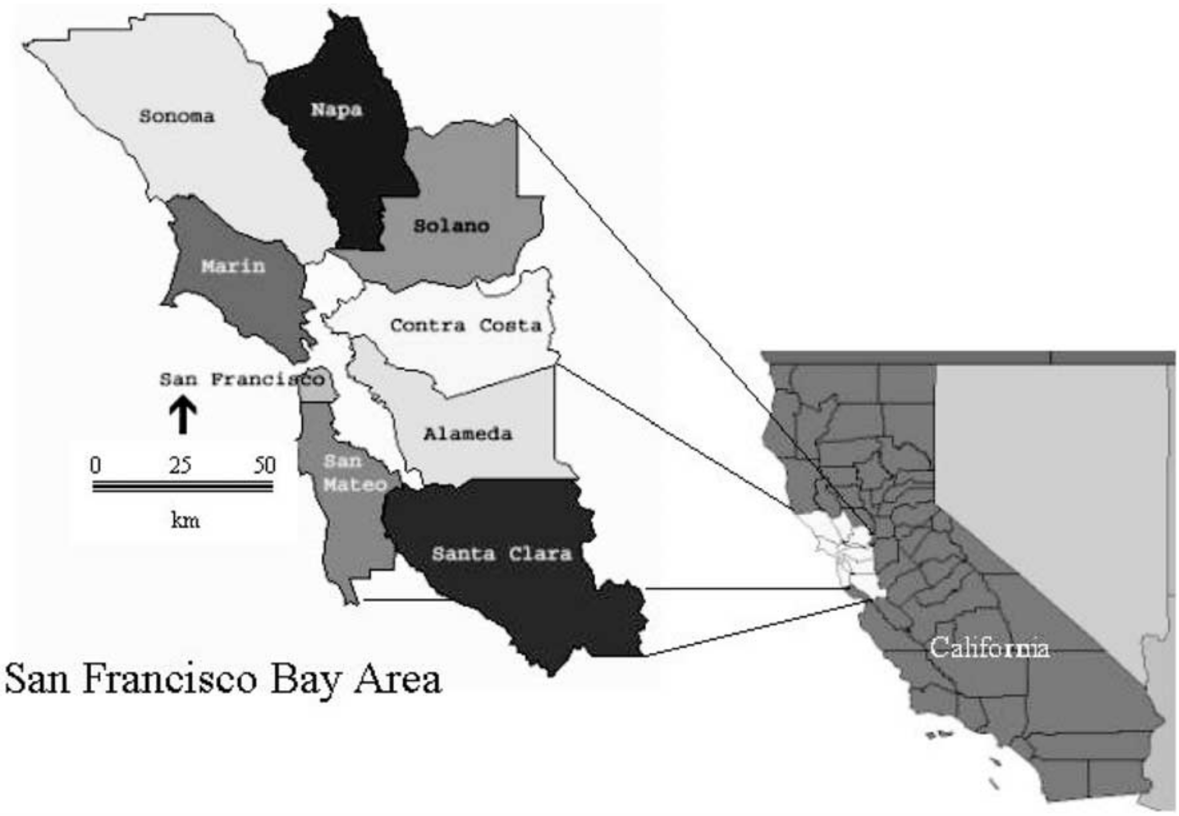

Figure 1. The Bay Area – a nine-county region surrounding San Francisco Bay.

urban region as the lands and waters both embedded within and surrounding areas of intense urban land use. These lands include fragments of un-built land within urban districts as well as remnant patches of natural habitats and agricultural land not yet converted to urban land uses, including parks and natural areas within or on the periphery of urban lands. We include this variety of land within our concept of an urban region since these lands and the biota they harbor are likely to be affected by activities associated with the nearby urban lands.

The Bay Area was long populated by indigenous peoples. Five Spanish missions were established in the late 18th century in the Bay Area to integrate the indigenous peoples into the Mexican colony and protect its border. Just prior to the California gold rush of 1849 the Bay Area was populated by no more than a few thousand people. By 1880 the city of San Francisco and Alameda County had a combined population of 300,000 and was the largest urban area in western North America (Forstall 1996). Since 1930, the population of the Bay Area has more than quadrupled (Figure 2). Today urban areas almost completely encircle the bay

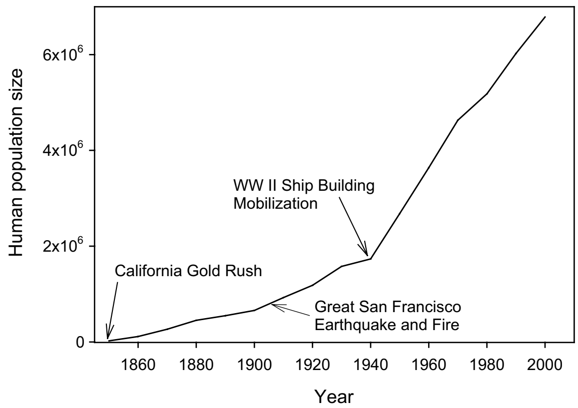

Figure 2. Human population growth in the Bay Area 1850–2000. Data from U.S.A. Census Bureau summarized by the Association of Bay Area Governments (2001).

(Figure 3). San Francisco has the highest population density in the region, but the largest population center is comprised of the city of San Jose and the adjacent region known as Silicon Valley (Table 1).

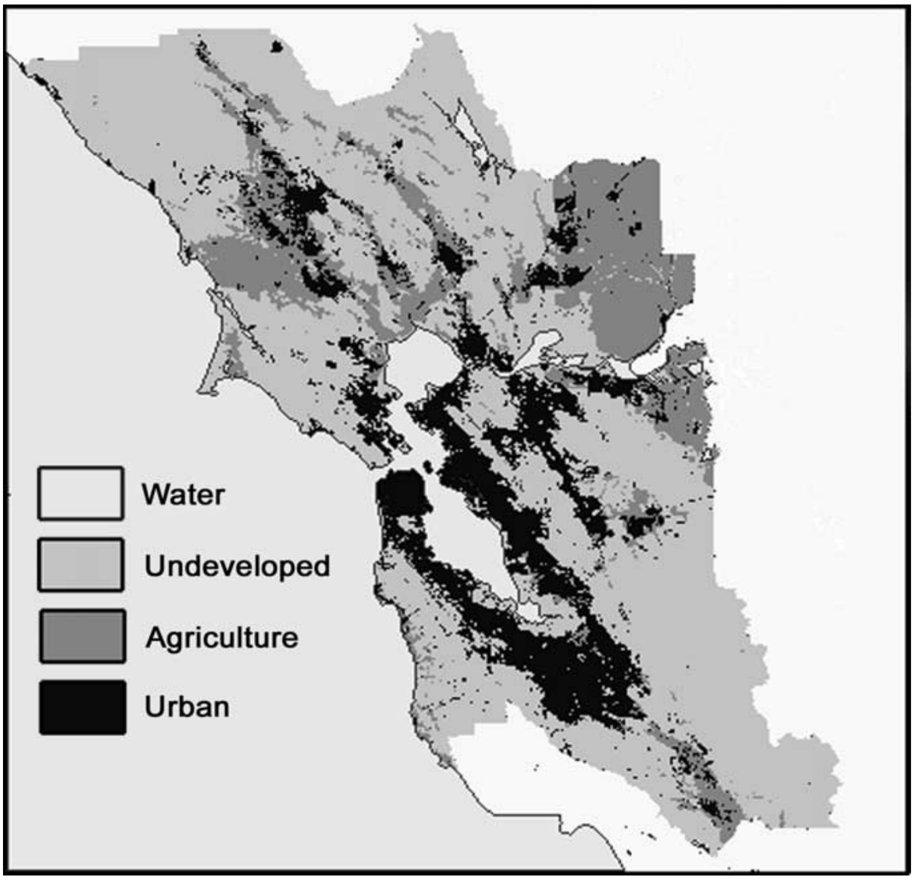

Figure 3. Land use map of the Bay Area. Map reflects land use patterns as of 1995 (Perkins 1996). Note that undeveloped lands include land in private ownership as well as public lands. More extensive areas of native forest lands occur at both the northern and southern reaches of the region.

Table 1. Population density, land area, extent of public lands, and insect species richness (based on pinned specimens in CAS collections) of counties in the Bay Area.

County	Human population density (number/km^2)	Area (km^2)	Area of public lands (km^2)	Proportion of public lands	Number of insect species
Alameda	755	1914	451	0.24	3441
Contra Costa	509	1867	734	0.39	3046
Marin	184	1347	554	0.41	4030
Napa	64	1954	608	0.31	2274
San Francisco	6378	121	17	0.14	2475
San Mateo	608	1164	521	0.45	2824
Santa Clara	503	3346	1442	0.43	3074
Solano	184	2146	181	0.08	553
Sonoma	112	4084	304	0.07	2846

Insect Diversity in the Bay Area

The high diversity of insects in the Bay Area arises for three primary reasons, its location in the California biotic province, the diverse local environment, and the entomologist-area effect. The California biotic province in its entirety is considered a biodiversity hotspot, hosting many endemic taxa (Myers *et al*. 2000). The topography, geology, soils, and climate of the Bay Area are heterogeneous in comparison to other urban areas in North America and Europe. The Bay Area is situated at 37° north latitude and has a

Mediterranean climate. Elevation ranges from sea level to over 1000 m, the area straddles the western margin of the North American and parts of the Pacific plate, soils vary from alluvial to serpentine, and the interaction of the ocean, mountains, and air masses renders the climates of locations only kilometers apart substantially different. Such heterogeneity in the environment has engendered a wide variety of habitats, high endemism, and a diverse local flora, which contributes to the high diversity of insects in the Bay Area. Finally, the Bay Area is home to the oldest and largest natural history museums in the western United States; this proximity has led to a disproportionate share of natural history exploration.

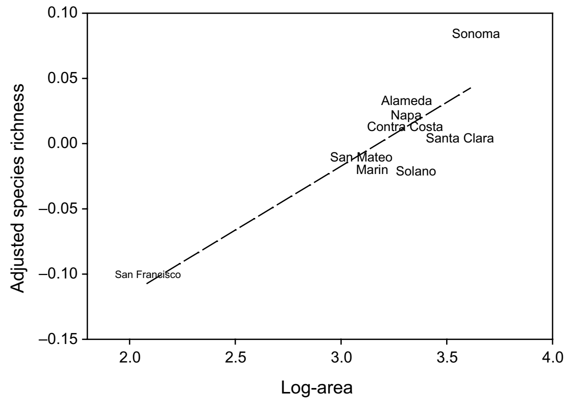

Figure 4. Species richness of insects in Bay Area counties adjusted for sampling effort in relation to land area. Estimates of insect species richness of counties in the Bay Area are based on records of the pinned insect collections in the CAS. Sampling effort is estimated as the number of specimens from each county in the CAS collections. After adjusting for sampling effort, variation in the log-number of insect species is significantly associated with log-county area and the proportion of land in public ownership (OLS multiple regression ($F_{3,5} = 538.4$, $p = 0.000001$).

Insect conservation in the Bay Area: The scope of the problem

It is difficult to know what insects occurred in the Bay Area prior to settlement by European colonists. The naturalists associated with the California Academy of Sciences (CAS), which was founded in 1853, first set out to explore and explain the natural world by focusing on the Bay Area. The 60,000 specimens in the Academy's insect collection would have been invaluable in reconstructing the entomofauna of the region had they not been destroyed by fire caused by the great San Francisco earthquake of 1906 (D. Kavanaugh, pers. comm.).

While records for areas that have long been occupied by buildings and roads can never be reconstructed, many insects live in remnant patches of habitat, gardens, roadside verges, agricultural regions, and in the remaining protected lands. However, it is a daunting task to tackle even the most taxonomically tractable groups because of the high diversity of insects in the Bay Area. The 248,565-pinned specimens in the insect collections of the CAS alone contain 8668 named species (Table 1 and Figure 4, we use species in the broad sense to include subspecies). We cannot compare this estimate of diversity to other urban areas in the United States because no other natural history museum has computerized specimen records with locality data. However, our estimate of the species richness of insects in the Bay Area based on the CAS collections rivals estimates of the diversity of invertebrates for Austria (9694 species and 4.6 times the area) and the former West Germany (10,290 species and 13.9 times the area – Wilson 1992, p. 258), and approaches the insect species richness of Great Britain (14,364 species and 13.5 times the area – DETR 2001). Furthermore, estimates of richness based on the CAS collections are likely to be substantial underestimates because: (1) they only include pinned taxa, (2) experts on some groups deposit specimens in other museums, and (3) the region has not been thoroughly sampled. In recent sampling, Frankie *et al.* (2002) found 72 native species of bees in Berkeley and Albany, four of which are absent from the CAS collections. Spring sampling of bees in oak woodlands has netted 33 and 31 species, respectively, in Napa and Sonoma Counties of which 17 and 10 species, respectively, are not in the CAS collections (G. LeBuhn, pers. comm.).

Urbanization of the Bay Area beginning in the 19th century resulted in the first recorded extinction of a native U.S. insect, the satyr butterfly (*Cercyonis sthenele sthenele*). This was followed in the 20th century by the extinction of the pheres blue (*Icaricia icariodes pheres*) and the Xerces blue (*Glaucopsyche xerces*); the species from which the insect conservation organization the Xerces Society takes its name. While the satyr went extinct before its habits could be recorded, both blues flew in the sand dunes that once dominated much of San Francisco, using *Lupinus* and *Lotus* as host-plants. Doubtless a number of other insect species in less well-known groups were also lost, but some may remain in museum collections awaiting discovery. For instance, the Antioch dunes shieldback katydid (*Neduba extincta*) was described from a single museum specimen after it had gone extinct (Rentz 1977).

Steiner (1990) reported that 142 species of butterflies have occurred in the Bay Area, only three of which have gone extinct. Hafernik and Reinhard (1995) reconstructed the butterfly fauna of San Francisco County using data from museum specimens, the literature, and unpublished records of sightings. Of the 46 species that they list as native to San Francisco, only 26 have been sighted within the last 15 years. However, most of the 20 species no longer found in San Francisco are found elsewhere in the area. We can calculate the expected number of species of butterflies that would be lost given that 86% of San Francisco's land area has been urbanized (Table 1). Assuming a species–area relationship (SAR) with a slope of $z = 0.25$ (an average value for many taxa, see Connor & McCoy 1979; 2000), calculations based on the SAR predict that 18 species would have been lost, while calculations based on an endemics-area relationship predict that an upper bound of 31 species would have been lost (Kinzig & Harte 2000). That only 20 species have been lost from San Francisco could either imply an extinction deficit, and/or that butterflies persist by using garden, roadside, and other habitats. No effort has yet been made to examine the status of other insect taxa in any part of the Bay Area. If patterns of diversity and its loss among butterflies mirrors that of other insect taxa, then 43% of the insect fauna of San Francisco is extinct within that county, but may persist in less urbanized counties.

While it might be difficult to gather very specific locality data from specimens, museum collections and the monographic literature could provide an estimate of what species once occurred in the Bay Area. Further field surveys, focused on groups at risk of extinction because of their small geographic ranges, low vagility, interactions with invasive species, or known reduction in their habitats, would permit us to determine the status of many species within the Bay Area. Such an approach might enable us to better define the scope and magnitude of the problem of conserving insects in an increasingly urbanized region.

The effects of urbanization on insects

The primary effect of urbanization on insects is via habit loss. The loss of 43% of the species of butterflies from San Francisco County probably arises largely as a result of habitat loss (Hafernik & Reinhard 1995). Only 14% of the land area of San Francisco remains in public ownership as parkland (Table 1), and we estimate that more than 40% of developed land is occupied by pavement and structures (Cappiella 2001). In Palo Alto, in Santa Clara County, Blair and Launer (1997) found that none of the butterflies that occur on the rural end of an urban–rural gradient occur in the urbanized business district – again largely the result of habitat loss.

Besides the direct loss of habitat, urbanization could affect insects via habitat fragmentation, and by changing the quality of habitat that remains embedded in the urban matrix (Rickman & Connor 2003). Both habitat loss and fragmentation arise inescapably from urbanization, yet neither is uniquely caused by the conversion of natural habitats to urban land uses. Habitat loss and fragmentation are inherent to the process of land conversion by whatever means. Any unique effects of urbanization must arise from the ways in which urbanization and human activity in urban areas affect the quality of habitat remnants or the probability of successful dispersal between habitat remnants while surrounded by a matrix of urban land. Changes in habitat quality could be manifested as altered host-plant quality, soil attributes, microclimate, or enemy attack. Pesticides, air pollution, changes in light, nutrient, and water regimes, soil compaction, and exotic species could cause such changes in habitat quality.

Changes in habitat quality caused by urbanization may result either in declines or increases in the abundance of insects. Some species of herbivorous insects that occur in urban areas persist at lower densities than in natural habitats (Luck & Dahlsten 1975; Driestadt *et al*. 1990), while other species are more abundant and inflict more damage to their host-plants than in their natural habitats (see Nuckols & Connor 1995 for a review, and Oksanen *et al*. 1996; Koslov 1996; van Rensberg *et al*. 1997; Speight *et al*. 1998). Higher densities of herbivorous insects in urban areas may arise for two reasons: because the urban environment stresses plants by water and temperature imbalances, soil compaction, and air pollution, which makes plants more susceptible to insect attack, or because populations of the natural enemies of herbivorous insects are lower in urban areas (Nuckols & Connor 1995). Furthermore, for some insects, exotic plants serve as alternative hosts that support larger populations than in natural habitats where the native host plants are sparse (Shapiro 2002).

Rickman and Connor (2003) examined the leaf-mining moths on *Quercus agrifolia* (coast live oak) in the Bay Area to assess the effects of urbanization apart from those caused by habitat loss and fragmentation. By selecting sites where natural habitats had been lost to either urban or agricultural land use, they attempted to distinguish the effects of urbanization from those caused by agriculture. They found no association between urbanization and species richness, and that for only three of the 18 species in this community was their abundance associated with the degree of urbanization – two positively and one negatively. Hence, for this insect community it appears that the effects of urbanization, apart from those caused by habitat loss and fragmentation, are species specific and no different from replacing and fragmenting habitats with agricultural land.

Effects of introduced species

We know little about the magnitude of invasion or impacts of introduced species on native communities of insects. Dowell and Gill (1989) and Powell (1992) report that 177 species of insects or five species/year invaded California between 1955 and 1988, but we have no information specific to the Bay Area. The extent of invasions into San Francisco Bay and to terrestrial plant communities provides an indirect measure of the potential importance of invasions into the Bay Area to native insects. Over 200 species that now account for 95% of biomass in some bay habitats have been introduced to make San Francisco Bay 'the most invaded aquatic ecosystem in North America' (Cohen & Carlton 1995). For plant communities, 543 species have been introduced into the Bay Area, which amounts to 10% of the flora of California (Randall *et al.* 1998). Clearly, the Bay Area has and continues to be colonized at a rapid rate by exotic species.

The high rate of invasion of species into the Bay Area arises because of the volume of trade channeled through the air and seaports that surround San Francisco Bay. While trade might be the source of many exotic species, the moderate yet heterogeneous climate and diverse habitats also provides many opportunities for exotic species to become established.

In spite of the number of exotic species that have established in the Bay Area, only a small number have become invasive. For butterflies, Hafernik and Reinhard (1995) reported 12 species from outside the area have established in San Francisco. However, there is no evidence that the reduction in abundance and local extinction of native butterflies has been caused by introduced species of butterflies. Yet exotic species of insects, amphipods, plants, and pathogens have become invasive and all may be affecting the indigenous insect fauna of the Bay Area.

Invasive insects and arthropods

The Argentine ant has invaded riparian areas and disturbed habitat throughout the Bay Area (Ward 1987; Holway 1995). Human and Gordon (1997) and Sanders *et al.* (2001) report that in areas invaded by the Argentine ant, native ants are virtually absent and other soil and litter-dwelling insects, such as Collembola, are reduced in abundance. However, Holway (1998) found no differences in the abundance of soil arthropods, spiders, and carabid beetles between areas invaded by Argentine ants and un-invaded areas. The only ants that remain in areas invaded by Argentine ants are species that forage under litter or in the soil (Human & Gordon 1997). Several species of ant-tended lycaenid butterflies occur in the Bay Area, two of which are endangered species (see below). Sanders *et al.* (2001) report that Argentine ants displace the ants that tend these lycaenid butterflies, so their persistence may be jeopardized by Argentine ants. We do not know whether the effect of Argentine ants is restricted to arthropods that use the soil surface, or extend to arthropods that inhabit microhabitats such as plant surfaces.

Native amphipods are found exclusively in marine and freshwater environments, but an exotic terrestrial amphipod from Australia, *Arcitalitrus sylvaticus*, has become abundant in San Francisco County (Baldinger 1993). *Arcitalitrus sylvaticus* joins a soil fauna that is numerically dominated by the introduced isopods, *Armadillium vulgare* and *Porcelli*o spp., and this fauna is likely to displace soil insects in invaded areas (Holway 1998). However, the effects of these exotic species on nutrient cycling and on native plant and insect species have yet to be examined.

Invasive plants

Several exotic plants have invaded natural habitats in the Bay Area, including trees such as blue gum (*Eucalyptus glogulus*), shrubs such as French broom (*Genista monspessulana*), and herbs such as iceplant (*Carpobrotus edulis*). For example, iceplant has displaced the native flora of coastal dune scrub and we presume that insects associated with native plants in this habitat have been reduced in abundance by this invasion. In a study on the effects of iceplant on a native plant, soil samples from areas where iceplant had been removed yielded fewer invertebrates than soils from areas never invaded by iceplant (C. Conser, pers. comm.).

Not all exotic plants have negative effects on native insects. Native insects use some exotic plants because native host-plants have been reduced in abundance by habitat loss. In the Bay Area several native butterflies, such as the painted lady (*Vanessa cardui*), the buckeye

(*Junonia coenia*), and many lycaenids and skippers, use exotic plants (Steiner 1990; Shapiro 2002). The anise swallowtail (*Papilio zelicaon*) is now found more often on two species of exotic plants, sweet fennel (*Foeniculum vulgare*) and poison hemlock (*Conium maculatum*) than on native plants (Steiner 1990; Shapiro 2002). Both *F. vulgare* and *C. maculatum* were introduced in the late 1800s, and *F. vulgare* thrives in a variety of habitats (Bossard *et al.* 2000). Because sweet fennel is perennial, it has also created the opportunity for *P. zelicaon* populations that were previously univoltine to become multivoltine. *Papilio zelicaon* may now be more abundant in the Bay Area than prior to the introduction of sweet fennel. The red admiral (*Vanessa atalanta*), once uncommon in the Bay Area (Tilden 1965), is now among the most abundant butterflies in San Francisco with its larvae feeding on the exotic *Parietaria judaica*. The use of exotic hosts by other insect taxa has not been examined but may parallel that observed for butterflies.

Invasive plant pathogens

The discovery of two pathogens that cause high rates of mortality among native oak and pine trees has alarmed environmentalists and forest management officials. *Phytophthora ramorum* the agent for Sudden Oak Death Syndrome (SODS) causes mortality of trees in the oak family and has become common in Marin and Sonoma counties (McPherson *et al.* 2000; Rizzo *et al.* 2002). The white pine blister rust (*Cronartium ribicola*), which causes mortality among the most abundant pines in the Bay Area, occurs just to the north and is poised to invade. The impact of these pathogens on native insects could be substantial. Insects associated with tree species that suffer mortality would be at risk, particularly host-specific insects. A similar invasion in eastern North America by the chestnut blight (*Cryphonectria parasitica*) led to a drastic reduction in the abundance of chestnut (*Castanea dentata*) and the extinction of eight species of insects (Opler 1979). This estimate of extinctions is likely an underestimate since no comprehensive assessment of the insect fauna was made before or after the arrival of chestnut blight.

Invasive biological control agents

The release of insects to suppress other introduced species also can have negative effects on native species. In 1975, the native Suisun thistle, *Cirsium hydrophilum* v. *hydrophilum*, was thought to be extinct; but in 1993 a few thousand individuals were found in Contra Costa County. In 1997, the U.S. government listed Suisun thistle as an endangered species (USFWS 2002). Many factors contributed to the decline in abundance of Suisun thistle, including predation by an exotic seed weevil, *Rhinocyllus conicus* (Coleoptera: Curculionidae). This weevil was imported to control introduced thistles, but expanded its attack from exotic *Carduus* species to native *Cirsium* species. By 1998 *R. conicus* was attacking one-third of the native California species of *Cirsium* (Louda 1998). In 1996 *R. conicus* was documented to attack Suisun thistle (Federal Register 1996). It is not known what effect *R. conicus*, a heavy feeder on thistle seed heads, will have on the population of this rare thistle. Suisun thistle hosts a native butterfly, *Phyciodes mylitta* (Mylitta crescent), which is shifting from a dependence on native to non-native thistles (*Carduus and Cirsium*) as native host populations dwindle (Steiner 1990).

Conservation plans for endangered species of insects

Protection for insects became a part of U.S. government policy with the passage of the Endangered Species Act (ESA) of 1973, a law that extended protection to all endangered plants and animals, including insects. In 1976, eight species of butterflies were proposed as endangered species. Three of these species, Lange's metalmark (*Apodemia mormo langei*), San Bruno elfin (*Incisalia mossii bayensis*) and mission blue (*Icaricia incarioides missionensis*), were from the Bay Area (Pyle *et al.* 1981). Since that time the number of listed species of insects in the Bay Area has increased to eight (Cushman 1993; Powell & Parker 1993; Weiss 1993, Table 2).

Each of these endangered species suffers from habitat loss and degradation. The delta green beetle is found

Table 2. Endangered insects in the Bay Area.

Order	Common name	Scientific name
Lepidoptera	Lange's metalmark	*Apodemia mormo langei*
	San Bruno elfin	*Incisalia mossii bayensis*
	Behren's silverspot	*Speyeria zene behrensii*
	Mission blue	*Icaricia incarioides missionensis*
	Callippe silverspot	*Speyeria callippe callippe*
	Myrtle's silverspot	*Speyeria zene myrtleae*
	Bay checkerspot	*Euphydryas editha bayensis*
Coleoptera	Delta green beetle	*Elaphrus viridis*

exclusively in vernal pool habitat, which has become scarce and degraded because of agricultural use and invasion by introduced plants (Essig Museum 2001). All of the listed species of butterflies are univoltine, monophagous as larvae, and have low vagility – traits that make them vulnerable to extinction (Arnold 1983). The combination of inherent vulnerability and extensive negative anthropogenic effects led to their listing under the ESA.

The listing of the mission blue and the San Bruno elfin, two butterflies from San Bruno Mountain just south of San Francisco, put these species at the forefront of conservation efforts and controversies in the Bay Area (Hafernik 1992). Housing projects proposed for San Bruno Mountain – the largest undeveloped parcel of private land on the San Francisco peninsula – were delayed until their impact on the survival of these butterflies could be determined. Under the ESA, any destruction of habitat for these butterflies was considered tantamount to taking and destroying butterflies and was prohibited. A political compromise between the developers and the U.S. government led to changes in Section 10a of the ESA (Nelson 1999). These changes allow the incidental taking of endangered species as long as the actions are deemed not to jeopardize the survival of the species. Development is allowed in the context of an approved Habitat Conservation Plan (HCP) that mitigates impacts on endangered species. The first HCP was approved for San Bruno Mountain and its endangered butterflies. As a result, much of the mountain was preserved as parkland while other lands, including habitat for the endangered butterflies, were developed for housing. The HCP continues to guide development of San Bruno Mountain and remains controversial, as does the overall concept of HCPs (Kareiva *et al*. 1999). While HCPs have not been developed for most other endangered insects in the Bay Area, the San Bruno Mountain HCP provided a model that is used nationwide to allow land development, even in the presence of endangered species. Besides protection of the habitat, most HCPs include measures intended to provide for the continued survival of the species by monitoring, management, and habitat restoration (Launer *et al*. 1992; Wilhere 2002).

One of the greatest success stories involving a Bay Area insect concerns Lange's metalmark, a species endemic to isolated sand dunes along the Sacramento River in Contra Costa County. The listing of Lange's metalmark as an endangered species led to the establishment of the first wildlife refuge designed to protect a rare insect, the Antioch Dunes National Wildlife Refuge. Introduced plants that stabilize the dunes, sand mining, and off-road vehicle use degraded the dunes and caused a decline in the metalmark and other rare species. From 1977 to 1982 the butterfly population declined from 2000 to 600 individuals (Powell & Parker 1993). Lange's metalmark uses auriculate buckwheat (*Eriogonum nudum*) as a larval host-plant and nectar source plant. Seedlings of *E. nudum* thrive on unstable dunes. To stem further decline of the metalmark, government and private entities took actions to prohibit mining, purchase land, obtain conservation easements on adjacent land, and implement habitat management – including barring off-road vehicles, removing exotic plants, and re-vegetation of *E. nudum* (Howard & Arnold 1980). After these restoration efforts, Lange's metalmark increased to pre-1977 abundances reaching 2442 in 1999 (Powell & Parker 1993). However, in 2001 the population declined to 737 due to the invasion of winter vetch, wildfires, and the natural senescence of the largest stands of *E. nudum*. Efforts continue to remove invasive species, replant *E. nudum*, and increase the area of dunes under protection (S. Spakoff, pers. comm.). With continued restoration efforts (and barring extensive wildfires) the prognosis for the Lange's metalmark is good (Opler & Robinson 1986; Essig Museum 2001; Natural Resource Projects Inventory 2002). However, this species will remain at great risk unless multiple, independent populations can be established.

Because of long-term studies begun in the 1960s by Paul Ehrlich and colleagues the bay checkerspot is one of the world's best-studied insects (Ehrlich *et al*. 1975; Ehrlich & Murphy 1987). Historically, this butterfly's range included five counties in the Bay Area. The bay checkerspot now persists as metapopulations in isolated habitat fragments within San Mateo and Santa Clara counties (Harrison *et al*. 1988; Murphy *et al*. 1990). Its reduction was largely due to urbanization and the invasion of non-native plants that out-competed its host- and nectar-source plants. Overgrazing in parts of the habitat and two years of drought in the mid-1970s also contributed to its decline. A proposed landfill in Kirby Canyon in Santa Clara County in the late 1980s threatened the largest known source population (Murphy 1988).

Since the bay checkerspot was listed as a threatened species in 1987, the Jasper Ridge populations made famous by the Ehrlich group have gone extinct with no checkerspots being observed since 1997. Short-term climate variation coupled with prior loss of habitat due to invasion of exotic grasses was the probable cause of these extinctions (McLaughlin *et al.* 2002). However, conservation efforts have protected the Kirby Canyon population while allowing the landfill to go forward (Murphy 1988). Cooperation between the landfill owner and government agencies led to establishment of a fund to conserve the bay checkerspot. Under the recovery plan, the landfill owner rotates land use over a 55-year period with use followed by habitat restoration, and 100 ha of adjacent land were leased to manage livestock grazing (Murphy 1988).

Habitat restoration for insect conservation

Endangered insects are not the only focus of Bay Area environmental advocacy groups interested in combating habitat loss and degradation. Many non-threatened Bay Area insects have experienced a decline in abundance due to habitat loss. Habitat gardens have been championed as a way to replace lost natural habitat. The International Federation of Butterfly Enthusiasts (IFBE), the North American Butterfly Association (NABA), and the National Wildlife Federation (NWF) all recommend creating gardens to promote butterflies. The NWF certifies gardens as *habitat gardens* if the garden contains food, water, shelter, and breeding sites for wildlife. There are over 150 Backyard Wildlife Habitat™ Gardens in the Bay Area many of which provide habitat for butterflies (D. Mizejewski, pers. comm.).

Studies have shown that adult butterflies use gardens to nectar, yet it is unknown if gardens can provide for oviposition and larval survival (Pullin 1995). In studies examining the impact of urbanization, Hardy and Dennis (1999) and Wood and Pullin (2002) found that butterfly abundance depended more on host-plant availability than on urbanization.

If butterflies can successfully use cultivated, native host-plants, then appropriate plantings in yards, parks, or other lands can increase butterfly abundance. Most enthusiasts assume that if nectar and host-plants are made available that butterflies will use garden sites and complete development in gardens. However, most gardens may be too small and isolated to be used by butterflies or even if discovered they may serve as population sinks rather than sources. Using the pipevine swallowtail butterfly (*Battus philenor*) and its host-plant *Aristolochia californica*, Levy and Connor (2003) compared use of garden and natural sites. They found that all life-history stages of *B. philenor* were more likely to be observed in natural than in garden sites, that egg density and survival were lower in gardens than in natural sites, and that the probability of larvae surviving to the last instar was lower in garden than natural sites. For *B. philenor*, butterfly gardening as currently practiced is unlikely to contribute to local abundance and population persistence. However, given plantings of sufficient size, maturity, and insolation we believe it likely that gardens can serve as net sources of butterflies.

Draining of wetlands for housing and industry – as well as channeling creeks for flood control – has greatly reduced and altered wetlands in the Bay Area (Hafernik 1992). These activities have contributed to local extinctions for many aquatic insects in the Bay Area, such as the San Francisco forktail damselfly (*Ishnura gemina*) (Hafernik 1992). The San Francisco forktail damselfly is red-listed by the IUCN as endangered (IUCN 2000) and has been the object of considerable study (Garrison & Hafernik 1981; Hafernik & Garrison 1986; Leong & Hafernik 1992). Its most intensively studied population, the population in Glen Canyon Park in San Francisco, went extinct in the late 1980s due to overgrowth of its habitat. Urbanization of the surrounding area has greatly altered the watershed and characteristics of Islais Creek that flows through the bottom of the canyon. The prior occurrence of the San Francisco forktail damselfly in the canyon led citizen groups to lobby the San Francisco Department of Parks and Recreation to promote restoration of creek and wetland habitats in the canyon. As part of a creek restoration project begun in 1996, Gene Hannon and one of us (Hafernik) reestablished this damselfly in Glen Canyon (Hannon 2001). After restoring habitat, adult damselflies from San Mateo County were released into the canyon and the damselflies were then monitored for two years. By the end of the first summer, damselflies were again emerging from the canyon and their survival rate soon approached that observed before they had been locally extirpated. However, because habitat management was not continued, the damselfly population crashed in subsequent years as the habitat became overgrown and shaded. Clearly, we need continued management of habitats since restoration projects cannot reestablish all the natural processes that once characterized an area.

Habitat restoration in urban areas is often difficult, not only because of the problem of restoring natural processes to highly altered systems, but also because of the variety of priorities that city dwellers have for open space. Some would prefer that urban open space be developed for playing fields for recreation rather than for preservation of native biodiversity.

Different priorities may even cause splits among environmentalists. In San Francisco, an area that was mostly treeless before urbanization, many areas of open space are covered with forests of introduced trees such as blue gum (*Eucalyptus globulus*). Restoration of native plant and insect communities often requires removal of some of these trees. Trees are highly valued by many citizens and proposals to remove even a few meet with strong opposition. In San Francisco many native butterfly species now use introduced, weedy larval food plants, which are targets for removal when restoring native plant communities. However, the benefit to native plant communities of removing introduced plants that have become hosts for native butterflies needs to be weighed against the potential costs incurred by reducing butterfly habitat, and offset by reestablishing the native host-plants where appropriate. Native plant restoration projects that require the suppression of introduced plants have met with opposition from those who fear that native butterflies will be negatively affected by these actions.

Synthesis and prospectus

The insect fauna of the Bay Area has suffered several extinctions and probably many others have gone undetected. However, because early records of the indigenous fauna were lost, and assessing the current status of most taxa is difficult, it is impossible to estimate

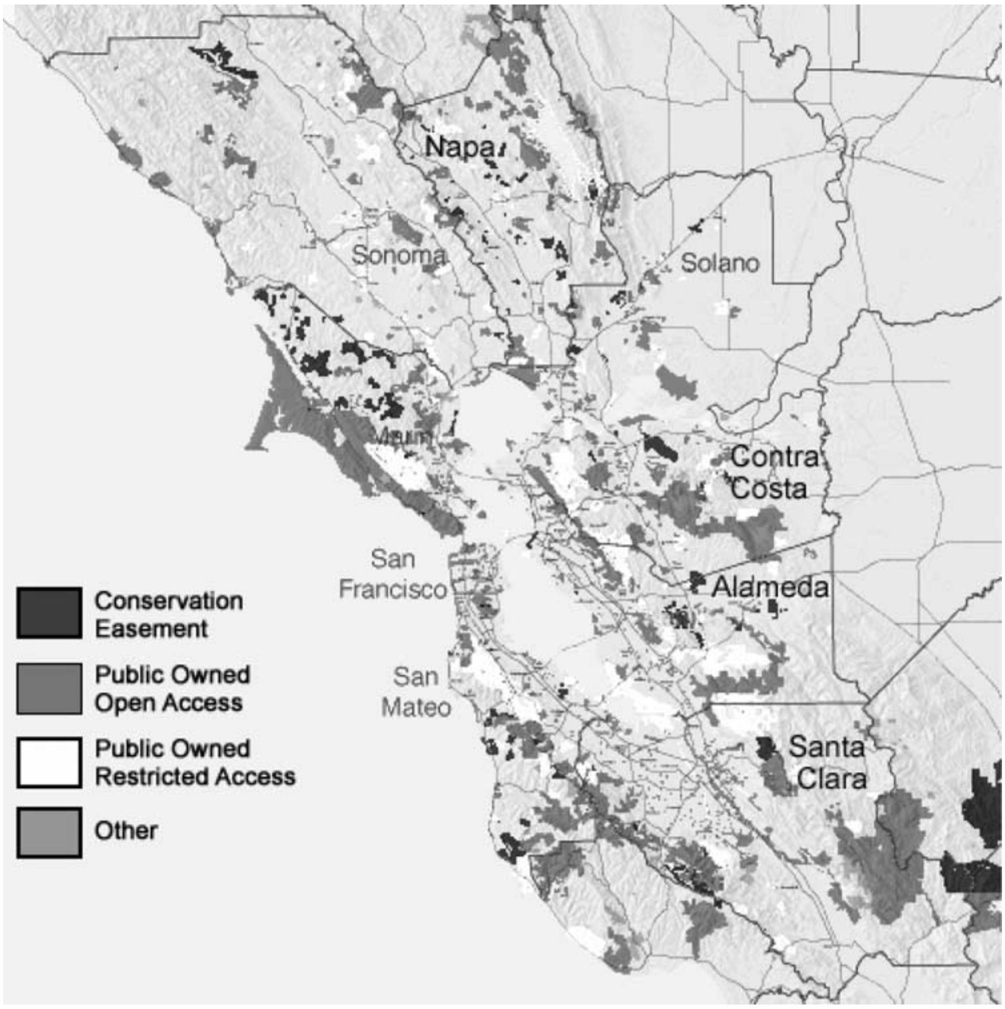

Figure 5. Map of protected lands in the Bay Area. Map is based on data compiled by the Bay Area Open Space Council (Bay Area Open Space Council 2002).

accurately the full extent of species loss. For only a few species of insects that persist in the Bay Area do we know how their distribution and abundance have been altered by urbanization, agriculture, invasive species, and other human activities.

Conservation efforts targeted specifically towards insects are rare in the Bay Area and elsewhere. Only the charismatic, large invertebrates – butterflies – have a grass roots following including non-governmental organizations that participate in their conservation. However, the Xerces Society has a broader mission in insect conservation that may yet engender support beyond the scientific community. Most actions taken to conserve insects involve government agencies acting under the ESA of either the U.S. government or the state of California.

Most insect conservation has been inadvertent or the by-product of actions taken to protect other taxa such as plants and vertebrates. In the Bay Area, 28% of the land area remains in public ownership (excluding playing fields and golf courses). In some counties, over 40% of the land is publicly owned (Table 1, Figure 5). These public lands serve multiple uses including recreation, open space, and conservation. Only the Suisun Marsh National Wildlife Refuge, San Bruno Mountain State and County parks, and land managed as part of the Habitat Conservation Plan for the bay checkerspot have been specifically set aside to conserve insects. The Bay Area is fortunate to host the Golden Gate National Recreation Area and the Point Reyes National Seashore, along with numerous state parks. Parks established for recreation and conservation benefit insects while providing refuge for marine mammals, mountain lions, bears, numerous birds, and a diverse flora. However, from the standpoint of biological conservation some of the most valuable public lands serve that role inadvertently because they were set aside for water conservation. To provide reliable water supplies to the urban population of the Bay Area, counties acquired lands to establish reservoirs and to protect their watersheds. San Francisco County acquired large land holdings in San Mateo County to satisfy its need for water, and most of the less urbanized counties also have extensive lands within their own boundaries for water conservation. Only Sonoma and Solano counties, which have the lowest percentages of land under public ownership (7–8%), do not have extensive land holdings for water conservation.

Without such extensive holdings of public lands, the prospects for insect conservation in the Bay Area would be considerably bleaker. It is projected that an additional 1.4 million people will settle in the Bay Area by 2025 – a 20% increase (ABAG 2002). Population growth will result in further land conversion for housing and employment, and additional pressure on existing public lands for use in recreation rather than conservation.

Beyond the issue of protecting habitat from urbanization and agriculture, the management of public and private lands for conservation is becoming ever more important for two reasons: increasing conflicts between agencies, organizations, and individuals interested in either consumptive, recreational or conservation uses of land, and a lack of the information necessary for management. What forms of recreation are compatible with conservation? How do we manage public lands to minimize the impact of invasive species? What role might private lands and improved agricultural practices play in conservation? These questions are essential to conservation, but are unlikely to be answered without greater cooperation between governmental agencies, non-governmental organizations, industry, and the scientific community.

Acknowledgements

We thank K. Connor for help in editing this manuscript, E. Rentz for help with the figures, J. Perkins from ABAG for land use information, B.C. Capps of the Bay Area Open Space Council for information on protected lands, D. Kavanaugh for access to the CAS collections database, and J. Nygard for assistance in compiling and extracting summary data from this database. We also thank D. Simberloff for directing us to the Suisun thistle story, and C. Boggs for an update on the status of the bay checkerspot. This manuscript benefited from comments by G. LeBuhn, S. O'Neil, C. Boggs, and two anonymous reviewers on an earlier draft.

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