Conservation of forest-dwelling arthropod species: simultaneous management of many small and heterogeneous risks[1]

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Abstract—The Canadian insect fauna is too inadequately understood to support well-informed assessments about its conservation status; however, the foregoing collection of synthetic papers illustrates potential threats from industrial forestry. Loss of forest species and dramatic changes in forest insect assemblages driven by forestry activities are well illustrated by studies from places where industrial forest management has been more intensive or of longer duration. Improved understanding of how arthropod species are coupled to habitats, especially microhabitats, appears to be central to progress toward their conservation. Studies of arthropods conducted at the species level are most relevant for applied conservation purposes, because only species-level work that is well documented with voucher specimens provides adequate comparative data to document faunal change. Although taxonomic infrastructure required to support such work is seriously under-resourced in Canada, entomologists can help themselves by producing useful modern resources for species identification, by undertaking collaborative biodiversity work that minimizes the split between taxonomists and ecologists, and by supporting incentives for work at the species level. Securing the future of arthropod diversity in Canadian forests through effective policy will require sound regionally defined bases for whole-fauna conservation that mesh with broader land-use planning. Building these will require a practical understanding of how "ecosite"-classification systems relate to arthropod diversity, accurate inventories of the predisturbance forest fauna in all regions, and development of sound monitoring plans designed to both detect faunal change efficiently *and* identify its drivers. Such monitoring plans should include both baseline inventories and monitoring of designated control areas. In addition, effective biomonitoring efforts will facilitate the development of suites of arthropod indicators, accommodate both seasonal (especially phenological) and annual variation, clarify the relationship between cost-effective samples and reality, and ensure adequate consideration of "rare" species. Return on investment in monitoring will depend on effective preplanned linkage to policy development that can respond to drivers of faunal change in a way that effectively addresses undesired changes.

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Résumé—La faune entomologique canadienne n'est pas assez bien connue pour qu'on puisse évaluer de façon avisée son statut de conservation; néanmoins, la présente série de travaux de synthèse signale des menaces potentielles posées par l'industrie forestière. Des études réalisées dans des sites où la gestion industrielle des forêts a été plus importante ou s'est faite sur une plus longue période mettent bien en évidence des pertes d'insectes forestiers et des changements spectaculaires dans les peuplements d'insectes forestiers causés par les activités forestières. Tout progrès dans la conservation des arthropodes semble être relié à une meilleure compréhension du lien qui unit les espèces d'arthropodes aux habitats, et particulièrement aux microhabitats. Les études sur les arthropodes faites au niveau de l'espèce sont celles qui sont les plus pertinentes pour atteindre les objectifs appliqués de conservation, parce que seuls les travaux faits au niveau de l'espèce et bien appuyés par des spécimens de référence fournissent les données comparatives adéquates pour évaluer les changements faunistiques. Bien que le personnel spécialisé en taxonomie nécessaire pour réaliser de tels travaux fasse sérieusement défaut au Canada, les entomologistes peuvent s'aider mutuellement en produisant des outils modernes pour l'identification des espèces, en travaillant en collaboration sur la biodiversité de façon à minimiser la division entre les taxonomistes et les écologistes et en favorisant les études au niveau spécifique. Afin d'assurer dans le futur le maintien de la biodiversité des arthropodes dans les forêts canadiennes à l'aide de politiques efficaces, il sera nécessaire d'avoir des données de base solides sur la conservation de l'ensemble de la faune à l'échelle régionale et de les intégrer à la planification de l'utilisation des terres. La mise en place de ces banques de données nécessitera une compréhension de la relation entre les systèmes de classification des «écosites» et la diversité des arthropodes, des inventaires précis de la faune forestière d'avant les perturbations dans toutes les régions et l'élaboration de plans de surveillance permettant de détecter efficacement les changements faunistiques *et* d'en identifier les causes. De tels plans de surveillance devraient comprendre à la fois des inventaires de base et la surveillance de sites témoins choisis. De plus, des efforts efficaces de surveillance biologique devraient inclure l'utilisation de séries d'arthropodes indicateurs, la prise en considération de la variation saisonnière (particulièrement phénologique) et annuelle, l'examen de la relation entre un échantillonnage à meilleur coût et la réalité pratique et un intérêt suffisant pour les espèces "rares". Le rendement de l'investissement en surveillance dépendra de la mise en place préalable d'un lien efficace avec l'élaboration de politiques qui réagissent aux causes de manière à contrer efficacement les changements indésirables.

[Traduit par la Rédaction]

Introduction

The world around us abounds with terrestrial arthropods (insects, spiders, mites, and their relatives). A small proportion of them are considered to be "pests" because they compete with humans for food and fibre or serve as vectors for diseases that attack human beings or other organisms that we value, or their abundance constitutes a significant nuisance for some humans. Although there is sound and abundant evidence that terrestrial arthropods are critical players in important ecological processes — and some of us dare to insist that they are beautiful in their own right — a large proportion of humans perceive arthropods as weird and somehow dangerous creatures to be avoided, if not exterminated. Thus, only broad-minded, well-informed, and insightful ecologists, and those who know and love arthropods, fret much over their extinction, even though such extinction and extirpation contribute significantly to the global biodiversity crisis (Erwin 1982; Wilson 1988; Reaka-Kudla *et al.* 1997). Even among professional biologists, terrestrial arthropods have been relatively ignored, at least in Canada, where species loss is not yet as obvious as it is elsewhere. Given the enormous abundance and functional significance of arthropods (and other hyperdiverse meso- and micro-biota such as fungi, nematodes, and bacteria) in terrestrial ecosystems, the low relative attention received by these organisms in conservation science suggests a problem with traditional biological education.

Loss of terrestrial arthropod species appears to be most severe in tropical forests, at least as extrapolated from the rate of habitat destruction (Simberloff 1986; Reid 1992; May *et al.* 1995; Pimm 2001). Should custodians of Canadian forests also be concerned about arthropod species extinctions in their jurisdictions? The answer to this question begs two subquestions for those who care about a scientific basis for management of biodiversity and about Canada's commitment as a signatory to the Convention on Biological Diversity (Secretariat of the Convention on Biological Diversity 1992): (1) Would it matter if species were lost — are there not so many that we could probably spare a few? and (2) Is there any evidence that arthropods of Canadian forests are directly threatened by human activities?

Unfortunately, the first question cannot be answered decisively for any particular species or situation, although even most dedicated conservationists would likely admit that ecosystems function with redundancy in species roles. Nonetheless, repeatedly it is discovered that individual species are unexpectedly important and that their loss can have widespread effects throughout whole ecosystems (Wilson 1992). Loss of inadequately understood species from complex and poorly understood ecosystems is similar to random removal of timbers from a trellis bridge. At some point the bridge will be compromised and may collapse, a process accelerated for ecosystems under the accumulated weight of human enterprise. The metaphor is imperfect, however, as biological systems adapt and reconfigure themselves in response to compositional and environmental changes. However, there is no guarantee that human beings will be happy with the results (*e.g.*, the collapse of the blue walleye, *Sander vitreus glaucus* (Hubbs), fishery in the lower Great Lakes and extinction of the subspecies following overfishing, eutrophication, and introduction of several alien species). As Aldo Leopold (1953) observed in his oft-repeated quote about intelligent tinkering with ecosystems, the precautionary principle advises us to keep *all* the pieces in our ecosystems. Species, of course, are the biological pieces of ecosystems and because of their functional connections to other species they all contribute to system function in ways that may be unappreciated before the species are lost. For the less anthropocentric, it is simply unethical to knowingly promote extinction of any species not known to be directly detrimental to human welfare. In addition to concerns about functional roles, faunal and floral diversity plays a central role in the ability of ecosystems to accommodate environmental change and to recover from disturbance (Wilson 1992).

The authors of the papers in this symposium, however, have not considered whether we *should* protect biodiversity; perhaps the point is moot because in Canada legislation insists that we must. Rather, this symposium focused on the second question posed above, *i.e.*, is there any evidence that arthropods of Canadian forests are directly threatened by human activities? Authors were asked to address the extent to which there is evidence that particular groups of arthropods are directly threatened by human activities in Canadian and other northern forests. The preceding papers suggest that there are real anthropogenic threats to groups that are relatively well studied, and those who are familiar with arthropods unflinchingly generalize this problem to include many groups that are less well known. Although perhaps presently non-urgent (see Lee and Jetz 2008), the threat of extirpation and extinction and associated challenges are real and ecologically significant with respect to the Canadian fauna and northern-forest arthropod faunas in general (Hanski 2007). Blindly trekking down the road of simple denial is likely to lead us (and our progeny) to a world that is less entomologically delightful and, as a direct result of species loss, less ecologically functional. Humanity's sad lament (with apologies to the visionary Canadian songstress Joni Mitchell) could be that we did not "know what we had until it was gone". Also — and this is most important — the scientifically real problem of threats to biological diversity will not be solved by advocating short-cut and cosmetic solutions (see Hanski 2007).

This symposium thus issues an unapologetic call to action for entomologists (among whom we happily include arachnologists for the purposes of this paper). In this final paper of the symposium we highlight the general dangers that have been identified, discuss what is known of their causes, and identify steps to reduce the risk of losing arthropod species as a consequence of human activities on forested landscapes in Canada. In particular, we focus on defining a healthy relationship between science and biomonitoring, the consequent nature of effective monitoring, and how science and monitoring might more effectively influence policies for managing public forest land. We have aimed also, as is strongly advocated in the foregoing papers, to provide a compelling rationale for encouraging work at the species level and we underscore why progress in conserving arthropods, unlike most vertebrate groups, continues to require strong connections with work in the fundamental disciplines of taxonomy and biosystematics.

Arthropods, forests, and the biodiversity problem

Forests are undoubtedly Earth's most complex terrestrial ecosystems, although from a distance they are sometimes naively viewed as uniform, tree-dominated wilderness (*e.g.*, Ronald Reagan's paraphrased 1966 quote (see Mikkelson and Mikkelson 2006)). However, beneath the green canopies of forest trees, even when these comprise only a handful of species as in the boreal forest, there is significant variation in plant species diversity and composition driven by historical and physical factors such as disturbance history, local topography, light penetration, soil type, water availability, composition and age of stands, and amount and distribution of dead woody material. Such variation dramatically influences the development of plant and fungal assemblages and the extent to which these form distinct vegetative layers that add further structural complexity to the system (Perry 1994). Vegetative features, in turn, also directly influence the composition of the fauna in combination with the physical factors listed above. In short, second- and third-order biological effects that increase habitat variety and trophic opportunities magnify underlying spatial variation in physical characteristics of forest ecosystems, supporting an explosion of arthropods and other organisms specialized for life in particular "ecotopes" (Whittaker *et al.* 1973; New 2007). It is no wonder that forests are the storehouses of such a disproportionate share of the planet's terrestrial biodiversity (Lindenmayer and Franklin 2002; Wilson 2002).

The most basic appreciation of why forest-inhabiting arthropods are threatened by human activities, even in the absence of significant deforestation, depends on understanding how they are connected to both their physical–chemical and biotic environments, and how this determines species distribution and abundance (New 2007). We agree with Janzen's (1977) suggestion that the general body size of insects and other terrestrial arthropods is associated with selective pressures that divide arthropod ecotopes into small units. This means that arthropods perceive the environment as generally more fine-grained than do larger bodied vertebrates. In fact, scientific work has repeatedly shown that insect populations depend on fine-scale differences in the environment that humans do not notice without serious study (Niemelä *et al.* 1992; Niemelä and Spence 1994; Jonsell and Nordlander 2002; Komonen 2003; Danks 2004; Subramanian and Sivaramakrishnan 2005; Horn and Ulyshen 2007; New 2007; Müller *et al.* 2008; Schreiner and Irmier 2008). Although this small-scale variation makes for a fascinating world, it is also a challenge for those who seriously wish to conserve arthropod diversity. Furthermore, such small-scale variation effectively precludes a "flagship-species" approach (Simberloff 1998; Andelman and Fagan 2000) to arthropod conservation. To the detriment of effective arthropod conservation there are still too many who advocate, or at least are willing to believe, that if we manage the broadly defined habitats that *we* recognize as a "coarse filter" for conservation in a way that ensures persistence of significant populations of a handful of vertebrates, all else will be safe. Because big mammals and many birds are coarse-grained integrators over broad habitat types generally obvious to us, management activities designed only to support their persistence may inadvertently and unknowingly homogenize much of the fine-grained variation that constitutes the myriad microhabitats on which the diversity of arthropods and other hyperdiverse and little-known groups depends (Spence *et al.* 1999; Work *et al.* 2003*b*, 2004; Niemelä *et al.* 2007).

Lately, much discussion about conservation of forest biodiversity, especially in northern regions, has focused on large-scale, "landscape" issues (*e.g.*, Andison 2003; Angelstam *et al.* 2005). Although perhaps useful for most vertebrate taxa, an exclusive focus on large-scale considerations is insufficient for arthropods, at least when "stand-level" considerations are held to be trivial relative to those at the "landscape scale". In fact, empirical evidence has often led to the opposite conclusion, *i.e.*, that incremental effects at the landscape scale are generally much less important than amount and quality of (stand-level) habitat, even for many vertebrates (*e.g.*, Harrison and Bruna 1999; Fahrig 2003; Niemelä *et al.* 2007; Taki *et al.* 2008). Of course, with a dramatic reduction in the amount of forested habitat, very much larger than is now anticipated in most Canadian forests, size and distribution of patches on the landscape could become significant for arthropods; however, these issues are presently less important than concerns about *quality* of stands subjected to industrial management in extensively managed forest on a large, contiguous, publically owned land base.

Any useful concept of scale depends on the organisms being considered. "Landscapes" are much smaller for most arthropods than for most vertebrates, especially the charismatic vertebrates (*e.g.*, woodland caribou, grizzly bears) that figure prominently in Canadian forest-management and -conservation plans. Under present forest-management plans a large fraction of public land in Canada is to be "extensively" managed for fibre exploitation in a way thought to conserve other values, especially biodiversity (Burton *et al.* 2003). However, apart from retaining a variable fraction of standing green trees at harvest, cutting and regeneration practices now commonly employed under the banner of "extensive forest management" in Canada are monotonously simple (Work *et al.* 2003*b*). Although this may be satisfactory for selected large or charismatic vertebrate species, the current ecologically narrow approach to forestry will undoubtedly fail to maintain the full range of ecotopes required to support arthropod diversity (New 2007; Niemelä *et al.* 2007) equivalent to that found in unmanaged forests. This hypothesis can be tested by examining how the habitat and species diversity in stands regenerated after harvest differs from that in stands or gaps regenerating after natural disturbance (Niemelä *et al.* 1992; Gandhi *et al.* 2001; Buddle *et al.* 2006; Pohl *et al.* 2007). If regenerated stands do not provide all required microhabitats and trophic opportunities (which may depend on small plants and fungi), arthropod species are likely to drop out, stand by stand, until they have disappeared over large tracts of landscape. Preservation of representative populations in a few widely dispersed and unmanaged forest reserves will be of little comfort if broadly important arthropod-mediated processes like pollination and nutrient cycling are compromised in extensively managed stands.

It is reasonable to consider the magnitude of risk for arthropod species. From studies in northern Europe it is well understood that a large fraction of species can disappear from forests managed for timber production (Siitonen and Martikainen 1994; Siitonen 2001; Hanski 2007). Furthermore, alteration of processes like natural succession, gap dynamics, and fire frequency by forestry practices also may place populations of many arthropod species at risk (Koivula *et al.* 2006; Gibb and Hjältén 2007; Jacobs *et al.* 2008). It is clear that small residual populations of insect species widely extirpated by anthropogenic deforestation can long persist in small, unmanaged pockets of forest, and that populations of such species can recolonize a landscape as more extensive and "natural" forests are redeveloped (*e.g.*, Niehues *et al.* 1996; Sroka and Finch 2006; Matern *et al.* 2007). Nonetheless, recolonization is slow (Niemelä *et al.* 1993) and repeated harvesting could extirpate many species from large tracts of former forest range. Furthermore, residual populations may experience genetic bottlenecks that reduce the general adaptability of a species and its ability to fully reoccupy its former range. Finally, and especially pertinent in view of the growing importance of invasive alien species (*e.g.*, Environment Canada 2004; Langor *et al.* 2008*a*), populations of habitat specialists confined to small residual patches are at risk of being eliminated by highly competitive native and non-native habitat generalists (Spence *et al.* 1996; Niemelä *et al.* 1997; Hartley *et al.* 2007). Fleeting abundance of native species in a few isolated patches of haphazardly retained habitat does not constitute an effective "landscape strategy" for preserving biodiversity. In fact, it may be simply symptomatic of "extinction debt", *i.e.*, the future loss of species as a consequence of past actions may flow from the ultimate failure of a network of suitable forest patches to sustain biological populations (Ward 1997; Hanski and Ovaskainen 2002; Tilman *et al.* 2002).

Maintenance of biodiversity is particularly challenging in the case of arthropods in North American forests because taxonomic and ecological knowledge of the biota, relative to vertebrate species, is at best rudimentary for the vast majority of arthropods (Langor and Spence 2006). Most serious studies of forest arthropod diversity in Canada turn up undescribed species or significant new jurisdictional records (Langor *et al.* 2008*b*) and, even for species that are well known taxonomically, accurate identification of all stages is generally fraught with difficulty and uncertainty (Richardson and Oberprieler 2007; Pohl *et al.* 2008). Furthermore, understanding of the biology and natural history of most arthropod species inhabiting forests is presently inadequate to support detailed, well-informed forest management. The work needed to resolve these fundamental deficiencies lies outside the mainstream of conservation biology and is often trivialized in the corridors of science, perhaps because it is mostly finished for vertebrates. Thus, such necessary work on arthropods attracts little standard scientific funding and interest (Danks and Ball 1993), possibly because it is widely regarded as "old-fashioned". As a result, some studies of arthropod diversity are not conducted at the species level and those responsible lament that they could do no better because of the collective taxonomic impediment. We argue that failure to consider responses and trends at the species level compromises the scientific rigor of the resulting data with respect to supporting clear decisions about biodiversity management. Furthermore, it does not support meaningful assessments of faunal change. Bluntly put, the "cop-out" of taxonomic expediency does nothing to improve a poor situation. Improving the understanding of Canadian arthropod species and their biology is essential for a mature understanding of insect diversity (see Danks 1996) and, as discussed further below, there is ample reason for Canadian entomologists to rededicate their efforts and influence to this task.

Assessment and management of forest arthropod diversity

Considerations of scale

A science-based framework for maintaining arthropod diversity in Canadian forests is still under development. Contributors to this symposium have identified many considerations that would be useful in developing a comprehensive and effective biomonitoring strategy that includes arthropod indicators (see below). However, meaningful incorporation of arthropods into monitoring systems first requires a commitment from designers and managers of such schemes to consider the biology of arthropods. In our experience this has not usually been evident.

Programs developed without *a priori* consideration of both arthropod biology and establishing drivers of faunal change will be wasteful of resources because they will be unconnected to actions that might be employed if undesirable changes are detected (setting aside, for the moment, the significant challenges of detecting changes in the first place). Developing conservation efforts that are effective and efficient requires consideration of both focus and scale. Although some more widely applicable monitoring strategies may be required in order to understand the overall regional impact of locally orchestrated land use, most of the impacts identified as significant for arthropods play out within forest stands (or individual water bodies) or require consideration of the mix of stands on landscapes dimensioned in relation to insect dispersal distances. This is particularly true for aquatic species (Richardson 2008) but also clearly applies to other ecologically important and presently diverse Canadian faunal elements (in particular, see Langor *et al.* 2008*b*; Work *et al.* 2008). For example, wind effects associated with harvest patterns may affect the fauna of individual lakes, and within-stand factors like the size distribution of coarse woody material are critical in determining the diversity of arthropod species (Siitonen 2001; Langor *et al.* 2008*b*; Müller *et al.* 2008). Most important, as emphasized above and amplified below (see also New 2007), is the understanding that number of microhabitats is generally the key to determining the variety of arthropod species that a stand will support. Significant and expensive monitoring programs developed in the absence of this fundamental consideration are doomed to disappoint and will ultimately fail as conservation measures.

Improving the species-level focus

Given the significant challenges of identifying many arthropod groups to species level, some researchers have abandoned species-level work in favor of the expedient approach of using higher level taxa as surrogates for species diversity (*e.g.*, Deans *et al.* 2005). We recognize the possible value of survey work at higher levels aimed at providing quick, initial recognition of areas with potential conservation value (*e.g.*, Williams and Gaston 1994; Cardoso *et al.* 2004; Richardson and Oberprieler 2007). Nonetheless, work at higher taxonomic levels simply misses the point with respect to protection of biodiversity, understanding ecosystem function, and contributing to effective scientific understanding of global change and what drives it in the long run. After all, species are the basic building blocks of biodiversity because they label reasonably well defined gene pools that have resulted from unique evolutionary pathways (Coyne *et al.* 1988).

The contrast between standards used for work with vertebrates and arthropods is perplexing. Just as an ornithologist would dismiss a conservation-oriented analysis that grouped gray jays, *Perisoreus canadensis* (L.), and blue jays, *Cyanocitta cristata* (L.), as "corvids", entomologists should be concerned about the scientific usefulness of invertebrate inventories conducted at the family level or coarser. Even at the level of genus, few would condone the use of an inventory that listed only *Corvus* L. and did not distinguish American crows, *Corvus brachyrhynchos* Brehm, from common ravens, *C. corax* L., especially if this was associated, say, with failure to note new breeding records of the northwestern crow, *C. caurinus* Baird, from Saskatchewan, perhaps as a result of climate change. Would anyone be happy to know that corvids were declared safe across the country because there were crows everywhere? Similar arguments about the critical nature of species-level work are regularly made or accepted without a passing thought in the case of most vertebrate taxa (*e.g.*, Mustelidae, Parulidae, Ranidae, or Salmonidae) that include species that are especially at risk in Canada. Without distinguishing species there is little practical value in either constructing inventories to meet conservation goals or making a serious study of factors controlling distribution and abundance. Otherwise, why bother to distinguish bull trout, *Salvelinus confluentus* (Suckley), from brook trout, *S. fontinalis* (Mitchill)? They taste about the same and we know of no strong evidence that stream ecosystems will fall apart if one or the other is present or absent! Similarly, analyses that help develop understanding of the nature of arthropod assemblages and how these change in space and time (*e.g.*, Work *et al.* 2008) will be only marginally informative if they are not conducted at the species level. In short, public statements and the actions of some entomologists that suggest that species-level work is not required for arthropods translate to an inconsistent message, *i.e.*, when it is easy, it is scientifically essential to work at the species level, but when it is challenging (but not impossible), a similar level of scientific rigor is purely a discretionary nicety. What is ineffective about the latter approach is that, by ignoring species, we forgo opportunities to detect significant and dangerous trends in environmental conditions, the consequences of which might be avoided through early detection and appropriate management intervention.

Even if, under pressure from those who are disinterested in “details”, we minimize the significance of “species counts” as the proper measure of diversity for hyperdiverse taxa, there are functional considerations that should not be ignored. Species are unique and the loss or replacement of any species must cause at least subtle changes in ecological pathways — changes that we are unable to appreciate and to understand retrospectively if we have thrown away the labels. Without such knowledge there is little we can do to *undo* unintended consequences. Species-level work is especially important for proper appreciation of community and ecosystem change. This is especially critical in the context of the growing threat and impact of exotic species. In conducting inventories aimed at improving sustainable forest management, for example, one might just group together all black beetles found in leaf litter. However, this approach would disregard the fact that deciduous forests across Canada are increasingly dominated by one exotic species from Europe, *Pterostichus melanarius* Illiger (Coleoptera: Carabidae) (Niemelä and Spence 1994, 1999; Niemelä *et al.* 2002; Hartley *et al.* 2007). If our grandchildren, two generations hence, encounter a problem that flows from this ongoing species replacement, the database that could help them understand and deal with the problem would be unavailable if we followed the locally expedient “black beetle” advice. Everyone is fundamentally equipped to meet the challenge of identifying these beetles, but entomological work done at the species level must be recognized as essential and be supported. Hand-waving dismissals that such work is not needed, perhaps because it is challenging, are not scientifically credible.

In general people do not *want* to behave ineffectively, so what can be done to encourage species-level work in insect conservation? As has been addressed abundantly elsewhere (*e.g.*, Danks and Ball 1993; Langor and Spence 2006), the basic disciplines of taxonomy and biosystematics need more public support focused on areas like entomology, where significant challenges remain. Furthermore, the basic infrastructure of Canadian museums and collections, essential to support these activities, urgently needs reinvestment. But, what can we ourselves do, as working entomologists, in the probable absence of an immediate increase in public investment?

We suggest three general responses to the need to support biodiversity work at the species level. First, those interested in taxonomy and biosystematics should rededicate a portion of their efforts to taxonomic revisions applicable to the Canadian fauna. Such work should be focused on groups that are inadequately understood and should include identification aids that employ the many advantages of modern technology (*e.g.*, LUCID keys for identification; see http://www.lucidcentral.org/keys/keysearch.aspx), the use of high-quality digital images (*e.g.*, Henri Goulet’s excellent work at http://www.cbif.gc.ca/spp_pages/carabids/phps/index_e.php), innovative outlets for regional keys (*e.g.*, the Canadian Journal of Arthropod Identification at http://www.biology.ualberta.ca/bsc/ejournal/ejournal.html), *etc.*, and synthesize as much natural history as possible at the species level (a masterful early example was provided by Lindroth (1961, 1963, 1966, 1968, 1969*a*, 1969*b*). As is emphasized by several authors in this symposium, information about juvenile stages of most arthropods is sorely lacking and furthermore such information is critical to meeting conservation goals (Buddle and Shorthouse 2008; Pohl *et al.* 2008; Richardson 2008). We are hopeful that renewed support for basic taxonomic work will follow rededication to the production of high-quality user-friendly and effective tools for identification and faunal analysis. Dedicated and patient work that delivers tangible and widely used products should foster support. Fortunately, many entomologists in Canada have taken up this challenge.

Second, those working primarily on biodiversity and conservation issues should work at the species level and in collaboration with the Canadian biosystematics community as required. All entomologists should strongly support measures to increase the resources required to deliver species-level work on the Canadian fauna.

Third, those responsible for setting the bar with respect to publication and professional advancement should take a dimmer view of "quick and dirty" science that dodges the challenge of species-level work, or at least recognize, through positive incentives, scientists who are meeting this challenge effectively. Simple paper counts, without reference to the effort and quality of the work, provide the wrong incentives with respect to encouraging species-level focus in biodiversity research. Scientific rigor will only matter to nonspecialists if scientific peers more universally and determinedly insist that it does.

The critical importance of habitats

The authors of the papers in this symposium, as well as other researchers, have provided one overriding and consistent message: conservation of habitats and habitat diversity is the key to insect conservation. As stated above, scales of activity and perception for insects differ markedly from those for humans. Fine-scale features like biofilms (Richardson 2008), size and decay stage of coarse woody material (Langor *et al.* 2008*b*), and many features (*e.g.*, aspect, tree species, shrub cover and composition, litter depth) of within-stand variability (Buddle and Shorthouse 2008; Pohl *et al.* 2008; Summerville and Crist 2008; Work *et al.* 2008) are crucial for supporting arthropod diversity. As we scale up to "landscape"-level considerations, retention of successional gradients (*e.g.*, Jacobs *et al.* 2008) and the associated variation that supports species with special adaptations such as pyrophily (Koivula *et al.* 2006; Wikars 2002; Gibb and Hjältén 2007; Langor *et al.* 2008*b*) are important features subject to management using an overall land management framework.

The "natural-disturbance hypothesis" has been touted as a basis for sustainable forest management, but remains largely untested (Spence 2001; Work *et al.* 2003*a*, 2004). In addition, the Canadian version of this approach has simply assumed that wildfire is the most important natural disturbance to be emulated by fibre extraction and regeneration activities. Although fire is a dominant consideration for landscape-level management across the boreal forest, little research has addressed emulation of other processes (*e.g.*, succession, gap dynamics, flooding) that contribute significantly to development of forest structure important for arthropod assemblages. These processes are more significant where fires are less frequent, as in eastern Canada, and they are potentially subject to management based on natural processes (Harvey *et al.* 2002; Groot *et al.* 2004; Kennedy *et al.* 2007). Even in western Canada, where fire-return intervals generally are shorter, few scientists will be convinced that harvest is ecologically equivalent to wildfire, based on present data (*e.g.*, Koivula and Spence 2006). Thus, it is unreasonable to attempt to eliminate, seriously constrain, or reduce the range of natural-disturbance processes (Langor *et al.* 2008*b*; Summerville and Crist 2008) and expect to retain biodiversity. For example, chronosequence studies in the boreal and cordilleran forest indicate that early-successional insect assemblages after wildfire differ markedly from those after harvest-caused disturbance (Buddle *et al.* 2000, 2006; Gandhi *et al.* 2004). It seems more appropriate to develop management strategies inspired by work to understand natural-disturbance processes so that a full range of microhabitat diversity can be retained, both within and among stands (Spence *et al.* 1999). To develop local habitat management strategies that conserve arthropod assemblages it is necessary to know the effects of variable retention on preservation and regeneration of microhabitats (Work *et al.* 2003*a*), especially those associated with dead wood (Langor *et al.* 2008*b*).

Managing only with respect to larger scale patterns and abundant species will not generally maintain arthropod diversity. For example, large-scale diversity patterns for carabid beetles depend on only about 7% of the species included in a large data set from the Canadian boreal forest (Work *et al.* 2008). Thus, managing to retain only abundant species with wide distributions would ensure the persistence of only a small fraction of extant species. In fact, Canadian diversity of most other groups included in the symposium has a markedly regional structure (Buddle and Shorthouse 2008; Langor *et al.* 2008*b*; Pohl *et al.* 2008). This means that suites of "indicator taxa" useful in monitoring plans must be developed for natural faunal regions. Regional variation depends on historical factors such as glaciation (Summerville and Crist 2008) but, at present, there is little or no clear guidance about how geographical zones should be defined to focus landscape planning with respect to biodiversity conservation. A good starting point was provided by Scudder (1979) but a new synthesis incorporating the intervening three decades of "biodiversity studies" would be useful. The central question concerns how detailed ecological land classification has to be in order to effectively organize land-use plans that meet conservation objectives for arthropods. Clearly, some Canada-wide commonality in understanding diversity can be achieved with focus on so-called "functional groups" (Richardson 2008), but protecting functional groups will not necessarily conserve species, which define the level of protection that we seek for other elements of the biota.

More effective monitoring programs

One widely embraced outcome of work on forest biodiversity and conservation has been an emphasis on development of monitoring programs (*e.g.*, Duelli and Obrist 2003). We caution against rushing toward expensive and complex monitoring schemes without appropriately serious consideration of relationships among program objectives, sampling protocols, and overall conservation goals that include forest arthropods and other hyperdiverse taxa (see also Langor and Spence 2006). In our view, successful monitoring programs ought to reduce the risk of extinction for all species, or at least provide data to specifically quantify that risk under different development scenarios so that explicit trade-off analyses are possible. The concept of "extinction debt" and efforts to model extinction thresholds on the basis of current understanding (Hanski and Ovaskainen 2002) suggest that we have already passed the margin of safety for many species on industrial forest landscapes. This hypothesis can be tested only by carefully designed monitoring programs that provide detailed and reliable information about species (Hanski 2007).

Even the most long-standing Canadian approaches (*e.g.*, that of the Alberta Biomonitoring Institute; see http://www.abmi.ca/abmi/home/home.jsp) are superficial and inadequate for collecting data about arthropods. In fact, we are aware of few monitoring schemes that provide integrated consideration of arthropods, although there are sound ongoing initiatives targeted on specific groups (*e.g.*, the United Kingdom Butterfly Monitoring Scheme; see http://www.ukbms.org/). In view of the overwhelming diversity of arthropods and their high degree of functional connection to ecosystems (Wilson 1992, 2002) plans that do not include arthropods have little well-founded connection to "biodiversity" *per se*. We remain hopeful that appropriate and effective considerations for arthropods will be forthcoming. The work presented in this symposium underscores the necessity of including forest-dwelling arthropod species in biomontoring plans. Although biomonitoring schemes have been designed to satisfy the values, objectives, indicators, and targets (VOITs) needed to meet regulatory requirements on paper, most have little tangible connection to the scientific problem of biodiversity decline (Hanski 2007). We strongly advocate the development of biomonitoring programs that effectively employ forest arthropods as indicators of desired forest conditions. Such plans must have at least six essential features, as briefly discussed below.

(1) *Baseline data*. To detect the fullest range of relevant change, biodiversity databases must include a starting baseline inventory from stands/forests that are minimally disturbed by human activities. In addition to being essential to setting faunal targets for the presence or absence of species in particular habitats, good baseline data may help establish the relevant "range of natural variation" (RNV) in abundance of species that could provide a basis for comparing postdisturbance measurements (see Andison 2003). However, without a clear understanding of specific factors that drive most natural variation in arthropod assemblages, RNV is likely to be so large for most arthropods that significant changes will be detectable against this simple standard only after they are quite advanced and likely irreversible.

(2) *Controls*. Programs should be designed to include and maintain suitable "control areas"

that will allow discrimination between effects of widespread environmental change and changes wrought by more localized anthropogenic disturbances. Without controls, the power to identify potential causes of biotic change is weakened, preventing the formulation of appropriate policy responses. Furthermore, well-considered controls are essential to dealing with the shortcomings of the RNV concept in arthropod monitoring. For example, it would be useful to be able to predict effectively the expected range of arthropod activity, given particular weather scenarios, and thus be able to interpret monitoring data in relation to a more relevant RNV.

(3) *Indicator taxa*. As is emphasized by Langor and Spence (2006), there are too many arthropod species to monitor effectively with a widely distributed sampling design. Thus, we need to develop suites of "indicator" taxa that can be dealt with at the species level and that respond to disturbances in ways that are understandable. The authors of the papers in this symposium strongly argue that such suites of indicators must be regionally specific, and we know enough about some arthropod groups to develop such indicators now. Of course, widespread monitoring of carefully selected species, however well considered, does not guarantee that other sympatric species will not decline or disappear. Monitoring programs should have a research component that focuses on continuing identification of taxa with useful indicator value and on techniques for reliably assessing their presence and abundance. Once identified, such taxa can be incorporated into monitoring programs through adaptive improvement. The problem of impacts on species that are not monitored can only be solved by establishing more detailed and regionally representative faunal assessments and trusting in generalization of the findings, and by keeping residual "by-catches" from monitoring work so that they can be reanalyzed if it becomes appropriate to do so. It is reasonable to expect that faunal dynamics carefully measured at one site can be generalized across a region, especially in combination with coarser data from the region.

(4) *Accommodation of arthropod phenology*. Sampling regimes for arthropods must take into account the fact that most of these organisms have short and relatively complex life cycles and that their phenology, including patterns of adult abundance, is intimately tied to environmental variables, especially temperature and moisture level. Temporal variation in arthropod activity, both seasonal and annual, renders it challenging to determine even species presence or absence using only a short sampling window during a single visit as is acceptable for assessments of vertebrates and many plants. Without reference to a nearby continuously sampled site, it is impossible to infer anything useful about arthropod presence and relative abundance at sites subjected to a single brief sampling. In many cases the best outcome of single-visit sampling will be that it is not known whether the species occurs at the site visited, *i.e.*, significant resources will be invested to secure no useful information. Detecting meaningful changes in arthropod population sizes over time simply cannot be accomplished without sampling individual sites for an extended period.

(5) *Specified relationship of samples to a fauna*. It is well understood that all but the most expensive and time-consuming sampling methods used for arthropods provide biased samples of assemblages (*e.g.*, Spence and Niemelä 1994; Oliver and Beattie 1996; Southwood and Henderson 2000; Esch *et al.* 2008; Missa *et al.* 2008; Pellet 2008). These biases have not been appropriately calibrated for most sampling methods in the context of monitoring plans. Therefore, making reliable comparisons among species is difficult, although comparisons within species, if properly controlled for phenology, have value. This problem is most acute for "rarely sampled" species (*e.g.*, McArdle 1990; Martikainen and Kouki 2003; MacKenzie *et al.* 2005), which constitute the majority of species in assemblages according to frequency–abundance curves (see Martikainen and Kouki 2003; Work *et al.* 2008) and are most threatened by forest activities (Siitonen and Martikainen 1994). Without additional basic research about sampling we simply cannot know if any species is genuinely rare and under significant threat. Thus, at present, the best approach is to employ several sampling methods simultaneously (Spence and Niemelä 1994; Buddle and Shorthouse 2008), trusting in the "Levins Principle" (Levins 1966) that "truth lies at the intersection of independent lies".

(6) *The power to detect rare species*. Setting aside the challenge raised immediately above, when it has been determined that a species is truly rare and can be reliably sampled, the effort required to accurately assess changes in its abundance is daunting (Martikainen and Kouki 2003). Because rare species are likely subject to high risk of loss, they must be considered in

any serious effort to conserve arthropods. This problem presented by rare species is a further compelling reason to pursue a small number of locally intensive studies comparing species abundance across sites subjected to different treatments. In such studies, rarefaction curves should be employed to determine when local faunas have been adequately sampled (Gotelli and Colwell 2001; Buddle *et al.* 2005). From such studies we may learn enough about rare species to recognize their habitats, which are also likely to be rare. With that new biological knowledge, targeted protocols can be developed that permit inclusion of representative "rare" species in more distributed and widely dispersed monitoring.

Faunal change and landscape-oriented biodiversity policy

There is no point in monitoring for the sake of monitoring because this is a resource-intensive activity and commitment to it will likely wane as the sociopolitical priorities of the day evolve (see Hanski 2007). The purposes of any useful monitoring program should be fully rationalized and clearly stated from the start to ensure that the right information is collected in an accurate and cost-efficient manner. Because we have only begun to understand "biodiversity" as a concept, it is unlikely that we will be able to quickly design formal schemes to monitor it effectively in relation to proper long-term goals. The European Union (EU), for example, has committed to developing an area-wide plan (EU-wide Monitoring methods and systems of surveillance for species and habitats of community interest (EuMon project)) that is sensitive to regional variation and inclusive of all taxa (see http://eumon.ckff.si/index1.php). Without well-focused biodiversity policy objectives for regions in Canada, specific biomonitoring objectives, likely to be useful over the long run, cannot be offered at this juncture. However, the following issues should be considered when the objectives of biodiversity-monitoring programs are formulated.

Arthropods should be an important element of any serious biomonitoring plan because of their broad ecological and economic significance. The constrained and fine-grained nature of habitat and niche ("ecotope") for most arthropod and other invertebrate species means that effective monitoring will require work at finer scales and using different "filters" than are required for most vertebrates. However, the presence or absence of insect species has high potential to tell us how completely forest systems have recovered after anthropogenic disturbances associated with management, or alternatively, how far they have departed from conditions associated with baseline arthropod inventories (Spence *et al.* 1999). To human observers, areas may seem to have recovered to a "healthy" forest state because the trees are there and growing well, but if the appropriate arthropod species are missing — or if inappropriate species are present — it is evident that the system has not fully recovered to its predisturbance state. When pieces of the ecosystem are missing, appropriate actions to promote full restoration or reverse unacceptable trends will depend on understanding the drivers. Thus, simple monitoring without concurrent collection of data about factors driving faunal change is relatively sterile and inefficient, yielding little tangible return on significant public investment. The "fact" of biodiversity loss or change can be reasonably well and much less expensively detected through a composite of scientific studies. Policy makers, however, will need to know the extent of the problem (*i.e.*, both the spatial extent of impact and the particular taxa involved), the drivers that contribute to the problem, and what actions will achieve the desired restoration results.

When a forest-biomonitoring plan that includes arthropods has met the considerations outlined above, its overall conservation value can be much improved if connections to policy development are also considered in advance (Noss 1990; Kangas and Kuusipalo 1993; Rockwood 1995; Failing and Gregory 2003). Thus, development of expensive biomonitoring plans should go hand-in-hand with discussion of feasible policy and management responses, especially with work to define "action thresholds" that will signal the start of activities designed to reverse unwanted faunal changes (Eiswerth and Haney 2001). Because stakeholders, including scientists, remain relatively ignorant of effective management possibilities, it is recommended that land-use planners set adaptive management experiments in place so that we may learn about system responses to management as we go, and thus do as much as possible to protect ourselves against unwanted and possibly irreversible biotic changes. Why collect voluminous data about biodiversity if they are destined to be shelved because reports are unused, or their adequacy is likely to be the subject of long debate before any management or policy implications lead to a constructive response?

Once we have a basis for understanding regional faunal change and confidently relating it to the habitat mosaic of a region, we will be able to manage more effectively on a “landscape” scale (*e.g.*, Noss 1990; McGuinness 2007). In our view, this will be best achieved in the context of specific biodiversity targets for each landscape subject to land-use planning. Planners can best achieve these targets by ensuring the mix and distribution of habitats that will maintain beta diversity (Condit *et al.* 2002; Drakare *et al.* 2006) and thus sustain the desired target biodiversity on particular management units. Under this approach biomonitoring would be employed in specific habitats (*e.g.*, forest stands, including microhabitats) to ensure that the appropriate mix of elements is maintained. With this linkage secured, landscape planners could simply mix and match the stands in relation to predefined targets. It is possible and fiscally desirable that with a proper understanding of fauna–habitat relationships, much spatially distributed biomonitoring could be implemented largely through remote sensing (*e.g.*, Mawdsley 2007), with well-trained professional “biological survey” units making regional spot-checks each year to ensure that the predefined habitat relationships remain predictive. Whatever scientifically mature and taxon-inclusive approach we develop, biomonitoring without a clear connection to desired policy goals is a wasteful use of public funds.

Synthesis and conclusions

Biodiversity science is in its infancy. This is especially so in relation to achieving significant applied goals in the conservation of forest insects. The papers collected in this symposium (representing a wide range of reasonably well understood taxa) suggest that Canadian forest arthropod diversity is potentially susceptible to negative effects of anthropogenic disturbances, as has been well documented elsewhere. The presently recognized key to minimizing loss of biodiversity is to increase species-level research directed toward understanding relationships between forest microhabitats and the arthropods that use them. Although increased resources will be required to develop and implement effective arthropod conservation strategies, there is much that the entomological community can do to better communicate these needs and to illustrate the importance of sound scientific work. Chief among these initiatives are rededication to the effort required to deliver sound species-level work for the Canadian fauna and support for incentives that encourage it within the entomological community. Those interested in arthropods and invertebrates in general must strive to ensure that stand-level studies of the microhabitats that are so critically important to these taxa are continued, despite the emphasis on landscape-scale work that has become the dominant focus (albeit often appropriately) of vertebrate conservation oriented work. To be effective in detecting change in arthropod populations, monitoring programs must be based on well-informed science about habitats, regional faunal variation, and sampling developed to take into account the biological features of representative arthropod species. Furthermore, monitoring efforts should be preplanned to provide information about factors driving faunal change and to ensure a direct and effective connection to policy development. A rush to implement expensive monitoring plans that exclude arthropods and are thus inadequately rooted in scientific understanding of the forest fauna is folly akin to Emperor Nero “fiddling while Rome burned”. Although such schemes may seem to meet presently defined sociopolitical goals, they are most unlikely to deal effectively with the underlying scientific problem of biodiversity decline (Hanski 2007).

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