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Introduction

Beetles and conservation

Beetles, the members of the insect order Coleoptera, are widely believed to be the most species-rich animal group that exists on Earth and, perhaps, that has ever shared our world. Comprising around one-quarter of all animal species, their richness and ubiquity led Evans and Bellamy (1996) to comment 'We live in the Age of Beetles'. That Age is a long one. Modern beetles, the outcomes of some 250 million years of evolution since the earliest beetle fossils found in the Permian period, are difficult to ignore. Collectively, they are immensely diverse in their lifestyles and ecology, and intrude on human consciousness and well-being in many ways. Our perceptions of beetles cover a huge range of human experience: as creatures of cultural importance and symbolism (such as scarabs in ancient Egypt), as objects of desire and fascination to naturalists and collectors, and as severe pests and our major competitors for crops and other commodities. Their countering positive values are as predators and biological control agents of other pests, as valued tools in environmental assessments of terrestrial and freshwater ecosystems, as study tools to help elucidate ecological functions, and as key components aiding the working and sustainability of the natural world. Much of the above emphasizes their ecological variety, with more than half the order in some way phytophagous. Plant-feeding apparently arose early in beetle evolution, with the ancestors of the current major radiations of angiosperm-feeding beetles (namely the weevils, Curculionoidea, and leaf beetles, Chrysomeloidea) existing in the Triassic, some 230 million years ago, and arising most likely from conifer- and cycad-feeding lineages (Farrell 1998). The massive radiations of beetles in the Cretaceous period paralleled the development and spread of flowering plants, and over about 100 million years

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Beetles in Conservation, 1st edition. By T.R. New. Published 2010 by Blackwell Publishing.

they developed a broad array of feeding guilds and occupied virtually all available biotopes (see Erwin & Geraci 2009). However, numerous beetles are predators, fungus-feeders or other, and the collective variety of feeding habits encompasses exploitation of the variety of accessible foodstuffs in natural and anthropogenic environments.

Thus, unlike butterflies, whose wide general appeal renders them invaluable ambassadors in promoting the values of insect conservation and which contain few pest or otherwise damaging or undesirable species, the public image of beetles is decidedly mixed and more complex. Indeed, the same species may be regarded as a pest or conservation target in different places and its status change over time, so that local and wider perceptions of its role (and sympathy for its conservation) may differ substantially across its range. One example is the oak pinhole borer beetle *Platypus cylindrus* (Platypodidae). This species is a serious forestry pest in parts of continental Europe, but was listed as rare and associated with veteran oaks in Britain (Shirt 1987). Since then, and following severe gales in Britain in 1987, it has become a serious pest of stressed and dead oak trees. Yet, whatever the practical perceptions of particular beetles may be, the group's richness and diversity renders them of immense importance in understanding the natural world and leads to human interests encompassing the extremes of conservation on the one hand to suppression or eradication on the other. The latter attitude may broaden from confirmed pest species to others, just in case they cause damage. And the various components of 'beetlephilia' (a term advanced by Evans & Bellamy 1996, drawing on E.O. Wilson's famous 'biophilia') ensure continued attention to some groups of beetles by hobbyists and others not concerned directly with either their welfare or slaughter. Perhaps tiger beetles (treated variously as Carabidae: Cicindelinae, or the full family Cicindelidae), many of which are brightly coloured and active by day, promote such attitudes particularly well, so that Pearson *et al.* (2006) introduced their book with a chapter entitled 'The magic of tiger beetles', and included comments such as 'Hundreds of otherwise normal people are passionate about an intriguing group of insects called tiger beetles' and 'tiger beetles elicit something more than a routine response to the necessities of employment'.

The appearance of many beetles can be dramatic, even bizarre; for example, the enlarged mandibles or pronotal horns of some Lucanidae or Scarabaeidae have long been objects of curiosity and appeal. Arrow's (1951) sentiment at the start of his book on these insects ('all who see . . . one of the great horned beetles for the first time cannot fail to experience feelings of astonishment') remains entirely suitable, whilst many smaller beetles may impress just as much by some feature of colour or morphological extravagance.

In short, such liking and sympathy is an important positive component of insect conservation. Perhaps particularly for beetles embedded in national or regional culture, public interest in conservation can be garnered readily. Thus, the Genji firefly (*Luciola cruciata*, Lampyridae) in Japanese traditional agricultural environments has always attracted exceptional public interest (Takeda *et al.* 2006) and is an important flagship species for conservation. The earliest literature records of these fireflies are reportedly in Japan's oldest collection of poetry in the late eighth century (Masayasu 2005), and their flight season (in early summer:

June, July) attracts tourists through events such as the annual Yokoyama Firefly Village festival that can promote interest in conservation. Larvae of *L. cruciata* are aquatic, and the species has suffered greatly from habitat loss and degradation through pollution, following likely over-collecting for sale in the past.

It may indeed be feasible to promote beetles (and many other invertebrates) responsibly for greater interest in ecotourism itineraries. Buprestidae and Scarabaeidae were listed among the sample invertebrate groups suitable for inclusion in such activities in South Africa (Huntly *et al.* 2005), the former as conspicuous spectacular-looking beetles often seen on flowers, and the latter for their dung-rolling activities. The Addo elephant dung beetle (see p. 74) has received particular attention, but the suggested approach for invertebrates has been to highlight particular features as part of an educational process. In this example, Buprestidae were promoted by contrasting the habits of pollen-feeding adults with wood-boring larvae, and dung beetles for their important ecological role in breaking down wastes and their elaborate behaviour (Huntly *et al.* 2005). These families were selected as among those easily seen in one game reserve, with ease of observation an important aspect of promoting insects to visitors. Surveys of tourists in South Africa have suggested that many people will embrace chances to broaden their experience beyond the major current focus on large mammals (mainly the Big Five) and to learn about other taxa. An important requirement to facilitate this is to train tour guides more effectively, so they can comment on invertebrates as well as the larger animals. Conversely, epidemics of pest beetles may deter tourism. The massive outbreak of mountain pine beetle *Dendroctonus ponderosae* in western Canada (see p. 134) has the potential to affect both the ecology of some national parks and the experiences gained by visitors (McFarlane & Witson 2008). Likely consequences on visitors include lessening quality of scenery, hazards from dead and falling trees, and effects on local economics by reduced tourist numbers, with this effect extending well beyond park boundaries. However, the role of bark beetle epidemics in public perception can be more complex. Whilst they are massively damaging to commercial forests, in national parks the beetles may be regarded instead as natural regeneration agents, helping to sustain the area's ecosystems (Muller & Job 2009). Despite the reaction of visitors noted above for Canada, surveys in an affected park in Bavaria (Germany) showed that the infesting beetle (*Ips typographus*) was generally accepted by tourists. A prevailing opinion was that control measures should not be introduced in the park (Muller & Job 2009). Information provided about the beetle's function and importance countered initial negative attitudes, as an education process fostering wider appreciation.

However, and perhaps paradoxically, disliking economically damaging or other pest beetles may also be important in promoting interests in beetles, because it leads to accumulation of information with considerable relevance in conserving their close relatives or other species occurring in similar environments. Some pest beetles, in stored products, timber, or as pests of agricultural, orchard or forestry crops, are among the best-studied insects. Much of that knowledge, as well as that on beneficial species such as manipulable predatory ladybirds (Coccinellidae) used as biological control agents, and the techniques by which it is acquired and analysed merits careful appraisal by insect conservationists.

The juxtaposition between the applied entomology literature and the conservation ecology literature is perhaps nowhere closer than for Coleoptera, and the wealth of detail in the former can provide invaluable ideas and leads in management of beetle species and assemblages for conservation. The appraisal of Coccinellidae by Dixon (2000), for example, is a broad biological foundation of interest for studying any member of that family in a wider perspective.

As well as contributing enormously to evolutionary and ecological understanding in numerous different terrestrial and freshwater ecosystems, beetles are important considerations in practical conservation. Their value and their roles range from the high-profile focus on single notable species threatened with decline or loss to documentation of the vast regional assemblages reflecting dependence on restricted resources threatened by human activity. Regarded widely as an easily sampled taxon, beetles have become an important group in addressing many questions of wide conservation relevance, so contributing to disciplines such as landscape ecology, reserve design and placement, and restoration or rehabilitation of most terrestrial and freshwater biomes. The bulk of ecological studies on beetles have not been undertaken specifically to address conservation issues. However, the leads they give, the background information accumulated on more basic ecology and biological understanding of how beetles work, and the methods and analyses pursued collectively lay a very sound foundation for more conservation-focused endeavours. It is also increasingly common for the discussions in papers on beetle biology to allude to the conservation implications of the work presented. It is impossible to summarize the ecology of beetles briefly, but their ecological specializations and variety may be considered to lie along a continuum from strictly monophagous and highly specialized species (with obligately small niches and frequenting only one or two habitat types, sometimes highly circumscribed as local endemics) to extreme generalist species (with wide niche breadths and in a wide variety of habitats across a broad geographical range) (Dufrene & Legendre 1997). Any terrestrial or aquatic beetle assemblage in a restricted habitat will thus include the two major elements of (i) obligate specialist species restricted or largely restricted to it, and (ii) generalists that may either extend casually into that environment or, by actively selecting particular resources or other attributes, become more abundant there than elsewhere. Whereas conservation interest may gravitate predominantly towards the specialist species, which tend to become detectably threatened more easily than many generalists, the operating environment for such species includes the assemblage of which they are part, and with which they may interact. Slightly more broadly, it is useful to separate three major ecological categories that transcend any individual trophic category: (i) ubiquitous species, i.e. those that are geographically and ecologically wide-ranging; (ii) eurytopic species, i.e. those found in a variety of habitats but over a more restricted geographical range; and (iii) stenotopic species, i.e. those that are much more specific and found in one or few habitats, as specialists. The first group, ubiquitous species, are commonly also eurytopic, because they occur in a variety of habitats, so are then distinguished by the extent of their distribution.

Highly specialized ecological oddities abound among Coleoptera, so that many broad generalizations about their habits and biology are subject to increasing numbers of exceptions as biologically novel or unexpected traits are discovered. Some may augment conservation interest as informative evolutionary lineages, or by demonstrating unusual adaptations that render them resistant or vulnerable to environmental changes. One recently appraised oddity is the fairy shrimp hunting beetle (*Cicinis bruchi*), a highly unusual carabid (Erwin & Aschero 2004). Unlike most ground beetles, this species (formerly known from only two specimens and characterized, in an intriguing image, as 'the carabid equivalent of a crocodile') is aquatic and the nocturnal adults swim on the surface of alkaline water bodies, salt flats, in Argentina. The salt flats are very extensive, but Erwin and Aschero (2004) believe that the beetle's distribution there was restricted by that of 'tiled' soils providing refuges for the beetles during the day. The beetles feed solely on anostracan shrimps. At present, the extensive habitat area seems not to be threatened, but the future influence of global warming may pose a severe threat in this semi-desert environment.

Beetle extinctions and extirpations

In his magisterial *The Biology of Coleoptera*, Crowson (1981) commented (p. 650):

> The immense diversity of the recent beetle fauna of the earth is the product of extremely diversified ecosystems which have maintained considerable degrees of stability for very long periods of time. Both the diversity and the stability are now being destroyed, at an increasing rate, by human action. In the process large numbers of Coleoptera must inevitably become extinct . . .

and (p. 689) 'we fear . . . the early extinction of large and scientifically interesting parts of the present world fauna of Coleoptera'. Stability or stasis of many beetle species is inferred strongly from the record of Quaternary beetle fossils (or subfossils), which comprise fragments that resemble closely, and indeed are often identical to, the equivalent parts of modern beetles. Many of these, including elytra, pronota, heads and sclerotized male genitalia, enable fossils to be identified reliably as modern species. Many such fossils (which can occur in large numbers in sediments) retain structural and pigmented colours, together with setae and micro-ornamentation, and provide strong indication of the long periods for which some species have existed, notwithstanding the many gaps in the record. Crowson's sentiment has been echoed repeatedly, for example by Erwin (1997) in referring to the vulnerability of tropical forest beetles: 'current human activity and that of the immediate future will exterminate a large percentage of these species'. In general, fear of extinction of enormous numbers of species, including beetles, within the next few decades (Dunn 2005) is a vital rallying call for urgent conservation measures throughout the world. More specific contexts occur, with many general warnings of likely demise of particular beetle taxa. For example, surveys of the large montane bess beetles (Passalidae) roused the comment from Schuster *et al.* (2003, p. 302) that 'In general *Proculus*, as well as other montane species of passalids, is probably in danger of extinction throughout its range due to the elimination of most of the forest where it occurs'.

With few exceptions, however, specific knowledge of such extinctions does not exist, particularly over most of the tropics where beetle diversity can be extraordinarily high. Indeed, Mawdsley and Stork (1995) could enumerate only 10 recorded global species extinctions of beetles, all of them from isolated islands. Even in the Quaternary fossil record, beetle extinctions seem to be few, with stasis (accompanied by, sometimes dramatic, range changes; p. 135) more common, reflecting the sequences of glacial and interglacial periods over which vegetation may change through advance and retreat over several thousand kilometres. Coope (1995) and others have suggested that the perceived lack of extinctions may be partly due to this long-term series of changes, associated with a high degree of population mixing with resulting homogeneity of populations diminishing the chances of extinction by countering genetic impoverishment. Indeed, Ashworth (2001) could cite only two possible extinctions over that period, the dung beetles *Copris pristinus* and *Onthophagus everestae* from the La Brea asphalt deposits, but, following Miller (1997), suggested caution in declaring that even these Pleistocene species had really disappeared. The twin concepts of structural extinction and sampling extinction differentiated by Gaston and McArdle (1994) are important components of understanding, whereby the latter emphasizes the difficulties of evaluating small, elusive and perhaps cryptic taxa. This dichotomy was explored by Didham *et al.* (1998a,b) in their study of forest fragmentation effects on beetles in Amazonia, and in which they attempted to appraise the likelihood of extinction from changing abundance across sites of different sizes and conditions (see p. 96). Habitat fragment size was apparently a key predictor of extinction risk for some species. Some insect extinctions are indeed difficult to prove, and declarations of extinction may reflect periods where the species is not recorded, but often with little indication of the amount of targeted search effort for it. It is not particularly uncommon for beetles to be rediscovered decades after they were last seen. One such example is the New Zealand dytiscid water beetle *Rhantus plantaris*, described from a single specimen in 1882 and found again in 1986 (Balke *et al.* 2000). The site where it was then found was a small perennial pond with water diameter only about 5 m, so that its existence may still be regarded as rather tenuous, but at least in 1986 it was not extinct! Whilst McGuinness (2001) remarked that three beetle species had been reported to be extinct in New Zealand, his own inferences were more cautious. For the carabid *Mecodema punctellum*, not seen since 1931, McGuinness (2002) noted ‘this species *may be* extinct’ (my italics). However, sometimes repeated and specifically targeted surveys have not revealed the beetle sought. The large flightless ground weevil *Hybomorpus melanosomus*, endemic to Lord Howe Island, formerly occurred there under logs and in rotten wood. It is known from a few specimens in collections and has not been collected since the 19th century. Soon after, it was considered to be extremely rare or possibly extinct (Oliff 1889), even before the introduction of rats to Lord Howe Island early in the 20th century. Intensive invertebrate surveys over several recent decades have not yielded specimens, and the weevil is now listed as presumed extinct under New South Wales Government legislation.

Strong declines and more local disappearances of particular beetle species are documented more commonly and effectively for parts of the temperate regions, particularly in the UK (from where Hambler & Speight 1996 listed 12 species believed to have become extinct since 1900, and Hyman & Parsons 1992, 1994 noted a number of species that had not been seen for at least several decades, but did not categorize these as extinct in their rankings), parts of western continental Europe, and parts of North America. These declines and extirpations are the source of much modern conservation interest, with the species brought to attention in this way the usual candidates for conservation. Studies on islands have also led to documentation of many such extirpations: several Tenebrionidae have been lost from particular Iberian islands for example (Cartagena & Galante 2002). In contrast to full extinctions, local extirpations are frequent and many of the threats noted later for recent beetles have had influences well before people became concerned about them (Whitehouse 2006). The riparian beetle faunas in northern Europe include a number of Carabidae that have been lost through river regulation and canalization, changes to nearby vegetation and bank structure, and pollution, with some peculiar to areas with particular substrates such as stones or sand (Andersen & Hanssen 2005). As another example, the Californian tiger beetle *Cicindela tranquebarica joaquinensis* was historically found over much of the San Joaquin Valley, associated with alkaline habitats. However, most populations have been extirpated because of intensive agricultural development, such as cultivation and changes of water for irrigation supply, so that the specialized habitat has been largely lost. Only three populations, each on a patch of habitat less than 3 ha in area, were known to Knisley and Haines (2007). As another striking example, the historical distribution of the American burying beetle *Nicrophorus americanus* (p. 145) was formerly extensive across the eastern half of the USA, but has now been reduced to three small disjunct areas (Fig. 1.1) (Lomolino *et al.* 1995; Sikes & Raithel 2002). Collectively, most of the more reliably evaluated recent losses are within the areas for which beetle faunas have been described most completely, as a continuing legacy of collector interests spanning some 150–200 years and the progressive availability of series of identification guides and handbooks that render the fauna at least partially tractable to people taking up their study.

Beetle diversity

Elsewhere, our knowledge of modern beetle diversity and its distribution is highly uneven, although broad historical biogeographical patterns within the order can be traced with the aid of the substantial fossil legacy (Coope 1995), so that many of the better-studied regional faunas can be defined and, in many instances, alien species recognized reliably. Thus, Australian beetles are often recognizable as regional endemics, and their presence elsewhere in the world (be they pests, beneficial species or with more neutral impacts) definable. Conversely, beetles from elsewhere are commonly detectable in Australia. Very commonly, knowledge from studies on alien beetles, undertaken to clarify their impacts or management to suppress or foster them, comes to exceed that available from within their natural range, and may have direct applications in conservation. Likewise, searches for beneficial insects, such as biological control agents, can

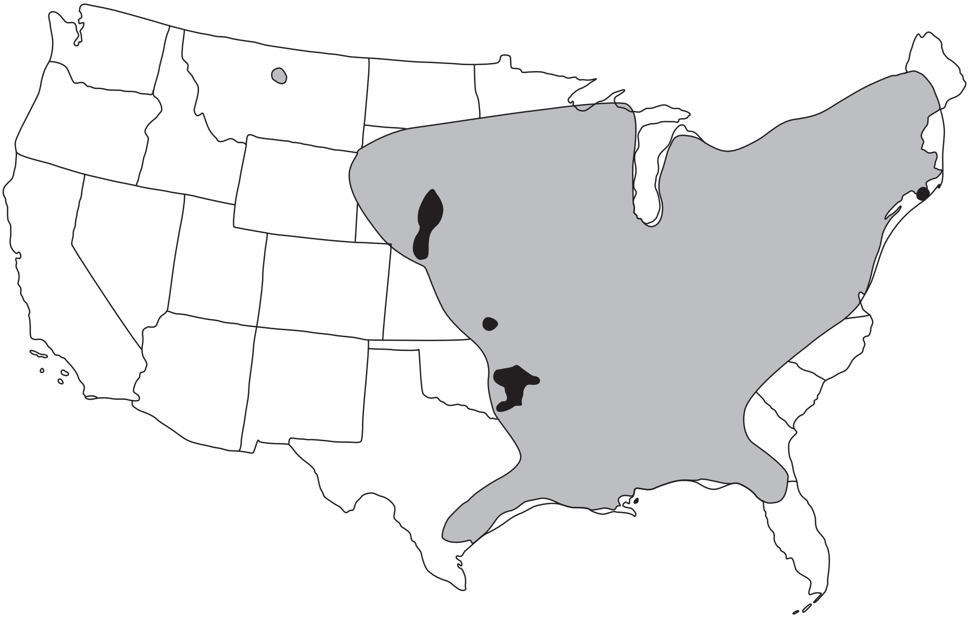

Fig. 1.1 The historical (shaded) and current (black) distribution range of the American burying beetle *Nicrophorus americanus* in North America. (After Lomolino *et al*. 1995 with permission.)

stimulate detailed investigation of possible source faunas: for example, Koch *et al.* (2000) noted the 'intensive, wide-ranging dung beetle collection programme' and resulting comprehensive reference collection of specimens from Australian exploration for South African dung beetles suitable for importation to Australia. However, in broad terms for much of the rest of the world, beetles are much less effectively documented than in Europe or North America; even though a strong systematic framework exists, many families have not been documented completely and a high proportion of species are unnamed and undiagnosed. We have little realistic idea about how many species of beetles occur on Earth; certainly several hundred thousand species have been described, but estimates of their total richness extend to several million species, and these figures continue to be debated. A tally of 358,000 described species (Bouchard *et al.* 2009) includes several earlier authoritative estimates, with the six largest families enumerated being Curculionidae (60,000 described species), Staphylinidae (47,744 species), Chrysomelidae (36,350 species), Carabidae (30,000 species), Scarabaeidae (27,800 species) and Cerambycidae (20,000 species). As Grove and Stork (2000, p. 735) commented 'In reality, and despite the best efforts of a number of researchers, we are still little nearer to determining the true extent of beetle diversity'. And, from Zimmerman (1994), 'Estimates of the numbers of described weevils are as variable as the opinions of those making the estimates'. However, several families are very large, whilst many others are small. The bulk of described beetles belong to only about eight families including those listed above, namely Carabidae, Staphylinidae, Scarabaeidae, Buprestidae, Tenebrionidae, Cerambycidae, Chrysomelidae and Curculionidae. An estimate by Gaston (1991) suggested that these together contained about two-thirds of beetles decribed at that time, and that high proportions of undescribed species would also be referable to these groups. Simply studying these families, whose members range over many trophic guilds and habitats, would alone provide a very strong practical framework for conservation.

However, considerably greater variety occurs. Thus, for Australia, around 23,000 beetle species have been described (in more than 120 of the global total of 166 families listed by Lawrence & Newton 1995 and, as an aside, a scarab beetle *Haploscapanes barbarossa* was the first formally named Australian endemic animal), but predictions of 80,000–100,000 species (or even more) have been made (Yeates *et al.* 2003). Such uncertainties are common, and render many aspects of evaluation based on fundamental documentation of biodiversity difficult and sometimes unconvincing, little more than 'guesstimates'. Within such large faunas, with their characteristic high levels of endemism, many beetles are ecologically specialized, and many are scarce or highly localized. Background knowledge and sampling effort is, in most cases, simply inadequate to detect their loss or continued presence in very low numbers, even if they are recognized as distinct entities. However, valuable information on assemblages can accrue relatively easily, because a high proportion of beetles can be allocated with reasonable confidence to feeding habit or guild, from knowledge of related taxa elsewhere. As an example from the tropics, in the poorly described beetle fauna of Sarawak, Malaysia, Chung *et al.* (2000) could confidently assess over 40% of the more than 1700 species they accumulated as predators, as well as determining that more than 15% were saprophages and fungivores and 10–13% herbivores, so that assemblage changes based on changing frequency of such guilds could be estimated and compared. Nevertheless, a high proportion of beetle species diagnosed or named from most of the tropical regions are known from few individuals, many of them from single specimens, and the biology of most of these is simply unknown, and can be inferred only in general terms by comparison with any better-known related taxa. Many beetles are known only from an inadequately documented, sometimes old, type specimen or description. The reality of studying beetles, and assessing their relevance to ecological sustainability and needs for conservation, involves acceptance of this vast uncertainty and learning how to treat it responsibly.

However, despite the taxonomic uncertainties which ensure that only low proportions of species in most general surveys of tropical beetles may be identifiable to species level (see below), studies of assemblage composition and the changes associated with disturbance or changing patterns of land use, made either along gradients (see p. 102) or more patchily, have commonly utilized beetles as signals or indicators of habitat condition. Many analyses of beetle assemblages have focused on particular families, so that differences or changes in richness and composition are correlated, sometimes tentatively, with habitat characteristics.

In any part of the world, and with information encompassing most continental and island areas, many beetles are regional or much more localized endemics, and most of the species signalled individually for conservation concern have highly restricted distributions. Additionally, Hammond (1994) recognized a category of near-endemics, illustrated by a number of intertidal/coastal beetles in Britain, but which are scarce or very restricted elsewhere in Europe. For example, some Staphylinidae in this category are known from very few sites outside Britain, and then only from Europe-facing Channel coasts or similar restricted ranges. For most parts of the world, patterns such as this cannot be defined with confidence, but there is no doubt that levels of narrow-range endemism among beetles can be very high. Two Australian examples illustrate the scenarios likely to be paralleled widely elsewhere.

1. Many flightless beetles in Australia's northern wet tropics (a World Heritage Area) are restricted to a single forest subregion (Yeates *et al.* 2002). The large number of such species with presumed low dispersal ability in several families (namely Carabidae 86 species, Scarabaeidae 32 species, Tenebrionidae 87 species) implies that many, together with a variety of other beetles and insects of other orders (particularly Hemiptera: Aradidae), may indeed be vulnerable there as highly localized taxa.
2. Many of the dytiscid water beetles from underground calcrete aquifers in Western Australia (see p. 115) are known only from single aquifers which, following results of mitochondrial DNA investigations on the beetles (Cooper *et al.* 2002), may represent a series of subterranean islands with independently evolved beetle taxa.

The bewilderingly high richness of tropical beetle faunas, although long suspected, was brought to wide attention through Erwin's (1982) classic study of sampling beetles from the tropical forest canopy in Panama. His analysis founded later debate on the magnitude of tropical insect species richness. For the first time, Erwin provided testable hypotheses by which richness could be estimated and, although his assumptions have been challenged in detail, they have formed the foundation for considerable later evaluation (see Stork 1997). In acknowledging the massive diversity of beetles in tropical forests (as 'biodiversity at its utmost'), Erwin (1997) noted that they had been little used in interpreting environmental disturbance, for environmental monitoring or for understanding how tropical communities are structured, and also emphasized their great potential for augmenting our understanding of evolutionary biology and conservation. The sheer amount of information potentially available from tropical beetle faunas would have unique and massive importance in these areas of endeavour. The problems remain over how to harness and employ that information from such hyperdiverse groups and to overcome the current impediments to doing so. Much information on diversity emanates from studies on single sites or small regions, and the reasons for varying distributions and high beta diversity may be difficult to assess. Again from the Neotropics, only about 2.6% of the beetles of seven selected families from fogging samples were common to surveys from near Manaus (Brazil) and Tambopata (Peru) (Erwin 1988). These sites are separated by about 1500 km but, in a wider discussion of species turnover with distance across sites, Bartlett *et al.* (1999) noted that interpretations of distributions based on such separated samples are 'fraught with intensive site-specific differences that confound distance effects'.

The central paradox and values of beetles in conservation flow from their vast abundance and taxonomic and biological diversity. On the one hand, they offer abundant opportunities for study and evaluation of environmental changes. Almost every terrestrial or freshwater biome supports a wide taxonomic array of beetles, many of them responsive to some or other environmental change, whether natural or imposed, and many of them commanding attention as declining, either alone or as an entire specialized assemblage. The long-term interest in beetles noted earlier has laid a solid foundation of taxonomic and biological knowledge that aids some such appraisals, as well as suitable (ecologically informed) study and sampling methods. On the other hand, the bewildering variety of beetles is sometimes a barrier to understanding: we may indeed find numerous species in a locality, occupying collectively all or most trophic roles in a biome, but the detailed ecology of most (even all) the species is likely to be fragmentary, and the mechanisms sustaining them may need to be projected from little background other than from related taxa, or from similar biomes undergoing apparently similar processes or change. For conservationists, beetles, whether directly as conservation targets or tools for wider applications, offer both severe impediments and massive opportunity for progress.

In common with other insects with complete metamorphosis, conservation of beetles must consider the biology and needs of two very different life forms, whose ways of life may demand very different resources and conditions. Larvae and adults of the same species may coexist, or be separated in space and time, utilize different foodstuffs and occupy different feeding guilds. As Dennis *et al.* (2006, 2007) have emphasized for butterflies, successful conservation must determine and ensure the needs for both these active stages in a wider milieu in which the entire life cycle can be supported.

In much practical insect conservation and faunal documentation, high species diversity is a very mixed blessing. Relatively low-diversity groups, perhaps with only a few thousand species (however formidable such numbers seem to people used to working with mammals or birds), are fundamentally more tractable to non-specialists in particular. Within the insects, butterflies comprise only around 20,000 species, with regional faunas typically much smaller, and many of the genera and species are recognizable through well-illustrated field guides. A framework for their biology is also likely to exist, perhaps by reference to close relatives in the area or elsewhere. In contrast, with tropical beetles we are dealing with much larger numbers of taxa, most of whose biology and distribution is almost entirely unknown, and many of which are undescribed and undiagnosed. Many beetles may not be identifiable easily much beyond family level, and some to that level only with considerable difficulty attendant on small size and complex or confusing morphological characters. As Erwin, and many others, have emphasized, the decline of the taxonomic workforce has ensured that most of these taxa will not receive such formal treatment in the foreseeable future. In the terminology of Yeates *et al.* (2003), many beetle groups are 'taxonomically orphaned' by the absence of any specialist able to evaluate them in a regional or the global fauna, and comment on their affinities and peculiarities. Beetles are by no means alone in this regard: the situation may be even worse for parasitoid Hymenoptera for example (even in the best-documented temperate-region faunas; Shaw & Hochberg 2001), and paralleled in many families of Diptera and other diverse insect groups. Perusal of taxonomic journals (such as *Zootaxa*) in which numerous descriptive papers on beetles are published may convey misleading impressions: whereas many taxa are indeed being described, and many groups progressively revised, the size of the demand and the task ahead remain daunting.

Beetle recognition and identification

The practical ramifications of this absence of data are important. Lack of formal species' names and lack of ability to obtain those names (the situation sometimes termed the 'taxonomic impediment'; see Taylor 1983 for background) is exacerbated by high diversity to the extent that need for formal taxonomy cannot be fulfilled as a prerequisite for basic documentation, and is viewed widely by non-scientists as equivalent to lack of importance or interest. However willing and interested they may be, lack of taxonomic resources ensures that the few specialists on any individual insect group are substantially over-extended. Employer demands may effectively prevent such people participating in identification of ecological survey material for other people, and related activities. And, for groups such as beetles, the amount of material collected during such exercises can be formidable in both abundance and variety. It is one thing to ask a specialist to identify a single beetle or a few voucher specimens of particular interest or relevance to a study and within that person's sphere of interest (commonly a single beetle family or part thereof), but quite another to confront him or her with the entire outcome of a substantial survey, comprising perhaps hundreds of species across a wide array of families. Examining such collections is often a major research exercise in itself. However, lack of up-to-date guidebooks or other non-specialist publications renders such exercises almost impossible (and, at least, often unwise) to undertake without specialist direction and access to a major and well-curated institutional collection for comparison. Handbooks for many families are indeed available for many parts of the northern temperate zones in particular, and identification can then be undertaken with relative confidence, but it remains wise to attempt to have a series of voucher specimens checked by an experienced coleopterist, as recommended later for any survey in which the results may be used in recommendations for conservation management. The situation remarked by Crowson (1981), that few countries outside Europe have even reasonably comprehensive handbooks for beetle identification, although guides for particular families may exist, still pertains. Broad-based introductory illustrated handbooks to tropical beetles, such as those by Tung (1983) for Malaysia and Gressitt and Hornabrook (1977) for Papua New Guinea, are immensely valuable introductions to those faunas but can do little more than titillate for the wealth not included. Nevertheless, as Tung hoped, they can stimulate people to take up the study of beetles in such regions and lead to advances in knowledge. Clearly, the resources for the interested ecologist or conservation biologist to identify beetles easily and unambiguously beyond family level in much of the world simply do not exist, particularly locally. The practical dilemma is that for beetle faunas with high proportions of poorly documented species, non-specialist identifications are likely to often be erroneous, and specialists unlikely to be routinely available to help interpretation. Larochelle and Lariviere (2007), writing on New Zealand Carabidae, go further and state (p. 160): 'Species-based information should never be published or databased unless a carabid specialist has confirmed the validity of genera and species involved'. They noted also that isolated descriptions of new taxa, sometimes motivated by need to provide names for conservation targets, are misguided, and that beetle taxonomy should be pursued in the context of revisionary studies rather than piecemeal.

When, and if, a particular species of beetle is described formally is often serendipitous, and depends largely on the interest of a specialist examining that family or genus group at that time. Other factors also intervene: for the well-known British fauna, most larger beetles were described earlier than many small ones (Gaston 1991). The latter are commonly (i) more difficult to differentiate without close microscopical examination, or dissection of genitalic structures, and (ii) less attractive to many collectors and so less important unless with direct economic or other intrusive values. Gaston suggested that the smaller beetles may be simply less conspicuous, and harder to collect. This trend is by no means universal, as Allsopp (1997) found for the Australian scarabs, for which wide-ranging species were generally described earlier than many highly localized taxa, irrespective of their size. Many of the earlier-described species were those found closest to major human settlements (so that the south-eastern fauna was for long better documented than the fauna of the remote northern regions). However, importantly, all scarabs are at least moderately large beetles, and thereby reasonably conspicuous. Allsopp (1997) pointed out another possible anomaly relevant to conservation assessments – the probability that some of Australia's recently described scarabs currently have small defined ranges *because* they have been described recently, so that there has been little time to accumulate comprehensive information on their real distributions, which might be substantially underestimated from the material available. For Iberian Scarabaeidae, Lobo *et al.* (2007) also noted that mapping schemes (see p. 41) may show considerable bias, because initial records of species may be based on localities favoured by collectors seeking particular rare species and on more thorough exploration of places near to investigators' homes. Many hobbyists, seeking particular species but with limited recreational time available, will opt to visit traditional localities to seek their specimens rather than explore new areas that might not yield their targets.

Keys to beetle families are included in many general entomology texts, but regional bias may limit their usefulness. Most textbooks, for example, cater predominantly for one or other temperate-region fauna as their primary market and, at the least, the examples of beetles used to illustrate key characters may not occur widely elsewhere, or other faunas include additional families not treated in that text because of regional scarcity or absence.

Most information in texts, and most of the work referred to in this book, deals only or almost solely with adult beetles as the life stage most amenable to consistent recognition, easy collection and quantitative or semi-quantitative sampling. Yet, the major impacts of many beetles on human interests occur during the larval stage: the damage caused to pastures by subterranean scarab larvae, the variety of timber-boring larvae of several families, of leaf beetle larvae on crops and ornamental plants, the depredations of stored products pests, and so on. With the notable exceptions of some such pest groups or complexes, recognition of beetles to species or near-species level is best achieved on the adult stage, because many larvae have not been described, placed into a robust local taxonomic context nor associated unambiguously by rearing to the corresponding adults. Adult beetles in all parts of the world are documented more effectively than their larvae. As with any such bland statement on beetles, exceptions occur: excellent global keys to families and other higher groupings of larval beetles exist, with those to lower levels most developed for the northern temperate regions. Treatments such as that by Luff (1993) for larval Carabidae for a region of northern Europe are of immense value in recognition to finer levels of some relatively well-known groups. However, many, perhaps most, beetle larvae are not identifiable readily to species level, except by inference or clear association with likely corresponding adults. This situation reflects a point to be emphasized repeatedly, that the biology and life histories of most beetle species is incompletely known, so that constructive augmentation of this basic information is a common need in assessing conservation. Drawing on the wider literature on recognition of beetle larvae (from Boving & Craighead's 1931 survey onward), it may still be possible to detect particularly unexpected or unusual novelties in samples of beetle larvae but, in general, larvae have played little part in the development of beetle conservation studies. Whilst recognition of larvae underscores the integrity of much applied ecology of economically important beetles, equivalent importance has yet to be facilitated for conservation.

As implied from Larochelle and Lariviere's (2007) comment above, decription of a species, either adult or larva, does not alone convey unambiguous recognition. Isolated descriptions of beetle species (many of which, particularly until the early decades of the 20th century, were brief, unillustrated and based on character suites that are by more modern standards regarded as superficial or inadequate) may not provide adequate comparison with close relatives or, if based on few specimens, may not recognize individual variability. Published dichotomous keys encapsulate diagnoses of known species, but users must be aware of their limitations and some possible caveats on their uncritical use. As one common example, discovery of additional species renders any such key incomplete, so that species may be forced spuriously into the best available category (name) by a non-specialist user, even if it is abundantly distinct. Some groups of beetles are much more prone to this augmentation than others, and it is useful if compilers indicate possible problems by, for example, (i) noting the relative likely completeness of the material used (are there likely to be many unincluded species or is the key based on reasonably comprehensive appraisal?) and (ii) noting if particular key couplets are unsatisfactory or indicate possible or actual complexes of species rather than solely the name provided. Zimmerman (1994) prefaced some of his weevil keys with a comment to the effect that the keys were simply to separate specimens examined, not necessarily all the species. Traditionally, taxonomists, of beetles or other organisms, have tended to write for their peers; in conservation the needs for unambiguous species recognition and detection go far beyond that clientele, and need to be understood by people with little specialist knowledge of the insects.

Not unexpectedly, some beetle families are better known taxonomically and biologically than others. In particular those families containing larger and more conspicuous or colourful adult beetles have long been popular objects for collectors, and the philatelic aspect of beetle collecting has stimulated their study and provision of names. In recent years, it has also led to production of many well-illustrated (by paintings or photographs of all available taxa) books (many of them expensive, and of varying quality and scientific value) on selected families, such as Carabidae, Lucanidae, Cerambycidae, and larger scarabs, to cater for this interest. As indicated above, size matters to many collectors, and the largest and most spectacular beetles are commonly also those easiest to identify and also those for which accessible identification guides are most likely to be available. The black holes in beetle taxonomy and the greatest challenges for faunal interpretation are indeed mainly within the smaller beetles: the insect equivalent of the little brown bird of ornithologist 'twitchers' is assuredly the little black beetle! However, even a beetle in the hand may be extremely difficult to allocate easily even to family level. Most small members of many beetle families are not sought by most general collectors and remain the province of a few specialists, but also may have far greater economic importance than some of the more charismatic taxa, so that recognition of species has major importance in designing pest management: again, scientific study has a basis in need to understand those taxa, either as pests or as beneficial species. The latter emphasis collectively includes considerable variety, reflecting that particular beetle families or subfamilies may have very distinctive ecology as herbivores, predators, fungivores, detritivores (or other trophic category) and collectively exploit any available foodstuff in terrestrial or freshwater ecosystems.

However, whereas beetles participate in virtually all ecosystem processes, limitations in species-level taxonomy pose two main restrictions to evaluating these in many places. First, that taxonomy of most beetles is adequate for confident appraisal by non-specialists only in a few places, such as the UK. Second, some families are far better known than others, and wider geographical appraisal is thus feasible only for such biased subsets from the order. Notwithstanding this, individual beetle species from many families have aroused concern because of perceived declines and apparent threats to their well-being. Usually, these must be considered as isolated cases rather than as members of a well-studied fauna. It may indeed be a formal requirement for such species to have scientific names as a condition of listing for conservation interest, so compounding the dilemma noted earlier.

In addition to their ordinal diversity and the presence of individual notable species, beetles have three major advantages over most other animals in ecological projects and those directed at environmental assessment of various kinds.

1 Many of the more diverse families can be characterized easily to that level. Even if the individual species cannot be named easily, the general appearance

allows for easy and largely unambiguous recognition of a ground beetle, rove beetle, scarab or weevil in samples. The insects present can subsequently be allocated to consistently recognizable categories such as morphospecies to enable some level of quantitative analysis that does not rely for its integrity on full species-level taxonomy. Many such families are distributed widely, have a broadly definable trophic role in communities, and contain numerous species. They are thus informative to ecologists, as beetles may be available for studies of almost any ecological role, process or interaction, either directly or as surrogates.

2 Methods for collecting or more formally sampling beetles are well established, and many of them rely on cheap, easily obtained and easily transported equipment. Most methods developed by hobbyists can, at least to some extent, be modified easily to form the basis of rigorous sampling with varying levels of standardization and replication needed to afford quantitative or semi-quantitative interpretation. The variety of traditional collecting techniques is limited only by the ingenuity of the practitioners. Background literature on the limitations and caveats attendant on most methods is extensive, and each method has its devotees, its detractors and its values in particular contexts, which need to be defined and understood. Many beetles can be reared easily, so that larvae and adults can sometimes be associated clearly from multispecies samples. However, many large beetles have long lifespans (see p. 146), so that the time available for a survey may not allow this exercise to proceed.

3 Specimens can be processed or prepared for study or exhibition easily, a factor that has contributed to their popularity as collectable objects. The importance of synoptic collections or well-prepared and well-documented voucher specimens of all species (or morphospecies) found during a survey or other study cannot be overestimated. They are the essential points for future reference and comparison, and for the validation of identifications as taxonomy progresses in the future.

Sampling and surveying beetles for conservation

In conservation or other ecological survey assessments, sampling beetles may be undertaken for a variety of purposes. Broadly, beetles may be used to illustrate ecological patterns in space and time, and also be important functionally in ecological processes within any biotope or more broadly. As individual targets for conservation, information on individual beetle species may be a priority. As tools in wider assessment, primary emphasis may shift to wider aspects of beetle assemblage composition and its changes. These approaches thereby include the following.

1 Inventory: an attempt to produce a list of all taxa occurring in an area or habitat, or in association with a particular resource such as a specified plant species. It may be necessary to employ a considerable variety of approaches to increase comprehensiveness of sampling for a more complete inventory,

or to focus very specifically to exclude unassociated species from a resource. At either scale, the intention is to accumulate the greatest representation of the species present as a measure of richness that can reflect the importance of the sampling arena and, perhaps, serve to compare or rank it within wider comparisons either across sites or across habitats within a site. For any comparisons, sampling methods and effort must be standardized across sites or occasions. The most informative inventories include samples taken over a sufficient period (of at least several intervals throughout a year) to accumulate seasonally apparent taxa. Many beetles are either present for parts of each year or have seasonal periods of activity and consequent amenability to trapping. For example, some carabids in Tasmanian eucalypt forests may be present for most of the year, but their activity may vary substantially at different seasons, so that their representation in trap catches varies considerably with season (Michaels & McQuillan 1995). The outcomes of an inventory survey are presented most usually as species lists, with or without measures of relative abundance of the taxa represented. Completing such inventories is a lengthy process, of course: for beetles in his home garden in central England, Welch (1990) kept records to accumulate around 760 species over 16 years, with new species found every year. For perspective, this total represents almost 20% of the British beetle fauna. In contrast, most practical inventory studies can be undertaken for only limited periods. A similar approach may be used to evaluate the richness of particular taxonomic groups, such as major families, or feeding guilds in an area.

2 Detecting the presence of particular signal species, such as those known to be threatened or otherwise of conservation interest, or the establishment of introduced species such as biological control agents. For such exercises, it may not be appropriate to kill specimens, so that the spectrum of techniques is restricted to those that are non-destructive. Particularly for threatened species, quantitative data (although valuable) may be secondary to simply determining presence at a site as a basis for pursuing conservation. The converse, proving absence of such a species (especially on sites where it has been known previously), is much more difficult. A reasonable basis for this is that sufficient effort has been made to detect it that it is likely to have been discovered if it indeed occurred there. Traditionally, many beetle collectors have heeded the maxim of deliberately seeking particular rare or elusive species rather than general collecting, as the more common species are then likely to be collected anyway (see Walsh & Dibb 1954 for background). With such an aim, seeking all available biological and distributional information beforehand to aid effective searching parallels the needs for any conservation survey.

3 Single-species studies may expand to fuller autecological studies, undertaken for a variety of purposes, commonly including aspects of seasonal development, population dynamics and distribution. These are based on sequences of sampling events over time and perhaps replicated across sites. In addition to studies undertaken to help understand the biology of species of conservation interest, common contexts include (i) understanding the dynamics of pest species as a foundation for designing management and (ii) monitoring

the presence, establishment and impacts of predatory species used in such management. Extensive surveys may also be needed to monitor effects of management of threatened species and to modify management in response to the findings.

4 Allied to the above, studies on species of conservation interest sometimes address impact of particular threats or suspected threats, either by correlation with different ecological regimes in which the purported threat is displayed, or by direct causal investigations. The latter can be more complex for rare species, simply because sufficient numbers may not be available for replicable manipulative experiments, particularly without risk of causing further harm.

5 Studies of assemblages may incorporate the need to monitor any imposed change, so that the focal beetles are used as an index of diversity or other form of indicator to provide wider ecological insight or inference. Changing species richness or composition can reflect environmental and seasonal conditions, so that inter-site comparisons must be based on samples taken at the same time of year, by the same method and comparable sampling effort, and avoiding any other sources of unplanned variation that render such comparisons dubious. Seasonal patterns of beetle apparency, whether based on life cycles or suitability of the local environment, are very varied. In temperate regions, some can be highly predictable. Particularly in the tropics, many insect species exhibit complex patterns of seasonality (Wolda 1988) and even in relatively aseasonal environments there, some beetles can be highly seasonal. As demonstrated later, evaluation of beetle assemblages may need to consider altitude, climate, vegetation type and seasonality each as a key influence on composition, in addition to issues arising from sampling techniques and analysis.

Whatever the primary purpose of a conservation-oriented field study on beetles, the scale of the study must be considered realistically. The extent and causes of changes in beetle abundance and distribution may reflect local environmental factors (such as microclimate or individual host plant condition) and/or larger-scale influences such as fragmentation in the landscape (see p. 92). Heterogeneity in distribution of species and assemblages can be unexpectedly high, with different patches of agricultural land each supporting local assemblages that differ in detail from those on apparently similar patches in their vicinity, but which draw variously on the same regional pool of taxa. Example studies in which various ecological scales have been incorporated include carabid beetles on farmlands (Kinnunen *et al.* 2001) and bark beetles in forest stands (Peltonen *et al.* 1998), both in Finland; there are many others.

At this stage, it is also appropriate to note an important aspect of interpreting assemblages arising from lack of taxonomic information (see p. 68), namely the trend to use higher-level taxonomic levels, rather than species, for analysis. We read repeatedly of family X or genus Y as entities in insect surveys, either as components of richness or as indicators (see p. 47). Use of such larger entities saves massively on costs of analysis, and is logistically very attractive because of this. However, it is commonly fundamentally inadequate to provide the information desired as an objective of the surveys undertaken, because it masks the detail afforded by species-level studies. A compelling case for species-level appraisal of assemblages and diversity (Spence *et al.* 2008, echoing similar sentiments from others over recent decades) has emphasized yet again that individual species differ in ecology and functional role, genetic constitution and conservation need. The authors' argument, which is paralleled in numerous surveys in which beetle families or genera are the taxonomic levels employed for interpretations, sometimes leading to far-reaching management decisions, illustrates some limitations. Spence *et al.* suggested the parallel that ornithologists would dismiss conservation-oriented appraisals that grouped the several ecologically different species of North American jays as corvids, and noted that even generic groupings of birds (such as *Corvus*) would probably be discounted or ridiculed (as would groupings such as parrots or honeyeaters in Australia, or finches in Europe), simply because these groups, however valid as descriptive entities, are sufficiently well known to reveal the major differences between constituent species – it also shows the absurdity of lumping such biologically disparate taxa together. As Spence *et al.* (2008) noted, insects are no different to vertebrates in this regard. Many families and genera of beetles manifest massive ecological variety at species level, and there may be little value in obscuring this by shallow or uncritical taxonomic penetration: inventories for conservation evaluation may be of little value unless constructed at the species level, with the practical proviso that consistently recognized morphospecies may need to be employed rather than taxonomic species in many places. Morphospecies maintain an equivalent level to species for richness estimations and consistent focus for compositional changes, but their persistent value depends on responsible deposition of voucher material (see p. 16). Without this, many entomologists are perhaps guilty as charged in suggesting that species-level work for arthropods is scientifically essential when it is easy, but discretionary when it is difficult to achieve! Wherever feasible, taxonomic analysis should be viewed as an important facet of increasing the value of assemblage descriptions, changes or functions.

One of the more comprehensive surveys of tropical beetles was of weevils (Curculionoidea) in Panama, where Wolda *et al.* (1998) used light traps at seven sites (from sea level to 2200 m), with climates ranging from sharply seasonal to almost aseasonal, and spanning a variety of habitats (from natural tropical forest to highly altered areas). Altogether, 2086 species were accumulated in sampling over three consecutive years at each site (collectively spanning 1976–85), and this was considered to be only a small proportion of the species present, because many weevils are not attracted to light. Species ranged from those with very strict seasonal incidence to those occurring year-round, with those at climatically seasonal sites tending to be most abundant at the start of the rainy season. As noted earlier, pronounced seasonality is common in beetles, and particular species may exhibit very characteristic patterns of appearance. In temperate regions, for example, some species of tiger beetle emerge only in midsummer, others only in autumn and hibernate before reproducing; in drier regions adult emergence may be associated with onset of seasonal rains. Trying to predict any seasonal pattern in a poorly known fauna may be diffficult. Use of information compiled from specimens in museum collections may sometimes be useful, but may reflect the seasonal activity of collectors as much as that of the beetles! One example is for riverine tiger beetles in South Africa, for which most collection records are from the rainy season but, from additional systematic survey at other times of the year, the beetles are suspected to be active for much of the year (Mawdsley & Sithole 2007).

For the above purposes, and the numerous intergrading situations that can arise, several survey techniques are commonly used. Many of these are so-called passive techniques that trap and in many instances kill beetles for later examination. These cannot be deployed in studies where any such mortality may be harmful or undesirable, as for studies on rare or threatened species, and must be curtailed immediately if known threatened species are unexpectedly found in catches on sites where they were not previously known to occur. Preliminary investigation may be wise, and certainly responsible, in cases of doubt over such occurrences. In some conservation exercises, it may be necessary to modify standard methods to capture the beetles alive, for example for translocation exercises. As one such modification, Weber and Heimbach (2001) used pitfall traps with floating cork 'islands' to prevent carabids drowning in wet weather.

A selection of beetle sampling techniques is summarized in Table 1.1. Whatever approach is used, care must be taken not to damage the habitat, not to over-collect or over-sample, not to have untoward side effects such as excessive bycatch, and not to transgress the conditions of any permit or access conditions, and to ensure that the material taken is treated responsibly. All too often, massive numbers of invertebrates are captured indiscriminately and killed during surveys, and many are never examined or analysed critically. Many are regarded as bycatch (representing non-target groups) and may simply be discarded. At the outset of any survey for beetles, pragmatic decisions must be made over the resources needed for sample interpretation and processing of specimens, in particular which taxa are to be used, and at what taxonomic level. It is very easy to collect far more material in an insect survey than can be appraised realistically during the planned life or budget of that project. The limitations of any method used in relation to the purpose of the study must also be understood clearly; for example, some species of Carabidae are underestimated in pitfall trap surveys (Halsall & Wratten 1988), so that using this technique alone may misrepresent information on the supposedly sampled assemblage. Full details of the methods used should be included in any report or publication flowing from the study. Many variables affect trap catches and efficiency, and simply listing and assessing these is an important component of assessing trapping effort. Thus, although baited pitfall traps are a standard tool for trapping dung beetles, only recently have serious attempts been made to determine the capture arena of such traps by investigating distances over which beetles may respond. Mark–release–recapture trials with the small scarab beetle *Canthon acutus* in Venezuela suggested that traps should be separated by at least 50 m in order to be considered independent (Larsen & Forsyth 2005), a distance far greater than the 5–10 m spacing commonly employed with presumption of trap independence in surveys.

Some techniques have become standards for particular beetle groups, and are used almost universally in their study. For example, pitfall trap surveys for ground beetles and dung beetles have yielded a high proportion of the specimens used

Table 1.1 Summary of some sampling/collecting methods for beetles and used in surveys for conservation studies (see text for examples including many of these).

Method	*Principle and targets*	*Variables and conditions*
Pitfall traps	Containers sunk in ground Surface-active beetles fall in Non-selective	Size (diameter), spacing, duration of exposure, use of drift fence Preservative and baits may be included Easy replication Can be roofed Semi-quantitative
Tullgren funnels	Samples of leaf litter heated and dried from above Beetles fall into jars of alcohol or other preservative Many small taxa collected Use also for soil cores	Dry loose litter best Volume, duration Need power supply Semi-quantitative One to a few days extraction time
Winkler bag	Samples of litter sifted and bagged Hung so animals drop, as above Based on animals moving to reach shelter rather than responding to heat	As funnels, but no power needed
Litter sifting	Direct inspection of litter in field, by sieving or sorting Yields many small beetles from riverine litter/debris or other restricted habitats	Based on volume or ground area samples for replication Can be time-consuming and laborious

Table 1.1 *Continued.*

Method	*Principle and targets*	*Variables and conditions*
Direct netting	Use of typical butterfly net to capture individual beetles in flight or on the ground	High selectivity in capturing voucher specimens
Sweep-netting	Strong net used to 'swish' repeatedly through low vegetation Dislodged beetles removed individually from net	Vegetation must be dry Time of day and weather may be influential Semi-quantitative rapid method, can be area based for replication
Beating	Canvas tray held horizontally under low tree/shrub branches Branches struck sharply with stick, dislodged beetles collected on tray (many may not move, and be cryptic)	Vegetation must be dry, as above Can standardize search times for collecting from tray
Suction sampler	Vacuum cleaner used to collect insects from low vegetation into container	As above Can be applied to individual vegetation units May accumulate much debris and require further sorting
Insecticide 'fogging'	Mist blower used to 'fog' tree canopy with pyrethrin insecticide, catching falling insects near ground, in funnels or on trays Many beetles found only in canopy layer	Forest canopy otherwise inaccessible to sampling Can be very specific by sampling individual trees Considerable time needed to set up Equipment heavy
Bait traps	Variety of procedures involving use of attractants, mainly for flying beetles, in conjunction with pitfalls or other retention device	Specific cases include use of dung (Scarabaeidae), carrion (Silphidae), fruit or pheromones Considerable variety of uses
Trap logs/wood	Placement of cut or fallen logs or billets, and later examination to rear or collect timber-infesting and bark beetles	Comparative values of different woods: host specificity trials May take a year or more to gain information needed

Light traps	Attraction of flying insects to ultraviolet light Collect in container or when resting on white sheet or background	Weather, time of night, phase of moon, season, etc. all important influences
Malaise trap	One of several patterns of intercept trap Flying insects contact vertical fine black mesh barrier, being directed upwards into container	Passive, acting by day and night High bycatch
Window trap	Intercept trap for flying insects Contains vertical panel of glass, mesh or perspex, from which insects drop into trough of preservative	As above Best for larger beetles Can be roofed to prevent flooding
Emergence traps	Enclosure, often of mesh, vegetation, wood or other substrate, with provision to capture insects emerging from it, such as by funnelling upwards into container	Can be used in aquatic or terrestrial habitats
Eclector traps	A form of emergence trap, usually a plastic or other funnel attached to an area of bark or wood to catch emerging beetles and others	
Dip-netting	Use of, usually, triangular long-handled net in water to capture insects from water column or amongst submerged vegetation Variety of small, otherwise elusive, beetles	Can be used in standard way, as aquatic sweep net
Direct searching	Often very rewarding in yielding species not otherwise obtained easily Can combine with sifting	Universally applicable Often a valuable adjunct to other sampling methods, and can help to provide more specific information on habits and associations Use by day or night (with head-torch)

to interpret species assemblage compositions, changes and distributions. However, use of any particular trapping method must be tailored to local conditions and faunas. Within the Hawaiian Carabidae, for example, Psydrini are best sought by a suite of direct searching methods, and Liebherr and Zimmerman (2000) made no mention of pitfall trapping in their commentary on this substantial archipelago fauna. Beetle trapping methods can sometimes be standardized within narrow limits for evaluating sampling effort. Any single method used in the belief that it is indeed the best can still not usually secure all species present, so that for inventory studies some form of sampling set (or combination of different methods selected to be complementary) is wise. Thus, Davis *et al.* (2001) used baited pitfall traps and flight intercept traps to assess richness of dung beetles in Malaysia. Both methods draw on normal beetle behaviour in dispersing to find and exploit dung. Collectively, the two methods yielded 35,279 beetles, representing 86 species. Application of species richness indices to predict numbers of species (Chao 1 and Chao 2) gave 78 and 79 species from the pitfall data and 88 and 85 species from the flight traps, implying that the latter method may provide a more comprehensive evaluation of beetle richness. In this example, the accumulation could be evaluated against a much fuller one available for the area (97 species from 68,481 individuals sampled) to assess its representativeness. Often no such background resource exists to provide realistic perspective, and richness indices or sampling accumulation curves may then be useful estimators of sampling adequacy. In another informative survey, Larochelle and Lariviere (2007) individually noted the techniques preferred to collect each genus of Carabidae in New Zealand. Altogether, about 25 collecting approaches were noted. The most frequently cited were (i) pitfall traps (for 54 of 86 genera in the fauna) and (ii) turning over of fallen trees, logs, stones and other ground materials (for 52 genera, and reflecting high incidence of such cryptozoic taxa). Several ecologically specialized taxa demanded correspondingly more specialized approaches to retrieve them, but such detail may become apparent only after considerable survey effort and experience. Studies demonstrating the different spectrum of beetle species from different trapping methods abound. As another example, comparison of boreal forest beetles captured in Finland by window traps and pitfall traps showed 62 of the 435 species only in pitfalls, 250 only in window traps and only 123 species in both trapping regimes (Simila *et al.* 2002). Again, the relative merits of several approaches to sampling saproxylic beetles were compared by Alinvi *et al.* (2007), who suggested a combination of window traps and eclector traps as highly complementary methods. Window traps sampled the local species pool by intercepting the beetles attracted to dead wood, whereas eclector traps provided more detailed information by capturing the beetles emerging from particular pieces of wood. Of the 148 beetle species captured in Sweden by these methods and bark sieving, only 22% were taken by more than one method. The differing arrays within the four predominant families (Table 1.2) indicate the magnitude of differences that can arise in assemblage data based on only one sampling method, and that cannot itself be evaluated without comparative studies.

More generally, beetle surveys undertaken in underexplored areas or faunas may depend initially on methods well tried elsewhere, and development of

Table 1.2 Relative representation of four dominant families of forest beetles taken by three sampling methods from logs of spruce (*Picea alba*) in Sweden. Values are given as percentage of species or individuals captured, with actual numbers in parentheses.

	Method		
	Eclector trap	*Window trap*	*Bark sampling*
Number of species			
Carabidae		6% (7)	
Curculionidae	31% (9)	11% (13)	23% (10)
Leiodidae		11% (13)	
Staphylinidae	28% (8)	52% (60)	43% (19)
Number of individuals			
Carabidae		8% (65)	
Curculionidae	69% (100)	6% (51)	74% (474)
Leiodidae		12% (97)	
Staphylinidae	18% (26)	67% (536)	18% (112)

Source: Alinvi *et al.* (2007) with permission.

comprehensive or locally informed sampling sets not be easy. Different sampling methods may differ less obviously than in their broad approach, with small differences in design affecting the catches markedly. Different baits in pitfall traps, for example, may yield different spectra of dung beetle species, so that Larsen and Forsyth (2005) suggested baiting traps with vertebrate carrion, invertebrate carrion, rotting fruit and rotting fungus as well as with 'basic dung'. Lack of standardization of method details renders comparison of the results from different beetle surveys very difficult, even though very similar basic methods are employed.

However, specialized investigations sometimes require considerable ingenuity and inventiveness to devise suitable techniques, so that novel sampling methods for beetles abound, and continue to be developed. For example, a backpack vacuum cleaner was used to extract debris (including beetle larvae and remains) from deep hollows in old standing trees (Bussler & Müler 2009), with living larvae replaced after identification. A key focal species in that study, *Osmoderma eremita* (see p. 165), is viewed as a surrogate for wider richness of beetles in this habitat (Ranius 2002). In a further innovative sampling approach, Svensson *et al.* (2003) demonstrated the values of sampling air in the tree hollows to detect male *Osmoderma* beetles by presence of their sex pheromone (R-(+)-γ-decalactone) by gas chromatography and mass spectrography. The chemical, giving the beetles a characteristic peach-like odour, appears to be a reliable indicator of beetle presence, but a limitation is that its absence does not necessarily mean that beetles are also absent, as it dissipates quite rapidly. A somewhat similar approach using attractants for beetles was discussed by Chapman *et al.* (2002) for *Lucanus cervus* (see p. 198), as a basis for long-term and non-destructive population monitoring. Pheromone sampling is widespread for some pest beetle monitoring. Fireflies (Lampyridae) can sometimes be estimated by simply counting flashes over a given interval, with Yuma (2007) reporting counts of Genji firefly in Japan (see p. 2) over 25 years, and calibrating counts by comparison with mark–release–recapture assessments. Cerambycid infestations in wood may even be detectable by the sounds made by larvae, with this approach examined recently for the economic pest Asian longhorn (*Anoplophora glabripennis*, Cerambycidae) in North America (Mankin *et al.* 2008). Use of acoustic technology has been pursued for this species as a possibly more satisfactory alternative to current laborious physical inspections of trees, but determining the signal profiles and distinguishing them from background noise remains difficult. Mankin *et al.* noted, for example, the difficulties of detecting beetles during high winds or in high traffic noise.

Many sampling methods for beetles have been investigated most critically for common beetle species, such as agricultural or forest pest species, for which detailed information on dispersal and behaviour may be important in management. These contexts may aid more critical focus for species of conservation interest and indeed many others in similar biomes or landscapes. Even for common beetles, a novel or previously untested approach may lead to major revision of the conventional wisdom of ecological knowledge. The bracket fungus-infesting *Bolitophagus reticulatus* (Tenebrionidae) in Europe was long believed to have very low dispersal capability, reflected in low trap catches across several studies. This inference was challenged by results from investigation of the attractant effects of volatile chemicals (Jonsell *et al.* 2003), demonstrating both high attraction of flying beetles and an intense but short major flight season. The beetle appears to disperse sufficiently well that early concepts of it forming metapopulations (with individual *Fomes* fungi the component units) may not be correct, and the population in a forest may indeed be continuous. For some forest beetles, distributions may be evaluated through use of aerial photography to detect changes in tree condition, with this approach now becoming highly refined since earlier realization that particular spectral bands may provide fine-scale estimations. For the seriously damaging southern pine beetle (*Dendroctonus frontalis*), early attack could be detected by changes in tree colour through chlorosis. Carter *et al.* (1998) used pixel sizes of 1 × 1 m ground areas, so that individual trees could be assessed for condition from photographs taken from a flight altitude of 1830 m. Although not a conservation survey method, this, now early, example indicates some of the potential of remote sensing techniques for beetle surveys, and several more pertinent approaches are noted elsewhere.

The above categories of survey are all predicated on beetles being the primary focus of the survey exercise. However, discovery of unusual beetles during surveys directed initially at other taxa, or in more general appraisals, may elevate their priority from these and lead to more targeted study. Assemblage studies have sometimes arisen from more general insect studies, such as use of pitfall traps for ants, that commonly also trap numerous beetles as bycatch (see p. 121). It may then become important to refine the initial sampling regime for greater effect in assessment, or to protect such taxa.

The sampling regime must reflect the precise questions being asked, so that defining the objectives of any beetle survey before it is started is important.

Table 1.3 Activity distribution amongst dung beetles surveyed by baited pitfall traps in French Guiana illustrating occurrence of guilds of species with different daily activity patterns. The pool comprised 63 species (with six species not categorized), and richness and relative abundance are shown, with percentages in parentheses.

Activity pattern	*No. of species*	*Abundance*
Diurnal	27 (42.9)	901 (33.8)
Nocturnal	13 (20.6)	431 (16.2)
Dawn and dusk active	14 (22.2)	367 (13.8)
Nocturnal–diurnal	3 (4.8)	934 (35.1)

Source: Feer & Pincebourde (2005) with permission.

Contexts such as those noted above must be appraised in relation to the scale of sampling needed and the resources available for an ideal programme to go ahead, sufficiently planned and replicated in time and space where relevant. Many demands for conservation surveys, for example, are for one-off investigations without provision for comparisons over time or across sites, and they may have severe limitations for providing definitive information. Possible questions of scale include whether a notable species is to be sought at a single site, across a series of sites within a given region, or in other likely areas across a wider inferred or historical range. Likewise, are quantitative data or ecological knowledge needed and, if so, what are the projected uses and analyses for that data? Another context is whether the study forms part of a larger endeavour and needs integration (or predetermined sampling approaches) based on that but initiated elsewhere. Such considerations are easy to overlook, but emphasize the need for very careful thought and experimental design (sometimes involving collaboration with other scientists or agencies) early in a survey plan, not least to facilitate costing of the exercise and assuring the needed logistic support. Perhaps the most important decision is how to ensure that sufficient sampling is undertaken, by the most suitable methods, to answer the questions posed adequately, whilst not incurring extra costs by undertaking work that is not needed. For more general objectives, a suite of more general methods may be needed; for more targeted questions or single-species studies, these methods may need more careful fine-tuning in relation to the species phenology and biology. Short-term or one-off sampling may even need to consider patterns of diurnal activity of beetles, with many species active (and thus trappable) only at particular times. Differences constitute one important aspect of ecological segregation, common in many different insect groups. Daily flight activity patterns of Scarabaeinae in French Guiana revealed distinct cohorts of diurnal, nocturnal and crepuscular species (Feer & Pincebourde 2005) (Table 1.3), with the first about twice as rich as either of the other guilds. Distinct diurnal and nocturnal separation of dung beetle species has been documented quite extensively in several parts of the world. Feer and Pincebourde found two distinct patterns among diurnal flyers: some species flew predominantly in the first half of the day, while others flew throughout the day. Most nocturnal species flew during the first half of the night; some crepuscular species flew at both dawn and dusk, but others only at dusk.

Greater dominance by diurnal species may reflect greater dung deposition by mammals during that time, with the reverse more likely in Australia where most tropical mammals are nocturnal.

Studying rare species

Many rare species, including almost all the beetles scheduled for conservation attention, are particularly difficult to study and survey, simply because they occur in very small numbers and very low densities. In addition they should not be sampled by any technique that might cause loss or harm to individuals or populations. Even experienced specialists searching intensively for taxa with which they are familiar may find few specimens of their target group. Bell (1985) noted that he spent 3 months at Wau (Papua New Guinea) during which he searched for a group of carabids (Rhysodini) in logs. He described these as 'uncommon, secretive beetles, spending most of their lives within decayed wood'. Bell found only eight logs with these beetles, collectively yielding 37 adult beetles representing six species. Experimental manipulations of such 'genuinely rare and elusive' species may be impossible, and need for statistical analyses may dictate particular sampling approaches to provide the data in suitable form. This problem has been addressed for red-listed saproxylic beetles in Sweden (Hedgren & Weslien 2008). Two sampling regimes involved random sampling (selecting position by GPS within stands of spruce and sampling the nearest dead tree) and subjective sampling (dead trees in the same stands selected on available biological knowledge as being those likely to host the beetles). The latter approach was significantly more efficient (red-listed beetles found in 28 of 78 subjective samples, compared with 56 of 360 random samples). However, both series yielded a substantial set of these rare species (12 in subjective samples, 13 in random samples, with a combined pool of 17 species). The method preferred may be dictated by the aim of the study: subjective sampling may be more cost-effective for rapid surveys to determine conservation value of a stand, whereas random sampling may yield new knowledge and provide data more accessible for formal analyses because it is more objective and easily replicated; it may thus be preferred for purposes such as long-term monitoring.

Because of the unpredictability of finding rare beetle species in samples, rendering the enumeration of these taxa very uncertain, Martikainen and Kaila (2004) suggested that reserve selection based on these species should be cautious. In their 10-year survey of beetles in birch-dominated forests in Finland, 258 of the 583 species captured were saproxylic, but many of the rare species were not found until after several years of investigation, and most were then seen only in very small numbers. For example, the only individual of the vulnerable *Phytobaenus amabilis* (Aderidae) was taken in year 6, and that of the endangered *Neomida haemorrhoidalis* (Tenebrionidae) in year 8. Such species indeed appear to be extremely scarce, and only four of the 16 species of individual conservation concern yielded more than 10 individuals over the extended sampling period. Accumulation curves for species of saproxylic beetles in the two forests sampled (Fig. 1.2) revealed that a high proportion of the common species

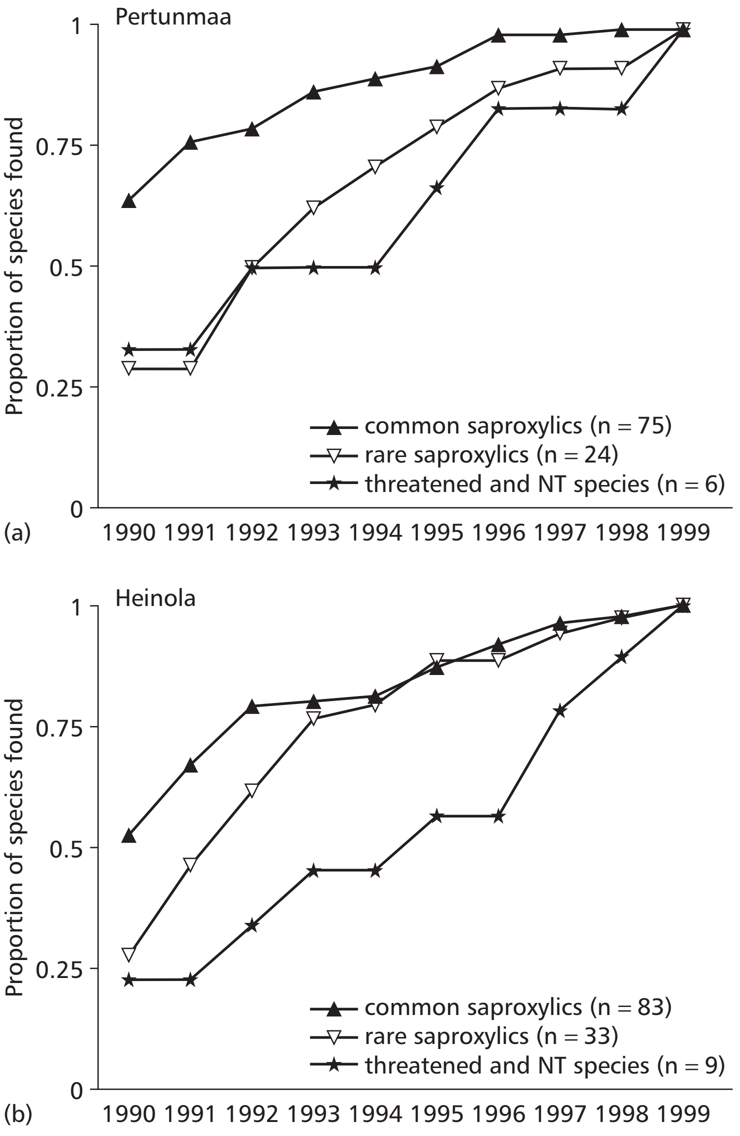

Fig. 1.2 Accumulation of species richness of three categories of saproxylic beetles (common, rare, and recognized threatened and near-threatened species) in two birch-dominated forest sites in Finland: (a) Pertunmaa; (b) Heinola. (From Martikainen & Kaila 2004 with permission.)

(those represented by 51 or more individuals in total) had been detected after 2–3 years of sampling. Accumulation of rare species (less abundant than the above) was much slower, with sampling asymptotes not reached after 10 years. The accumulation of threatened and near-threatened species appeared highly incomplete, with additional species still accruing at the end of the survey period. In short, even after this lengthy survey, the number of saproxylic beetle species in the forests remained unknown. Martikainen and Kaila recognized the possibility that the resident fauna had indeed been sampled adequately, and that the newer records were of vagrants from other habitats. They argued that, should this be the case, those species should perhaps be common in other habitats and so more common in the samples, and suggested that the ecologically specialized nature of many of the more recently accumulated rare saproxylic beetles might indicate resident species that are not detected easily. As with some other studies, rare species were sampled comprehensively only with considerable difficulty, and the uncertainties over what factors influence their incidence and abundance render reliable comparison of different areas or habitats very tentative.

It is obvious, though not always acknowledged openly, that any survey can benefit from knowledge of the taxa sought, so that redundant sampling effort can be avoided in both space and time. This knowledge becomes particularly important when targeting particular species, to help avoid wasted effort, but may also apply to assemblage studies. Writing on South African dung beetles, for example, Davis (2002) noted that failing to survey particular local habitats and dung types may result in absence of records for many species. Numerous dung beetle species around Pretoria were extreme specialists on sand, and some were recorded only from particular soil or vegetation types. Seasonal variations in appearance also occur. More generally, most dung beetles in the region are characteristic of particular ecoclimatic regions, some of them constituting areas of substantial endemism. Similar patterns are found in numerous other beetle groups.

Especially suitable habitats for beetles may be very small, and dispersed widely in a landscape. Actual critical sizes of habitat patches are difficult to assess but are of vital importance in considering values of fragments (see p. 94) or small 'island' habitats (see p. 109). Likewise, small habitats may be difficult to detect in complex landscapes. However, with a sound framework of what characterizes good habitat (see p. 77) for particular species, remote sensing approaches may have value. For tiger beetles, Mawdsley (2008) used two web-based systems (Google Earth, Microsoft Terranova) to help locate small patches of potential habitat in complex landscapes, and considered that the approach 'shows great promise', especially for landscapes where visual contrasts may indicate suitability. Many important variables, such as soil salinity or organic content, may be important for tiger beetles and cannot at present be appraised by this approach.

For inventory studies, a high proportion of the species retrieved are likely to occur in very small numbers, many of the beetles by singletons, and thus be rare in sampled assemblages.

The major dilemma for interpretation arises with the realization that the simple detection of such species targeted for conservation attention may require very considerable sampling effort, but those species may be the ones of major interest from the viewpoint of species conservation, with conservation interest enhanced by supposition of rarity. They are thus those for which quantitative information may be particularly valuable. Enormous numbers of beetle species must at this stage be considered rare, simply because they are known from only single specimens or very few individuals, and from single sites or samples. Many have been the subjects of targeted surveys that have proved futile, but it is often difficult to determine whether a species is genuinely rare or simply not retrieved. Klausnitzer (1983) noted a species of *Rhipidius* (Ripidophoridae), then known from only one European specimen caught in 1867 with a second specimen found in 1929, as 'probably the rarest beetle in Central Europe'. Rarity is by no means confined to small or obscure beetles; one of the world's largest species, the South American *Titanus giganteus* (Cerambycidae) was for long known only from very few specimens, and its detailed biology remains undocumented.

A typical sampling pattern will continue to yield additional low-abundance species with additional sampling, so that the number of rare species in an inventory reflects sampling effort, and will increase knowledge of the richness of any local fauna. Typically, increased sampling effort will also lead to increased representation of the few abundant species, and continually add to the 'tail' of scarce species. Boreal forest ground beetles may be anomalous. Niemela (1993) demonstrated that they show a bimodal abundance distribution, with the few abundant species and more numerous rare species not linked by a continuum of intermediately common taxa. Several possible explanations for this anomaly were advanced, one being that only a few species had adapted sufficiently well to the boreal forest to be able to become abundant.

For much of the tropics, the natural abundance of many beetle species is unknown. Floren and Linsenmaier (2003) noted 'most Coleoptera of primary forests are extremely rare and faunal overlap in samples is very low'. Incidence of many low-abundance species is endorsed by numerous faunal studies in the tropics. In Papua New Guinea, Allison *et al.* (1997) collected 418 beetle morphospecies (in 53 families) by fogging eight individual trees of *Castanopsis acuminatissima*, and 199 of these were represented only by singletons. A further 83 morphospecies were each represented by two beetles, so that a high proportion of the taxa was apparently rare. Similar trends have been noted elsewhere; for example, Stork's (1991) 859 beetle species from canopy fogging in Borneo included 499 represented by singletons and a further 133 with two individuals. And a classic Amazonian forest beetle study (Didham *et al.* 1998a,b; see p. 95) yielded 45% of singletons across 993 morphospecies. Such patterns of relative abundance seem to be general. The *Castanopsis* study above exemplifies anther relevant facet of beetle diversity, namely that single plant species, or even parts, may support substantial diversity, perhaps as a specific critical resource on which some of those species depend. As another example, woody petioles of *Cecropia* trees (four species) in Costa Rica yielded 36 species of beetles, most of them Scolytinae or zygopine weevils (Jordal & Kirkendall 1998).

Tropical beetle richness, even on single tree species, can indeed be impressively high. However, increased sampling effort also detects changes over time, not simply through increasing take of what is already there at any given time. For Galapagos beetles, for example, Peck (2006) noted that the continuing dynamic pattern of faunal change, resulting in part from human activity, can be revealed only by continuing investigation. The number of species known there from only one or two specimens suggested the likelihood of others being present, but Peck also noted that poorly investigated habitats and novel sampling methods to augment earlier capability should be conducted routinely in such attempts to augment inventories. There will inevitably be some form of trade-off between sampling effort and the time/resources available. Most commonly, cost and time available will not permit surveys of indefinite length and complexity, and very careful planning is needed to optimize the field procedure in relation to answering precise questions and accepting the compromises that ensue. For dung beetles, Davis (2002) noted one such compromise as being failure to collect some of the rarer species at each individual site whilst increasing the number of sites sampled in order to increase the geographical representation of a survey. If assessing sites for typicalness or representativeness, determining the consistently present members of a beetle assemblage may be more relevant than retrieving every very scarce species present. Their presence may, of course, add conservation significance to a site but this may not be the primary aim of the programme. Again for dung beetles, Hanski (1982) differentiated between core and satellite species in assemblages, a principle of very wide relevance in clarifying community structure. The core species are those that are relatively common and present in all or most suitable sites all the time, not necessarily as ecological specialists but as reliable elements that can help to characterize the assemblage. Satellite species, in contrast, are rare (or more sporadic in incidence) and may frequently become extinct and be sustained by repeated establishment of new populations at sites, perhaps as metapopulations so that knowledge of regional dynamics becomes a central theme in their evaluation. Scale effects may be important in assessing this aspect of assemblage dynamics (see p. 65). For most groups of beetles, however, nothing is known of population dynamics or the factors that cause many species to be as rare as they appear to be. And, despite the academic attraction of undertaking more comprehensive surveys, short surveys may prove perfectly adequate for many purposes.

The presence or absence of threatened species, either particular individual species or broader representation from a local directory such as a red list or red data book, is widely viewed as fundamental information in designing and implementing conservation. However, the amount of sampling needed to detect all or even most such species is difficult to define. For boreal forest beetles in Finland, numerous saproxylic beetles, in particular, are of concern as regionally extinct, threatened or near-threatened (Table 1.4). The beetles of these forests have been studied intensively over several decades so that the conservation status of many species is reasonably unambiguous, and the presence of rare or threatened species in samples is used to indicate the conservation values of individual forests or to help dictate sympathetic forestry management. Martikainen and Kouki (2003) attempted to address the problem of the sampling effort needed to assess the presence of the significant beetle species, using window traps attached to the trees. The overall number of beetle species trapped in an area was a useful indicator of representativeness, and an almost exponential relationship was found between numbers of total beetle species and conservation interest species. Samples comprising fewer than 200 trapped species or 2000 individuals were considered ‘almost useless’ in surveying threatened or near-threatened species, and the probability of finding these taxa increased markedly when the number of beetle species trapped was greater than 400. In essence, very large sample sizes were needed, even using well-understood and effective sampling methods in order to reliably rank different forest patches for significance based

Table 1.4 Forest beetles in Finland: numbers of regionally extinct, threatened (divided into critically endangered, endangered and vulnerable) and near-threatened species, indicating the assemblage importance and diversity of saproxylic beetles.

		Threatened				
	Regionally extinct	*Critically endangered*	*Endangered*	*Vulnerable*	*Near-threatened*	*Total*
Saproxylic species	12	33	48	56	65	214
Other species	9	6	13	27	23	78
Total	21	39	61	83	88	292

Source: Martikainen & Kouki (2003) with permission.

on diversity of such notable beetles, in a fauna that can be regarded as well documented. In their example, Martikainen and Kouki (2003) noted that ranking 10 boreal forest areas in this way may require trapping of more than 100,000 individual beetles, analysis of which is simply not feasible as a routine exercise.

The presence of such notable species in samples is commonly largely a matter of chance, with their rarity (as low abundance and restricted distributions) rendering any attempt to detect them uncertain. Even enumerating the species not trapped is highly uncertain (Muona 1999) and, if possible at all, relies on extrapolation from previous records probably resulting from different methods, possibly long ago and in different (pre-disturbance) environments, and even from misidentifications. Sampling interpretation for most tropical forest habitats is far more difficult than for Finland, because of the larger overall numbers of beetle species present and because many or most will not be described or named, so that their conservation status will not be definable easily. Apparent rarity is not necessarily equivalent to vulnerability.

For Iberian water beetles, Ribera (2000) recognized four categories of rarity, and these have much wider relevance in conservation assessment, as they can infer very different conditions and security.

1. Species which may indeed have greater distribution and/or abundance than known, for example recently discovered species whose extent has not been explored beyond, possibly, the single site or population from which they are at present known.
2. Relict species, those which are now the isolated remnants of formerly wider distributions, perhaps as a result of long-term ecological change, such as in some alpine species.
3. Rare local endemic species, perhaps restricted to very small and specific sites (in Ribera's example to selected permanent stretches or headwaters of individual rivers or streams), and for which site protection is needed.
4. Species that have demonstrably become rarer as a consequence of human activity, as threatened species, for which the causes of loss or decline can sometimes be unambiguous.

However, such approaches are also predicated on adequate definition of which beetle species are acknowledged to have conservation interest or significance, rather than simply being rare or elusive. The term ‘rarity’ has a variety of meanings, as used above, but implies some form of scarcity and, perhaps, predisposion to threat. Although rarity and threat are commonly compounded or confused in conservation assessment, vast numbers of insect species are naturally rare but not necessarily threatened. The distinction is often unclear, simply because putative threats cannot be evaluated easily, and the three conditions of rarity (namely low abundance, narrow distributions and ecological specialization; Rabinowitz *et al.* 1986) may predispose a species or population to stochastic influences or localized threat. Although it is common for only one of the above three states of rarity to occur in a species, any combination of them can occur. The vulnerability of the tiger beetle *Cicindela deserticoloides* in Spain, for example, results from low abundance, small geographical range and habitat specialization (Diogo *et al.* 1999), so embracing the three parameters.

Evaluating conservation status and significance

The most widely accepted rules for evaluating threat to individual species flow from systems developed through the World Conservation Union (IUCN 1994, 2001), which involve assessment of each species against a suite of criteria to evaluate risk of extinction. These categories are illustrated in Fig. 1.3 and are the basis for placing species formally on a red list or similar document.

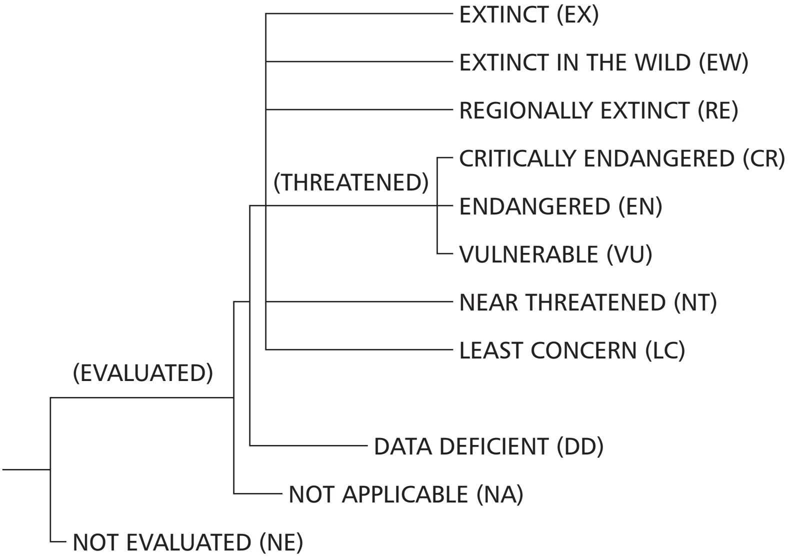

Fig. 1.3 Schematic summary of the IUCN Red List Categories, in which Threatened includes the three categories of Critically Endangered, Endangered and Vulnerable. (From IUCN 2001 with permission.)

Nevertheless, applying the IUCN Red List categories reliably to beetles is difficult; in common with almost all other insects, we usually have no data on population sizes and numerical trends of decline, or of the factors that enable estimates of probability of extinction. In almost every case, only selected criteria may be able to be applied. Most such concerns over threat have arisen from demonstrated loss or change to habitats, and thus related to declines in extent of occurrence or area of occupancy. Often, this is the only reasonably reliable information available and can transcend national or other political boundaries. For the 30 red-listed species of Cerambycidae in Finland (of a total of 81 species), Komonen (2007) classified the species variously as resource-limited (host plant), substrate-limited (to particular host plant attributes), or climate-limited. In Finland, many of the red-listed species are represented by peripheral populations on the edge of a wider European range, so that their importance nationally may be far greater than that over their full geographical range. Factors that limit distribution of beetle species, and which may create localized distributional ranges that accord them conservation interest, have frequently been suggested. For most, the historical events leading to the present distribution are not sufficiently known so that the twin scenarios of local endemism and relictualism (the latter reflecting survival after disappearance elsewhere as a consequence of habitat loss or other threats; see p. 72) may become confounded. Nevertheless, as indicated in particular by several studies of scarab beetles, the factors associated with extent of environmental tolerance or specialization and with dispersal capacity, are both highly relevant. Dung beetle distributions are thereby influenced by the amount and kind of dung available, reflecting in turn changes in the native mammal fauna or grazing stock regimes. Allsopp (1999) speculated that there might even once have been some Australian dung beetles associated with the prehistoric mammalian megafauna, extinct since the end of the Pleistocene. In Spain, limited distributions of *Jekelius* species are influenced substantially by the acidic or basic nature of the substrate, in conjunction with limited dispersal potential of these flightless beetles (Lobo *et al.* 2006).

Successive global red lists of threatened animal species each include several hundred beetle species allocated, sometimes tentatively, to one or other category of threat or regarded as ‘near threatened’ or ‘data deficient’. The listed taxa are geographically widespread, but actual numbers are sometimes uncertain. In addition to series of individually named beetle species, earlier directories in this series include entities such as ‘all species of genus X’. The most recent version of the *IUCN Red List of Threatened Species* (IUCN 2008) includes only 72 individual extinct or threatened beetle species, reflecting revisions from earlier lists, and uncertainties of current status. The major message, though, is that most beetles have not been evaluated on this scale, and the magnitude of conservation need based on numerical or range declines or habitat losses is likely to be far greater than appreciated widely at present. More complete directories are available for many countries, particularly in Europe, and indicate much higher levels of loss for some national or regional beetle faunas. Thus the UK Biodiversity Action Plan, designed in 1999, listed 54 beetles among its designated priority species, and many of these have received considerable attention to clarify their conservation status and needs. Later this number was increased to 87 species, but recent reports suggest that four of these have become extinct and that the future of others is parlous. More widely, around 250 of the UK's 4000 beetle species have not been found in the wild since 1970, and their fate is largely unknown. In contrast, more local scales of conservation reflect more local losses, so that conservation concerns arising from local threats, or to species perhaps more abundant elsewhere, are important. One British example, of many that could be cited, is for the flightless bloody-nosed beetle (*Timarcha tenebricosa*) in Warwickshire. It was formerly widespread in the county, but is now known from only two relict populations on small sites. Imminent threats include site losses through airport development and road construction. A local action plan (Lane 2003) sets out a number of measures designed to safeguard the beetle.

Any list of designated priority species is a useful initial filter for demonstrating conservation need, and collective benefit may be increased if ecological variety is represented among the taxa. For Britain's *Red Data Book*, Shirt (1987) listed 142 endangered, 84 vulnerable and 266 rare beetle species, collectively around 14% of the British fauna, a level which, although daunting, is not surprising. The most important habitat associations represented, by number of dependent beetles, include woodlands (40%, particularly ancient woodlands with about 90 endangered or vulnerable beetle species), coastal situations (21%), wetlands (19%) and grasslands (11%). For such well-documented faunas, it is possible to review the status and conservation significance of a very high proportion of the species present, and the review by Hyman and Parsons (1992, 1994) illustrates the kinds of information that can be derived from biological knowledge combined with distributional data from recording schemes (below). These form the foundation of many conservation exercises and plans, and aid considerably in establishing priorities among species. Many of the species are known from single sites or populations, others from very few localities, and each may independently merit and need urgent conservation measures. However, as Haslett (1997) put it, in any such listing or compendium of invertebrates we are 'spoiled for choice' as there are simply too many species that qualify for inclusion. Haslett advocated some focus in enlarging such lists to include representatives of species associated with habitats that are under-represented, rather than simply adding 'more of the same', so that those species could be representatives of ecologically functional groups essential to the continuity of the ecosystems concerned. Some such species (such as *Cerambyx cerdo*; see p. 45) and the cetoniine *Liocola lugubris* in Europe assume the roles of keystones whose well-being reflects that of numerous other coexisting taxa. In this case, widespread declines of *L. lugubris* may influence many other saproxylic species, and protection of ancient deciduous woodlands in part reflects the conservation needs of this beetle. Many localized or ecologically specialized beetles can be promoted as symbols or flagships for particular habitats or sites, with striking appearance or unusual or novel biological characteristics increasing public interest. Particularly notable species, such as the European stag beetle *Lucanus cervus*, can be important promoters of interest in insect conservation (Smith 2003). Individual species conservation plans (below) may be important in drawing attention to unusual habitats or sites. Thus, the North American delta green ground beetle (*Elaphrus viridis*) is one of a varied suite of taxa that highlights the significance of vernal pool ecosystems in California. Species plans may be complemented effectively by those focusing on suites of species, related either taxonomically or ecologically: British plans include those for three such ecological groupings of beetles, namely river shingle beetles, *Harpalus* spp. and saproxylic beetles, whereby suites of species with biological features and conservation needs in common can be appraised together (see p. 199). As a North American example, three beetles are among the total of seven invertebrates that highlight the importance of karst caves in Texas. This important theme is discussed further on p. 199, and is important in cases (i) where such species co-occur and are not sufficiently well understood to enable individual conservation plans to be prepared, or (ii) where the major need devolves on habitat protection for all the species involved so that conjoint effort is efficient.

Placing species on lists accords them priority for conservation, but the lists themselves vary considerably in primary purpose. Some are advisory in not carrying legal weight, whilst others are more formal documents that oblige action and responsibility. It is not uncommon for initial advisory listings to form the basis of regulations at some future time. Listing is thereby a responsible step, likely to influence how a recorded species may be treated in the future (New 2007) and it may take some time to consider and approve a nomination. At the least, a listed species may gain notoriety and additional publicity. However, formal listing is often accompanied by some form of prohibition of take, as a perceived threat to the species. For collectable organisms, such as many beetles, this prohibition may lead to illegal black market trade with high prices offered and paid for threatened species, including international poaching and smuggling and sometimes involving substantial damage to sensitive habitats by unscrupulous gatherers. Such provisos seem to apply to the several Lucanidae protected formally in Taiwan for example. Several examples are discussed later, but a subsidiary effect of protecting threatened (or putatively threatened) species in this manner is that hobbyists may be frustrated by attendant needs for permits and have their interest discouraged by an atmosphere of suspicion, causing them to transfer their leisure time to other pursuits. It is better known for butterflies (see Greenslade 1999) that the very people whose continuing interest is the major channel through which greater understanding of rare species can be accumulated and incorporated into informed conservation planning can be alienated by ill-planned prohibitions. Sometimes, these are not seen to aid conservation and alone are unlikely to reduce or remove threat. Decisions to designate species as protected must be responsible, transparent and justified after canvassing the widest possible advice from people who understand the taxa involved from field experience.

Further problems can arise when calls are made to formally protect beetles (or other insects) that are members of groups containing many very similar-looking species, simply because the individual species may be recognizable only by a specialist, because the insects are small or because the specific characters need careful appraisal, perhaps involving dissection or measurements. In some groups of beetles, individual insects of the same species may differ considerably in appearance or size. Indeed, one basis of desirability of beetles to collectors involves these features, with large or heavily ornate individuals of scarabs or stag beetles sometimes commanding far higher prices than smaller or less ornamented individuals of the same species. Most people (such as customs officers) responsible for enforcing any prohibition of take or trade are not specialists in the taxonomy of beetles or even entomologists or biologists, and it is both unreasonable and impracticable to expect them to recognize most individual species within these groups. Likewise, most ecologists examining assemblages or large multispecies samples of beetles are highly unlikely to initially recognize particular protected species of small beetles in their voucher series.

One avenue towards overcoming such problems is to widen the ambit of formal protection. Thus, listings of 'all species of genus X', noted earlier, may serve the purpose of protecting individual included species that merit this by including them with their close relatives with which they might be confused easily. Notwithstanding that some of those relatives may be abundant and of no current conservation significance, their protection acts as an umbrella for protecting the truly needy species. The approach can be contentious, but is simply a manifestation of the precautionary principle. In a few cases, such steps have involved a collectable group of beetles. The formal listing for protection of all species of jewel beetles in Western Australia by the state government in 1978 was motivated largely by their stated desire to protect some rare collectable species from trade, but caused considerable disquiet among hobbyists. The credibility of this legislation for conservation was thrown into doubt by subsequent authorized destruction of substantial areas of prime jewel beetle habitat within the state: protective legislation is not in itself conservation, but such listings may sometimes be an effective first step to enable conservation to occur.

Collins (1987) provided a list of specific Coleoptera selected for formal protection in many parts of Europe, either nationally or in particular regions within a country. A greater array of countries listed Lepidoptera, and in almost all places the list of beetles was considerably shorter than that for butterflies and moths. Indeed, many countries listed less than a handful of beetles, occasionally only one. However, as above, some broadening occurred sporadically. Thus, in Salzburg (as one of the separate Länder of Austria) the protected taxa list included 'all species of Cerambycidae except *Hylotrupes bajulus*', and that for another region 'Scarabaeidae: Cetoniinae'.

Particular beetles have long been heralded as of conservation concern but, as noted above, the real scale of the problem they face is vastly underestimated by lists of such species. Wells *et al.* (1983) included seven beetles in the first *IUCN Invertebrate Red Data Book*, sufficient to indicate the variety involved, but these are simply examples of the numerous species meriting such concerns, for a variety of different reasons. Lists of signalled species are invaluable initial guides to the status of regional faunas or taxonomic groups, but for such poorly known animals as beetles they reveal two main categories of problem. First, lists are almost invariably too short to be fully representative, and simply reveal the tip of the iceberg of needy species that have received sufficient attention to be nominated and validated for inclusion. Second, even though the lists are so short, they commonly still include far more species than can be properly managed or can receive adequate individual treatment from the resources available for practical conservation. Whereas single-species studies and management remain the most tangible and popular level of beetle conservation to many people, many other beetles are necessarily conserved only under the umbrella of wider studies. Nevertheless, many individual beetle species clearly need practical conservation, and debate will continue over how the most deserving targets are best selected, within the widely accepted framework that the most needy species may be accorded priority. However, basic biological knowledge of many threatened species is very poor and their scarcity renders them difficult to study effectively in order to improve this situation. There may be considerable uncertainty over where they occur, the form and size of their populations, factors causing conservation concern and even whether the species is still extant.

Recording schemes for beetles are proliferating in efforts to more accurately assess species' distributions and abundance, to help detect trends of decline or actual losses, and to generally improve the level of basic knowledge needed to properly assess conservation status and needs. Recording particular species, of course, depends on our ability to detect and recognize that species. Even for some spectacular and nominally well-understood beetles, difficulties can arise. The European stag beetle *Lucanus cervus* is a notable flagship species but, notwithstanding that around 1300 recorders participated in a survey of its distribution in Britain (Smith 2003), distributional data for some other parts of it range are still sparse. Thomaes *et al.* (2008) suggested that many sites remain undetected, reflecting that *L. cervus* has a very short adult flight season and is nocturnal, so that it is substantially under-recorded to the extent that data for reliable designation of suitable protected areas are not available. Particularly in parts of Europe, recording schemes can draw on substantial accumulated knowledge, and any such endeavour can include two main sources of information.

1 compilation of published records, and the transcribed label data from specimens in museums and private collections, are sources of historical information that may span a century and more;
2 current surveys, in which the most recent systematic arrangement can be applied to target particular habitats or taxonomic groups.

Other than for easily identifiable (generally equating to collectable) groups, anomalies of species naming are likely to persist through the historical record, so that the existence of voucher specimens to validate identifications is of critical importance. Categorizing accumulated records by time interval can indicate possible changes in abundance and distribution, but the data are almost inevitably sporadic and patchy, so that considerable care is needed in extrapolation. Other than for more systematic or comprehensive recording, such as occasionally for particular reserves in Europe, changes in abundance are almost impossible to assess from this information. The growing number of databases, of ever-increasing sophistication and incorporating reliably identified museum records and current data, are an invaluable investment in assessing changes in the future, as indeed are the specimens themselves. Unidentified material from ecological surveys, archived as 'ecological collections' (Danks *et al.* 1987), may be of critical importance as human demands on land and water proliferate. Even for better-documented insect groups such as butterflies and dragonflies, increased numbers and completeness of entomological surveys in recent decades may yield results far more complete than earlier records based on the efforts of a few recorders or enthusiasts. Many early recording schemes thus reliably include presences while perhaps including data from only part of the range, but sampling effort may not have been comprehensive and the interpretation of purported absences may be difficult.

Such databases are the template for assessing trends and change, based on species incidence, and can help to determine changes that have already occurred and as models to predict those anticipated in the future, for example as a consequence of climate changes (see p. 133). Beetle distribution recording schemes, in Britain and elsewhere in Europe in particular, are providing much information of conservation relevance, not necessarily restricted by political boundaries (see p. 39). The most thoroughly appraised example for insect recording is for the British butterflies, based on more than a century of recording a small and well-studied fauna, mapped on a base scale of 10 × 10 km squares (see Asher *et al.* 2001), and admired as a model for emulation elsewhere in both methodology and detail. This has allowed convincing interpretation of range changes in British butterflies and has become a major foundation for conservation activity and planning. Recording schemes for beetles have not yet achieved such venerability, but many are indeed accumulating, most focusing on beetles of particular families or habitat associations. A 10 × 10 km square represents a huge area to a beetle and each such unit is likely to include numerous different habitats. Nevertheless, as Eyre *et al.* (2006) noted for water beetles in Britain, 'there is little doubt that 10-km square records do constitute a measure of variation at the large biogeographical scale'. Data on even a few species can be revealing. With selected examples from only two families (Cantharidae, Buprestidae, drawing from a recording scheme for these groups started in 1984) in Great Britain, Alexander (2003) illustrated species that have remained largely stable in distribution, expanded their range, or declined considerably. The last of these give valuable clues to conservation need, not least because many declines can be linked with particular facets of habitat change attributed directly to human activity. Thus, declines were found in areas associated with agricultural intensification, and among beetles associated with ancient trees (see p. 84), coppice woodland and open woodland affected by changing management practices. Other range changes may be linked with climate changes (see p. 133).

One such example from elsewhere is for dung-rolling Scarabaeidae in Italy (Carpaneto *et al.* 2007), in which declines of these species were appraised using data accumulated since the 19th century and categorized by decades in seeking possible trends. The data included all literature records from 1865 to 2004 and 1413 unpublished records from collections, from all 20 administrative regions of Italy [within which 282 UTM (universal transverse Mercator) grid cells with more than 15% land area were assessed separately for records], to give a total of 6870 individual records. Three patterns of decline were suggested by frequency of records, as species starting to decline in the 1960s (two species), 1970s (three species) and 1980s (six species) respectively, so that all 11 species in the fauna manifested apparent declines. Several species appeared to have disappeared entirely from northern regions, and six were considered to have a high risk of extinction nationally. Even allowing for considerably greater recording effort in more recent times, these trends appeared real. Declines were attributed in part to changes in livestock systems, from predominantly free-ranging cattle to stabled stock with consequent unavailability of dung in the field, linked in part with loss of open pastoral areas to forestry or intensive agriculture. Increased predation on beetles by hooded crows (*Corvus corone cornix*) might also be a contributing threat.

Records of species incidence, whatever method was used to obtain them, can (once accepted as valid) be used to map distributions, and a number of beetle atlases for Britain or parts of western Europe are important aids to help demonstrate conservation status and its changes in individual species. In particular, declines of species may be linked with particular factors in the area, most commonly habitat change or loss. These are the only parts of the world where accumulated records of beetles identifiable to the species level across major parts of faunas have been made for more than a few decades, so that changes in incidence and distribution detected by comparing maps made for different periods may be based in reality, rather than simply reflecting sampling unevenness. Mapping or recording schemes may commonly arise from non-systematic sampling (Lobo *et al.* 2007, on Iberian Scarabaeidae), which later become more comprehensive as their values are recognized and consolidated, although historical biases over knowledge of species' distributions are likely to remain widespread for any group.

One notable example (Desender & Turin 1989) was developed from records on 419 ground beetle species recorded in Denmark, the Netherlands, Belgium and Luxembourg, and published in earlier atlases of Carabidae from these countries, each enabling comparison of the fauna before and since 1950. A total of 281 species were recorded in all areas, with Belgium and Luxembourg treated together. Most of the other 138 species recorded from one or two areas are rare, so that any estimates of their decline are not necessarily reliable. Nevertheless, many were regarded as 'seriously threatened', by decreased extent of occurrence within either the main section of the area (nine species) or the whole area (eight species), or 'threatened' with implications of wider decreases (37 species). Another 11 species were noted as 'probably threatened'. Of the wide-range species from all three areas, trends were appraised against ecological attributes (stenotopic to very eurytopic and tolerant to cultivation), geographical range in relation to being centred in the Netherlands, and habitat affinity on an 8-point categorization of xerophilous, more-or-less xerophilous, mesophilic or cosmopolitan, hygrophilous, more-or-less hygrophilous forest species; preference for shady sites and bushes; arboricolous; and synanthropic. Collectively, 142 species were considered endangered, with many apparently having disappeared. Declines were particularly high among xerophilous species, many of the stenotopic species and those found in habitats such as heathland and low-quality grassland. Drawing from the Netherlands data of that survey, Turin and den Boer (1988) considered that progressive isolation and loss of suitable habitat fragments may be a component of decline, as many of the carabids lost were poor dispersers. They emphasized the substantial loss of Netherlands dry heathlands from around 800,000 ha in 1835 to only about 40,000 ha by 1980, with additional degradation of much of the remainder by grass invasions. This scenario was revisited by Kotze and O'Hara (2003), who showed that the carabids that have declined are commonly the larger-bodied species and habitat specialists. However, flight dimorphic species (see p. 176) had been less prone to declines than species that were either wholly flight capable or wholly flightless, possible reflecting additional benefits of the ecological 'bet-hedging' that accompanies the twin strategies of dispersal capability and obligatorily staying put. Nevertheless, problems remain over clarifying fully the reasons for these declines. However, without the temporal base afforded by the recording schemes, no such sound template for discussion would be available.

Related applications include that among the 10 × 10 km recording units being used to classify these areas by the ground beetles present (Hengeveld & Hogeweg 1979), nine groups of squares were distinguished on the carabid representations. Estimates of land cover to correlate with beetles were broad, but clearly demonstrated the potential to use beetles in this context.

In another important contribution to understanding distributions of beetles in landscapes, Eyre *et al.* (2003a) used carabid data from Britain (namely presence/absence data of each of 356 species from 1687 recording squares) combined with land cover data derived from satellite information in order to determine the extent to which land cover may be able to predict the ground beetle species pool. Nine groupings of beetles were detected: three showed strong relationships with upland ground cover; three others were associated with deciduous woodland, coastal and tilled land; and three others, although not associated strongly with any particular form of land cover, differed in geographical position. However, because many of the cover variables were closely associated, it was sometimes unclear which factors the beetles were responding to. Eyre *et al.* suggested that, with further analysis, the relationships between carabids and land cover might indeed lead to their wider use in monitoring environmental changes across the countries. By analogy with the Netherlands data, this might extend even more widely across Europe.