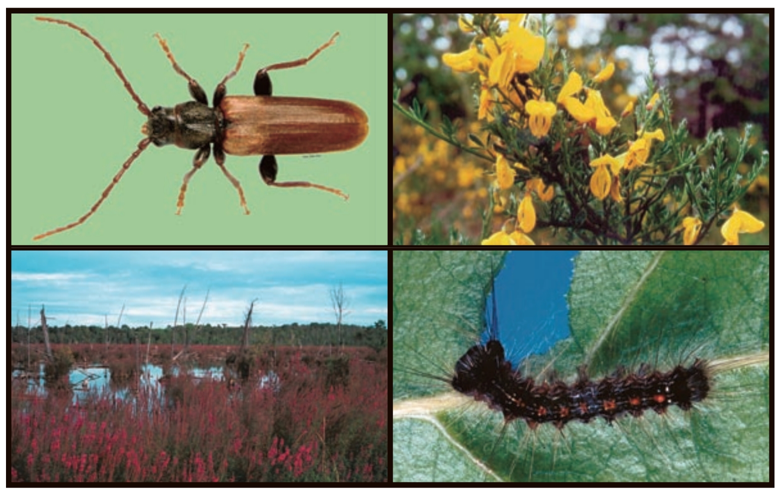
Canadian Forest Service

The potential impacts of exotic forest pests in North America: a synthesis of research



Information Report BC-X-387

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Pacific Forestry Centre

Victoria, British Columbia

Natural Resources Canada
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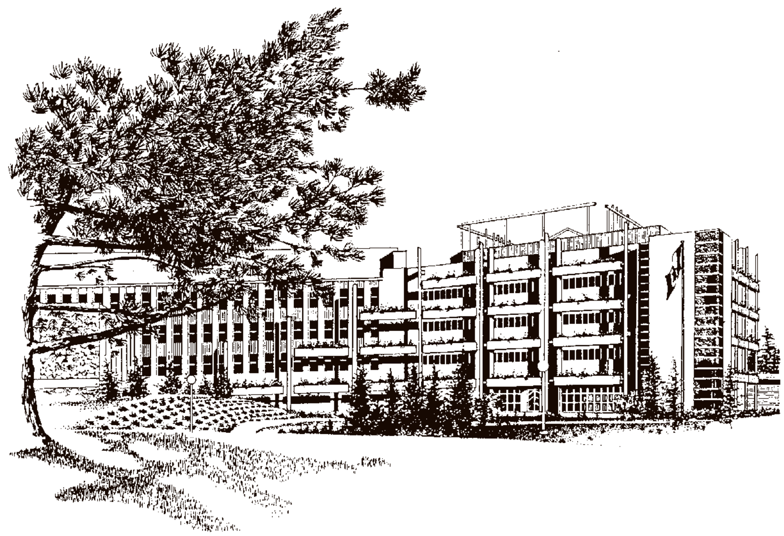

The Pacific Forestry Centre, Victoria, British Columbia

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The potential impacts of exotic forest pests in North America: a synthesis of research

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Front cover:

A	B
C	D

A) Lesser cedar longicorn beetle – *Callidiellum rufipenne*
(photo: Klause Bolte, Natural Resources Canada, Ottawa)

B) Scotch broom – *Cytisus scoparius*
(photo: Raj Prasad, Canadian Forest Service, Victoria)

C) Purple loosestrife – *Lythrum salcaria*
(photo: Eric Allen, Canadian Forest Service, Victoria)

D) Gypsy moth larva – *Lymantria dispar*
(photo: Lee Humble, Canadian Forest Service, Victoria)

Contents

Summary

- Exotic pests are defined as flora and fauna species extending beyond their natural range of potential dispersal, that are having a combination of negative economic, ecological or social impacts. The steps involved in an exotic invasion are introduction, establishment and spread.

- Not all exotic species that successfully establish and spread are pests. Indeed, exotics are an integral component of the North American economy and ecology; over 90 percent of North American food and feed production is derived from intentionally introduced exotic species.

- The probability of an exotic species becoming a pest is quite low. Successful establishment of an introduced organism into non-native habitat depends upon a complex interaction of several factors, including size of the introduction, adaptability of the organism, habitat suitability and the level of competition (predation, diseases, etc.). Although the likelihood of successful exotic spread is low, certain exotics that do become pests can have major negative impacts.

  It is estimated that over 300 tree-feeding insects native to Europe are now established in North America. A comprehensive US study estimates the total number of introduced species in the US exceeds 4542 and that 15 percent of these exotics cause severe harm in agriculture, forestry, industry, human health and to protected natural areas.

- The financial impact of alien forest pests in the US has been estimated at US$ 123 billion per year and annual timber losses at US$ 4 billion. While there are few impact studies in Canada, annual domestic timber losses to all forest pests (both exotic and indigenous) are an estimated 61 million m^3 or about one-third of the total annual commercial harvest. Allowing that this timber would have been harvested, the annual financial loss to provincial stumpage, royalties, and rent revenues is about $720 million.

  Ecosystem impacts of exotic species include suppression and replacement of native species, potential for extirpation (e.g., American elm, American chestnut), and the threat to rare and endangered species. Ecosystems of low diversity, such as the boreal forests, are relatively more susceptible to exotic invasion. Stressed and depleted forests afford reduced food and habitat for wildlife, and have altered forest fundamentals which are manifested in nutrient cycle impacts, forest hydrology and forest fire regimes.

  The social effects of exotic pests can include impacts on human health, government credibility, losses in aesthetic and spiritual values, public perception and support of forestry, employment and community stability, and international relations.

- The magnitude and nature of international trade directly affect trends in exotic pests. The increase in trade volumes and the emergence of new trading partners serve to increase the risk of exotic transmission. This risk is further strengthened by the speed of modern transportation, the use of containers, point-to-point delivery with inter-modal transport, and the use of “green” packaging materials. Travel, another source of trade and exotic introductions, has expanded dramatically and now includes many previously isolated regions. Any importation of living or untreated material (water, soil, air, wood, people, etc.) constitutes a potential source for the introduction of exotic pests.

  Canada is particularly vulnerable to trade transmissions of potential exotic pests because the US, our major trading partner, is also the world’s largest importer. The risk is further compounded by a degree of ecosystem integration between the two countries. Exotic pests can and do produce situations in which export opportunities are threatened and lost.

The control/eradication options for exotic pests are increasingly being limited or eliminated in response to improved information on efficacy, collateral damage to other organisms and the degree of public acceptance. The range of options includes baits and attractants, fumigants, repellants and barriers, traps, poisons, biological agents, bounties and commercial exploitation, and mechanical removal.

Given increased incidence of exotic pests, the magnitude of the expected damages and the limitation on control options, central to the control of exotic pests is an effective international effort to reduce the transmission risk at the source of introduction. This will require international cooperation, funding to support the required implementation in emerging exporters, monitoring provisions and established penalties for violations.

- Canada has a number of natural barriers to domestic spread of exotic pests. These include climate, distances and topographical barriers. It is important that the institutional structure be reviewed to ensure that it is positioned to complement these natural barriers.

Sommaire

- Les nuisibles exotiques sont définis comme étant les espèces animales et végétales qui s'étendent au-delà de leur aire de distribution naturelle et qui ont des effets négatifs combinés sur l'économie, l'écologie et les collectivités d'une région. Une invasion de nuisibles exotiques met en jeu les étapes suivantes : introduction, établissement et propagation.

- Les espèces exotiques qui réussissent à s'établir et à se propager ne sont pas toutes nuisibles. En fait, un grand nombre de celles-ci font partie intégrale de l'économie et des écosystèmes de l'Amérique du Nord : des espèces exotiques introduites intentionnellement sont à la base de plus de 90 pour cent de la production d'aliments pour les humains et pour les bestiaux.

- La probabilité qu'une espèce exotique devienne nuisible localement est relativement faible. L'établissement d'un organisme introduit dans un nouvel habitat dépend d'une interaction complexe entre plusieurs facteurs, notamment le nombre d'organismes introduits, leur adaptabilité, la qualité de l'habitat et le niveau de compétition (prédation, maladies, etc.). Bien qu'il soit peut probable qu'une espèce exotique parvienne à se propager sur une grande échelle, certaines espèces peuvent devenir suffisamment nuisibles pour engendrer des impacts négatifs importants.

  On estime que plus de 300 insectes parasites des arbres et originaires d'Europe sont maintenant établis en Amérique du Nord. Les auteurs d'une vaste étude entreprise aux États-Unis estiment que plus de 4 542 espèces exotiques ont été introduites aux É.-U. et que 15 % de ces espèces affectent sensiblement les récoltes, les forêts, la santé publique et les réserves naturelles.

- L'incidence financière des nuisibles exotiques dans les forêts des États-Unis a été estimé à 123 milliards $US par an et les pertes annuelles en bois à 4 milliards $US. Bien qu'aucune étude d'impacts n'ait été effectuée au Canada, on estime que les pertes domestiques annuelles en bois, tous nuisibles forestiers confondus (exotiques et indigènes), se chiffrent à 61 millions m3 ou un tiers de la récolte commerciale annuelle, soit une perte financière annuelle d'environ 720 millions $ en droits de coupe, redevances et revenus locatifs.

  L'effet des espèces exotiques sur les écosystèmes englobe notamment le déplacement et le remplacement des espèces indigènes, l'élimination potentielle de certaines essences (p. ex. l'orme d'Amérique et le châtaignier d'Amérique), et la menace d'une pression sur les espèces rares ou en danger. Les écosystèmes peu diversifiés, comme ceux des forêts boréales, sont relativement plus susceptibles de subir une invasion exotique. Les forêts attaquées par des nuisibles et qui perdent leurs arbres n'offrent plus qu'une nourriture et un habitat réduits à la faune. Leurs caractéristiques sont altérées et l'effet se fait sentir sur le cycle des nutriments, l'hydrologie locale et le régime des incendies.

  Au niveau social, les nuisibles exotiques peuvent nuire à la santé publique et à la crédibilité du gouvernement, conduire à la perte de valeurs esthétiques et spirituelles, affecter l'image que se fait le public de la foresterie, nuire au soutien éventuel que la population accorde à cette industrie, et enfin déstabiliser l'emploi, les collectivités et les relations internationales.

- L'échelle et la nature du commerce international influent directement sur la propagation des espèces exotiques. L'augmentation des échanges de produit s et l'émergence de nouveaux partenaires augmentent ainsi le risque de transmission de ces espèces. Ce risque est renforcé par la vitesse des moyens de transport modernes, l'utilisation de conteneurs, de livraison point à point par transports combinés et l'utilisation de matériaux d'emballage « verts ». Le tourisme, autre source d'échanges commerciaux et d'introduction de nuisibles exotiques, s'est considérablement étendu et inclut aujourd'hui de nombreuses régions autrefois isolées. Toute importation de matière vivante ou non traitée (eau, terre, air, bois, personnes, etc.) constitue une source potentielle d'introduction de nuisibles exotiques.

Le Canada est particulièrement vulnérable aux transmissions de nuisibles exotiques par voie de commerce parce que les États-Unis, notre principal partenaire commercial, sont aussi les plus gros importateurs du monde. Le risque est augmenté par l'intégration relative des écosystèmes des deux pays. Les nuisibles exotiques menacent le maintien de certains liens commerciaux et sont responsables de l'annulation de marchés d'exportation.

Les possibilités de contrôle et d'éradication des nuisibles exotiques sont de plus en plus limitées ou supprimées en réponse à l'information croissante sur leur efficacité, aux dommages collatéraux subis par les autres organismes et au soutien décroissant du public. Les mesures possibles comprennent l'utilisation d'appâts et d'attractifs, de pesticides fumigènes, de répulsifs, de pièges, de poisons et d'agents biologiques ainsi que la distribution de primes pour la destruction des nuisibles, l'exploitation commerciale de ces derniers et l'élimination mécanique.

Vu l'incidence croissante des nuisibles exotiques, l'étendue des dommages prévisibles et le nombre limité de possibilités de contrôle, il est crucial de mettre en place un effort international visant à réduire le risque de transmission de ces organismes à la source afin d'en contrôler efficacement la propagation. Un tel effort nécessitera une collaboration internationale, des capitaux pour soutenir la mise en place de contrôles chez les nouveaux exportateurs, de mesures de surveillance et d'un système de pénalités pour les infractions aux règlements.

- Le Canada possède un certain nombre de barrières naturelles à la propagation des nuisibles exotiques, notamment son climat, sa superficie et sa topographie. Il est toutefois important que la structure institutionnelle soit révisée de manière à complémenter ces barrières naturelles.

Introduction

In recent years the scientific community has sounded the alarm about the potential for exotic pest introductions to emerge as a serious contemporary ecological problem (Liebhold *et al.* 1995; Niemela and Mattson 1996). The magnitude of the financial impact and control and remedial actions incurred in responding to recent introductions and establishments is a clear testimony to the potential economic cost of such exotic pest invasions. In addition to the economic costs there are potential ecological and social costs to both the impact and the response to an exotic pest invasion. The emergence of and inability to eradicate an exotic pest can challenge public confidence in trade liberalization and scientific capacity. North American governments appear to have recognized the potential negative impacts from exotic pests and are initiating incremental activity on this complex issue. In the spring of 1999 a US Executive Order provided US$ 29 million in annual incremental funding and the development of a national strategy on combating invasive organisms. The announcement came after the removal of hundreds of mature hardwood trees in Chicago, which had been infested by the Asian long-horned beetle (*Anoplophora glabripennis*; Hagenbaugh 1999). This infestation is currently established in two states (New York and Illinois) and has been intercepted in at least eight other states as well as Ontario and British Columbia. However, it is not known if the Asian long-horned beetle is established in these other jurisdictions. The urban forest in New York City has lost more than one thousand trees to the Asian long-horned beetle (CFIA 1999).[1] This exotic pest is but one of many to become established in North American forests, albeit in this case it was high profile urban forests. It has been estimated that over 300 species of tree-feeding insects native to Europe have become established in North America (Niemala and Mattson 1999)

The purpose of this study is to summarize the available information on exotic pest invasions. This information is a prerequisite to the development of an integrated and interdisciplinary decision-making response in the framework of sustainable forest management. The scope of this study is to examine the existing literature to provide a historic synthesis of the potential impacts of exotic pest invasions to Canada's forests. Given the common land mass, integrated forest ecosystems, similar bio-geo-climatic conditions for exotic establishment, and the major trade activity between Canada and the United States, the US research on exotic invasions is particularly relevant to examining the domestic situation. There are also numerous examples of 'cross-border' spread of alien forest pests; the European gypsy moth (*Lymantria dispar*) in eastern North America and the larch casebearer (*Coleophora laricella*) which spread from Idaho infestations into British Columbia.

The preponderance of available and existing information is from American sources such as the United States Department of Agriculture (USDA), US government contracted agencies, and academic communities. This information is augmented through a compilation and review of Canadian sources of information on exotic pests, including publications of the Canadian Forest Service (CFS), the Canadian Food Inspection Agency (CFIA), and peer-reviewed publications. Additional insight and information was obtained through personal communication with researchers in government laboratories, regulatory agencies and universities.[2]

Species can arrive from their origin to new locations by natural processes and/or assisted by human activities. Adult or immature insects, plant seeds and fungus spores are blown into new areas by storms or other anomalous weather events or be transported by migratory animals thus overcoming natural borders such as mountains, oceans and large distances. Increasingly, however, the human factor provides an additional opportunity for species to overcome natural barriers and for their introduction beyond their natural range (Wilson and Graham 1983).

Globalization, particularly in the forms of international trade and travel, has served to increase the incidence of species transmission from point of origin to new areas. There is no standard terminology for such transmitted organ-

[1] The Asian long-horned beetle is a threat to Canada's broadleaf trees including the maples. The pest has limited natural predators in its native range (entomopathogenic fungi are a reported predator). Indeed, in Chinese plantations maples are planted as trap crops in an effort to protect fast-growth poplar from the beetle.
[2] CFS (1999a,b) provided a useful entry to a selection of the various dimensions of forest pests.

isms. Different terms have been used in the scientific literature: ”invasive,” “alien,” “exotic,” “foreign,” “immigrant,” “introduced,” “non-indigenous” and “non-native.” “Exotic” is used most frequently in this report, along with “non-indigenous” and “introduced.” These terms are employed for “a species being beyond its natural range of potential dispersal.” (OTA 1993). This definition, based on species ecology, recognizes the importance of human activities in species movement. Another widely used term “biological invasion” or “bio-invasion” refers to “the expansion of a species’ geographic range into a new area” (Liebhold et al. 1995). Exotic species, by this definition, need not originate from offshore. The movement of species within Canada or North America can also be considered exotic invasions.

Many deliberately introduced organisms are beneficial, such as crop plants, selected ornamentals, game animals, and livestock. “Exotic” refers to both beneficial and harmful introduced organisms, while “invasion” connotes mainly the expansion of a species. Exotics are invasive when they produce ecosystem changes by displacing native organisms through habitat alteration, predation, and parasitism or by competition for space, sunlight, food or nutrients. This study focuses on the impacts of invasions by forest pests – organisms that have produced negative impacts on the economy, forest ecosystems and sometimes society in the area invaded. Classifications of exotic pests vary, but they are usually sorted into three groups: insects, pathogens and plants.

Exotics that appear to cause the greatest share of forest damage are the invasive insects and pathogens, but introduced flora (woody species, ornamentals and weeds) are also proving to be destructive and highly competitive with native forest vegetation for space, nutrients, and water. For example, invasive exotic flora (Scotch broom [*Cytisus scoparius*] and gorse [*Ulex europaeus*]) is an additional threat to the sustainability of Canada’s rarest forest ecosystem, the Garry oak – Arbutus ecosystem (*Quercus garryana* Dougl. – *Arbutus menziesii*) on southeastern Vancouver Island and the southern Gulf Islands. This ecosystem is already strained by agricultural and urban development. Invasions of exotic plants have also become a major problem in the subtropical areas of North America (Hawaii and Florida). The paper bark tree (*Melaleuca quinquenervia*), native to Australia, was introduced into North America in 1906 as an ornamental plant. Since its establishment it has invaded the Florida Everglades causing a decrease in the fresh water supply to South Florida, an increased fire hazard, and losses in tourism and outdoor recreation (Liebhold et al. 1995). The ecological impact of the paper bark tree invasion also resulted in the suppression of a large number of native species (Bright 1998). Scotch broom, native to southern Europe and northern Africa, arrived in North America in the mid-19th century as an ornamental introduction. It is now widespread in the Pacific Northwest where it is invading native grasslands, pastures, parklands and roadsides.

The gypsy moth (*Lymantria dispar*) is an example of an intentionally introduced insect, which escaped and became a major pest in North American forests. In 1981, at the peak of its outbreak, the gypsy moth defoliated more than 6 million ha of US forests. One forest disease, chestnut blight, has changed the species composition of North America’s forests. Chestnut blight, caused by the Asian fungus *Cryphonectria parasitica*, was first detected in New York City in 1904. By 1950, almost all of the American chestnut trees in a land area of about 81 million ha had been killed by the chestnut blight (Liebhold *et al.* 1995).

Bio-Invasion – A Multi-Stage Process

A successful bio-invasion includes three elements: introduction, establishment and spread (Liebhold *et al*. 1995; Mooney and Drake 1986; Drake *et al.* 1989). A fourth element of particular interest is the impact of any invasion. Clearly not all insect introductions become pests, but among those that do there are a few that have produced devastating impacts (Cochran 1992; OTA 1993).

The common denominator of any bio-invasion is incomplete information. This includes delinquent information on which species will be introduced and become established, how they will be introduced, where and when this will occur, which of the introduced organisms will spread and become a pest, and the magnitude and character of the impact.

For example, despite extensive research on the pathways of exotic forest pest introductions many unknowns remain (USDA 1991, 1992, 1998a,b). Although the lexicon and objectives vary, bio-invasions are studied in a number of scientific disciplines working in population biology including epidemiology, ecology and population genetics. There are also a number of attempts to mathematically describe the common aspects of bio-invasions developed in these different disciplines (Hengeveld 1989).

Table 1. Level of uncertainty/risk associated with each stage of a bio-invasion

Stages of a bio-invasion	**Level of uncertainty/risk**
Introduction	very high uncertainty
Establishment	high uncertainty
Spread	high risk

The level of uncertainty and risk associated with each bio-invasion process is summarized in Table 1.

Introduction

Introduction is a process of organism arrival into a new geographical or ecological range either by natural processes or with the support of human activity. Most bio-invasions are the result of accidental introductions but not all. Many species, including most of North America's food and feed crops and livestock, were intentionally moved from their native habitat. Of the 235 invasive woody plants in North America, 85% were initially introduced for ornamental and landscape purposes (White 1997). Other introductions were made to reduce soil erosion or support target wildlife populations (Wallner 1997). Kudzu (*Pueraria lobata*), for example, was introduced into the US in 1876 as a forage crop and an ornamental plant. In the 1930s, southern US farmers were encouraged to plant kudzu to reduce soil erosion. However, soon after, kudzu was recognized as a weed and removed from the USDA list of permissible plants in 1953.

Deliberate introduction of exotics is not restricted to plants. Many animals have been introduced for commercial production, to fight native pests, in an effort of nostalgic replication, as exotic pets, or for hunting purposes. Some of these introductions have gone on to achieve quite spectacular populations and habitat ranges. Starlings (*Sturnus vulgaris*), the English sparrow (*Passer domesticus*) and Scotch broom are good examples of such introductions in North America. European rabbits (*Oryctolagus cuniculus*) introduced with settlers became a plague in Australia until another exotic, a Brazilian rabbit virus, stopped their invasion in the 1950s (Bright 1998). An amateur entomologist imported the gypsy moth to Massachusetts from France. In 1869, a number of the imported gypsy moths escaped, built up in numbers and twenty years later the population cycle boomed. Introduced non-native fish species in Jasper National Park are under scrutiny for removal to allow restoration of native species.

The arrival of exotic organisms is greatly facilitated by new transportation vehicles. The survival rate of exotic hitchhikers is much higher than in the past due to the speed at which these exotic organisms are transported to new locations and a suitable host. Aircraft cargo compartments are highly susceptible to invasion by moths and beetles, and wheel wells are known for housing the brown tree snake *(Boiga irregularis*). Bilge water, pallet wood, wooden crates and wooden dunnage are all recognized as pathways of introductions. Such invasions are often unaffected by any routine spraying efforts (Dale and Maddison 1984). Containerized shipments provide an attractive environment for a host of exotic pests including soil organisms on the container cleats. In summary, any importation of living or untreated material (wood, water, soil, etc.) constitutes a potential source for the introduction of exotic pests.

A proven additional pathway for the entry of exotic pests, albeit somewhat indirect, is via increased trade in live animals, fish and plant material. Such non-native introductions include the risk of associated pests: seeds and tubers carry plant diseases and insects, and animals can bring in seeds and new diseases. Importations of unprocessed logs and green lumber or wood chips constitute major pathways for invasive forest pests (USDA 1991, 1998a,b,c).[3]

Establishment

The majority of exotics introduced into a new habitat never become established. An introduced organism becomes established if it is able to reproduce and maintain a population that survives from year to year (Liebhold et al. 1995). Only a subset of introduced and established exotics successfully spreads or invades natural areas where they may reduce or eliminate native populations and even affect ecosystem functions such as hydrology (e.g., the invasive maleluca) and fire regimes (e.g., eucalyptus; see Wallner [1997] and Bright [1998]). Successful establishment of an introduced organism into non-native habitat depends upon a complex interaction of several factors, the major ones being size of the original introduction, habitat suitability and the level of competition (predation, diseases, etc.).

The possible time lag between the introduction and an observed outbreak is an additional source of uncertainty in bio-invasions. A number of European gypsy moths escaped in 1869 but the population exploded 20 years later. The first outbreak in Canada occurred in Ontario in 1969 (although defoliation was not observed until 1984), one hundred years after the introduction to North America. The fungus that causes chestnut blight was likely introduced into the US along with the Chinese chestnut (not atypically the Chinese chestnut species is more resistant to the fungus than American species). However, there was a time lag of 50 years between the importation of Chinese chestnut into the US and the successful establishment of chestnut blight in the US (Liebhold *et al*. 1995).

Although favorable climatic conditions and the presence of a suitable host are regarded as major factors in the successful establishment of exotic organisms, past introductions and establishments prove that exotic insects may change their feeding habits if there is no adequate host.

Spread

Spread refers to the expansion of an established exotic into adjacent areas. While the introduction and establishment of exotics have not usually been detected and observed at the actual time this occurs (except in very isolated cases), the spread of many invasives has been studied and well documented. Mathematical models of the spread of invasive exotics have been developed and these models have often shown acceptable predictive power where compared with observed rates of exotic spread (Liebhold *et al.* 1995). The characteristics of the typical invasive exotic species are host/nutritional flexibility, lack of predator competition, rapid reproduction, an effective rate of dispersal, and control difficulty.

Williamson and Fitter (1996) proposed the following rule of thumb for the establishment and spread of introduced plants: that 1 in 10 arrivals survives, 1 in 10 of those establishes, and 1 in 10 of those spreads and becomes a pest. Therefore, 1 in 1000 introduced species becomes a problem. This rule has to be used with great caution. The

[3] Allen *et al.* (1998) report that one single log bolt used in shipping granite blocks imported into Canada contained 1532 insects of 13 species. The small shipping bolt was supporting a community of imported insects.

data support using a range instead of a point rule: instead of a 1 in 10, a range between 1 in 5 and 1 in 20 should be used, depending on the plant (Williamson and Fitter 1996). However, the probability that an exotic insect introduction will become a pest, estimated at 0.035, is much higher than the 0.001 proposed for plants (OTA 1993).

Trends In Exotic Pest Introductions

History

Total numbers of both native and exotic species in North America are not known and there is wide variation of reported estimates. The US Congress Office of Technology Assessment (OTA 1993) estimates that the total number of introduced species in the US exceeds 4542 (Table 2). This estimate includes neutral, beneficial and harmful exotics. The OTA report also provides an estimate that 15 percent of all exotics in the United States cause severe harm in agriculture, forestry, industry, human health and protection of natural areas. Many more species than those shown in Table 2 have been established in North America, but they still represent a relatively small portion of total number of species (OTA 1993). The difficulty in quantifying the risk of exotic pests is further compounded because the pest status is not always a function of population density. The European gypsy moth is common in Ontario but is not a pest in that part of the country, whereas it is rare in British Columbia where it is a considerable pest.

A recent study by Pimentel et al. (1999) estimates that 50 000 exotic species have invaded the US.[4] The estimates employ different definitions. Because of high uncertainty associated with every stage of potential exotic organism invasion, a clear distinction between introduced and established species is crucial. Another issue in accounting for the number of exotics is identification of the sectors to be included in any impact estimate. Analysis of the impacts of exotics has traditionally focused on agriculture and forestry, but introduced pathogens can have a considerable impact on human health (e.g., AIDS and influenza) and induce high costs in health care, prevention methods and research.

Even more important than the accurate quantification of the absolute number of introductions is the rising rate of introductions over the last 100 years. Figure 1 provides an illustration of the introduction incidence of exotic organisms into North America. The number of insects and mites introduced into the US is graphed against the year of introduction. The figure reveals an interesting change in the trend of introductions. The number of introductions increases exponentially until 1920. After 1920 the increase is linear with an average annual increase of about 14 species. Sailer (1983) hypothesized that a change in the rate of introductions was the result of the 1912 Plant

[4] Pimentel *et al.* (1999) estimate that invasive exotic pests produce economic losses totaling US$ 123 billion per year in the US.

Table 2. Estimated numbers of exotic species in the United States

Category	Number	Percentage of total in the US species in category
Plants	>2000	–
Terrestrial vertebrates	142	6%
Insects and arachnids	>2000	2%
Fish	70	8%
Mollusks (non-marine)	91	4%
Plant pathogens	239	–
Total	>4542	

Source: OTA (1993)

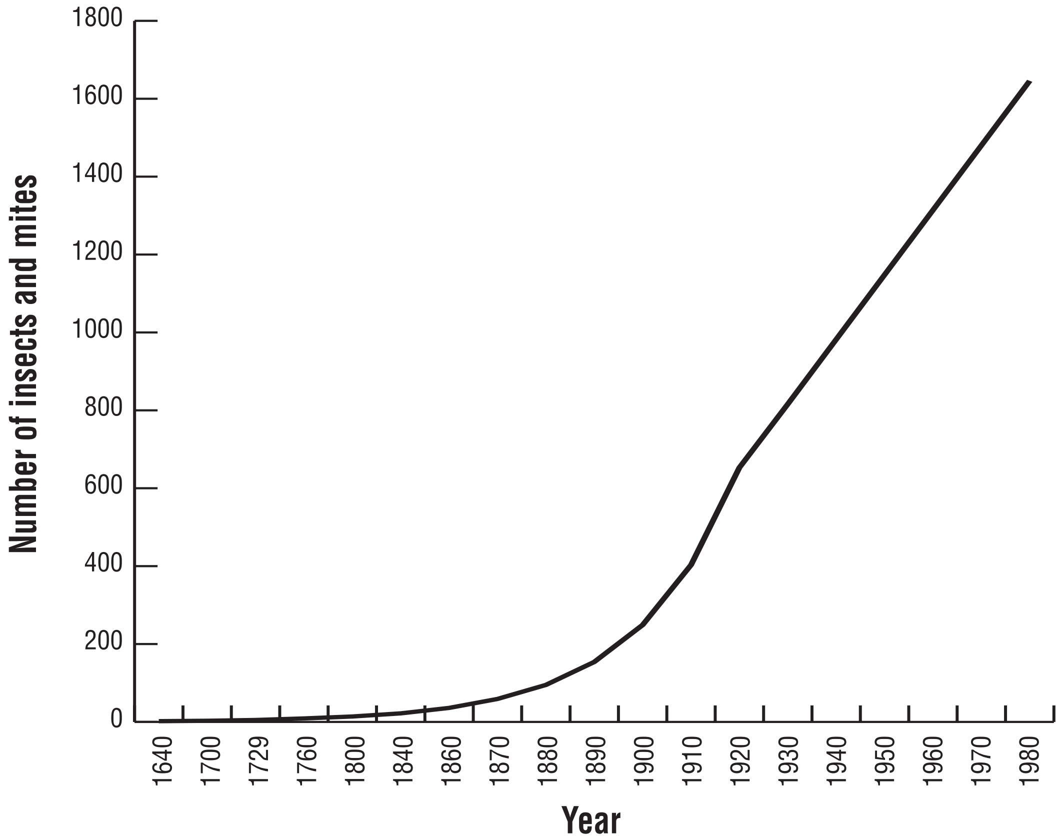

Figure 1. Cumulative number of insect and mite introductions into the US since 1640 *(After: Sailer 1983)*

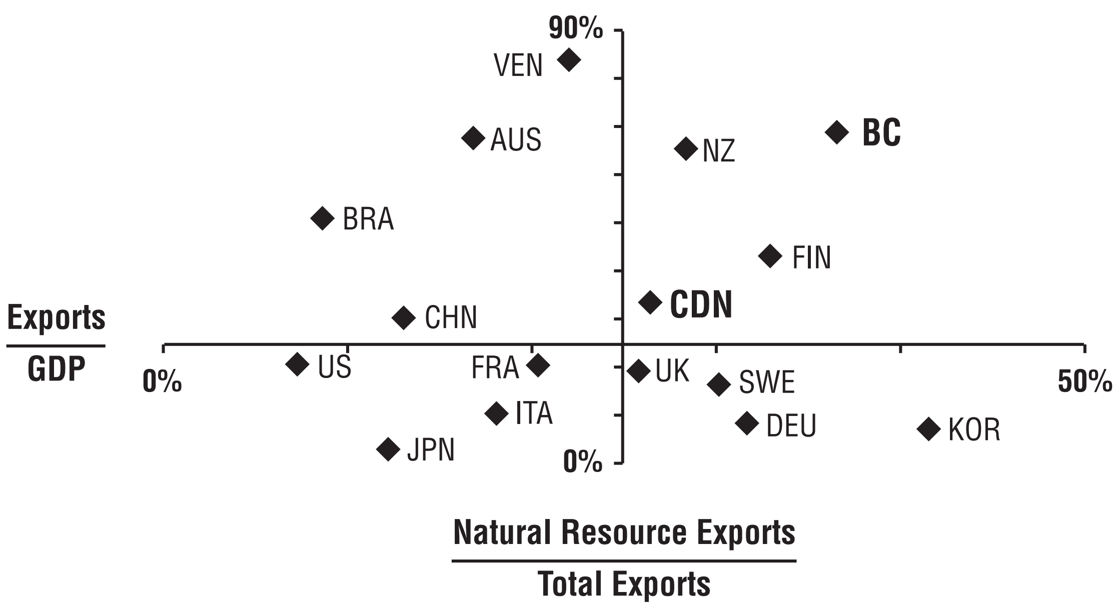

Figure 2. Relative trade dependence

Quarantine Act. It is likely that part of the increase is due to improvements in capability and diligence in detecting introductions. The graph covers a period up to about 1980. The rate of introductions in the last 30 years of the millennium is not likely to have declined. The increase in international product trade, international travel, shipping speeds, container use, and point-to-point shipment have all combined to ensure that the number of introductions will have continued to increase. The emergence of new trading partners will also ensure that many new exotics are afforded the opportunity to establish in North America.

International Trade

Research on trade patterns and trends can provide useful information on one of the significant factors contributing to the rate and nature of bio-invasions.

Bio-invasion started as a reasonably modest by-product of human activity but has become a significant companion to trade expansion and globalization. Economic theory is clear on the growth gains from trade, and established objectives of trade liberalization are worthy of pursuit. However, trade liberalization reduces border control and increases international movement. Consequently, the risk of exotic pest invasions is increased. Given the likely economic, ecological and social impacts of exotic pest invasion, it is important that due consideration be given to methods to reduce the introduction level and to provide for an effective response to establishments that will inevitably occur. This consideration is particularly important for countries with a commercial forest sector and for those with a major international trade component to the economy. Figure 2 illustrates the economic contributions of exporting and natural resources to Canadian economic performance in comparison with a selection of jurisdictions.

Increased access to the benefits of international trade inherently includes some additional costs associated with exotic pests (Laird 1984). Examples of such costs are:

1. increased monitoring, audit and reporting of pests;
2. development and implementation of packaging and shipping standards to reduce the risk of pest transmission; and
3. institutional prescription on market access for certain products (e.g., green lumber and wood chips, dunnage, crates, stickers).

Despite such costs the empirical evidence confirms the positive net gains from trade produces in the efficient utilization of resources and capital.

World trade continues to expand in volume and in value. Several factors have boosted trade both among developed and with developing nations. In the main trade liberalization efforts have focused on products (although there is a growing interest in moving forward on trade in services). The successful reduction in tariff barriers in combination with the economic emergence of some “new” exporting entrants have combined to increase North American exposure to exotic invasions. Other major factors include real price reductions in transportation and communication costs, tariff codification, and improvements in the supporting procedural vehicles and standards for improved efficiency. Various regional and multi-lateral trade agreements have also been a catalyst. The collapse of the former Soviet Union, Asian economic growth and the Chinese awakening served to open new markets. Finally, the record setting economic expansion of the world’s largest importer — the US — and booming trade in high-tech products have been major engines for global trade growth.

Canadian and US imports have increased considerably along with the expansion in global trade. Figure 3 presents a recent history of Canadian and US imports from Latin America (including Mexico), Europe and Asia. The trend in North American imports in the last four decades is similar to the trend in the introduction of insect and mites into the US. The difference between the exponential growth in imports versus the linear growth in exotic introductions can be attributed to a number of anomalies. For example, the information on exotic introductions does not include plants and the value aggregation of trade flows may mask linear growth in products conducive to exotic introductions. Research into the potential cause-and-effect relationship between trade growth and the increasing number of exotic introductions will provide some interesting information on control options.

Table 3. The world's top merchandise importers, 1998

Country	US$ Billions
United States	944
Germany	467
Japan	281
United Kingdom	315
France	286
Hong Kong	189
Italy	216
Canada	206

Source: WTO (2000)

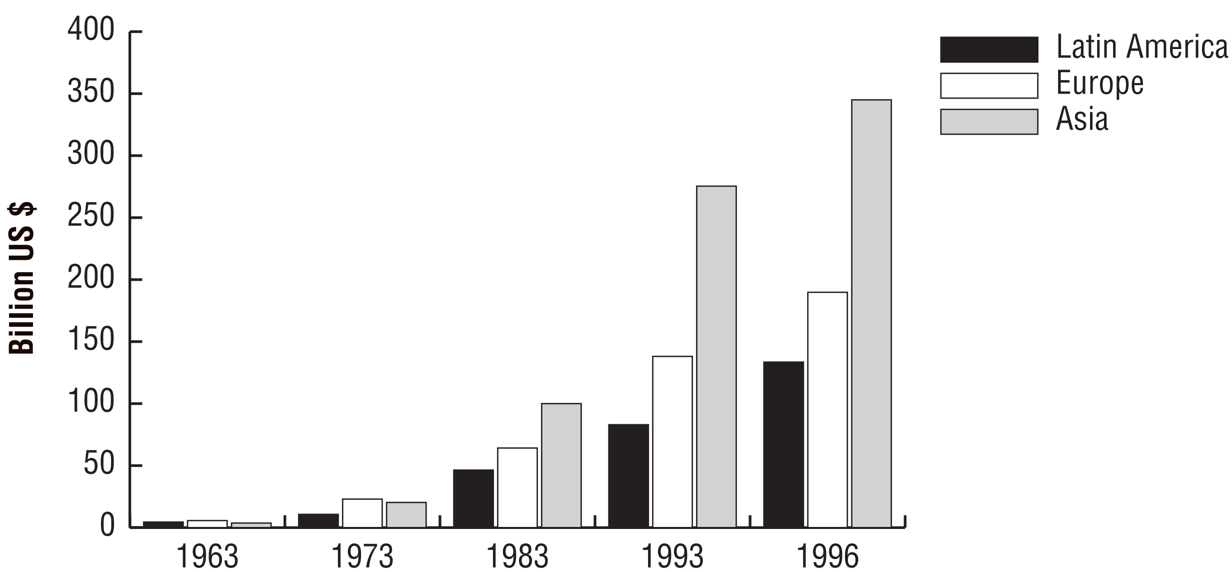

Figure 3. Total Canadian and US imports from Latin America, Europe and Asia, 1963-1996
Source: WTO (1998)

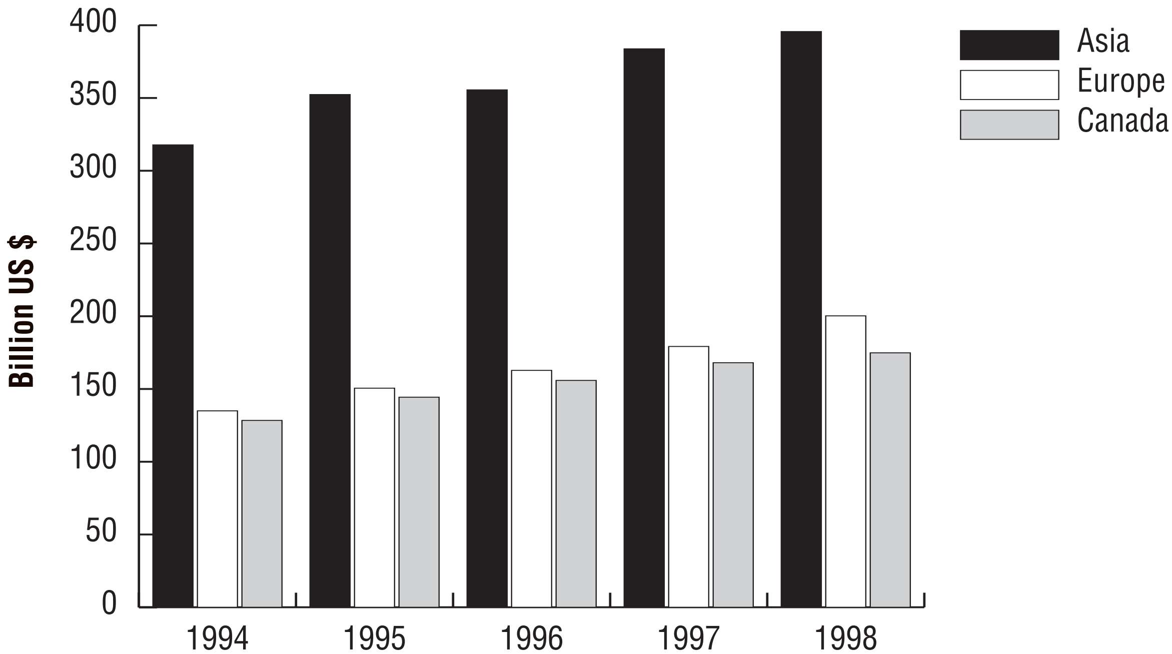

Figure 4. US Imports from Asia, Europe and Canada, 1994-1998.
(Source: Industry Canada, 1999)

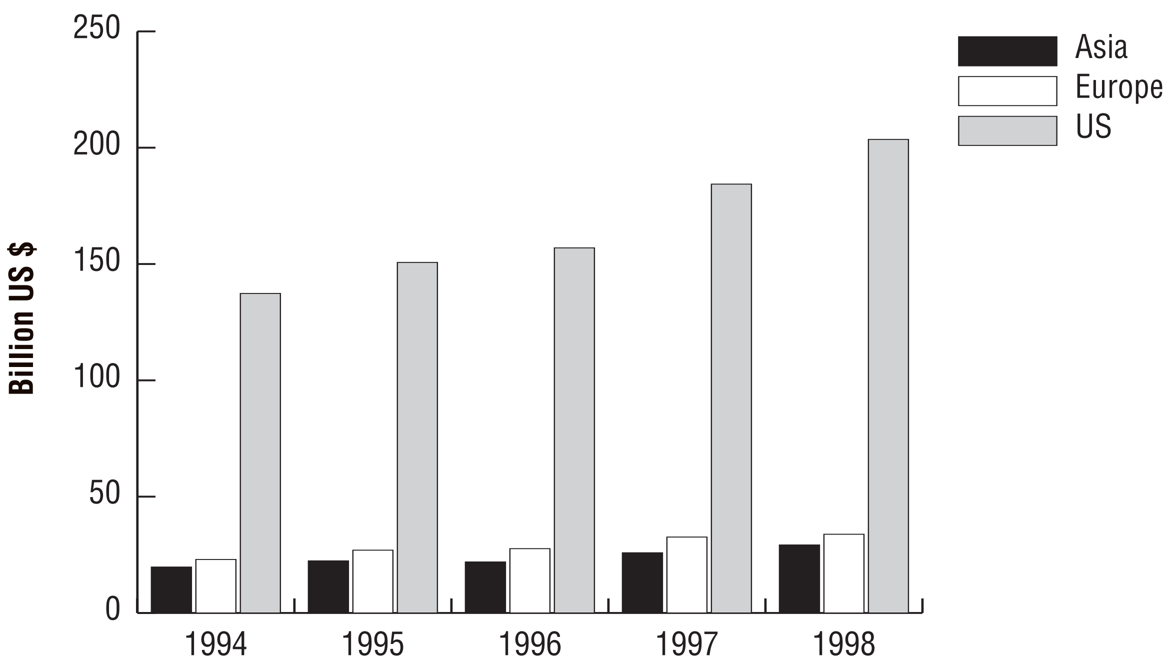

Figure 5. Canadian imports from Asia, Europe and the US, 1994-1998.
(Source: Industry Canada, 1999)

Despite the recent shocks to global economic performance from the Asian and European slow-downs, Canadian and US imports have remained high (Figures 4 and 5). Placing the magnitude of North American activity on international trade into perspective, in 1997 the US imported about US$ 944 billion (Table 3). Canada imported about US$ 206 billion. Measured in value terms, North American imports exceed European Union (EU) imports.

The highly integrated trading relationship and the large volume of bi-national travel between Canada and the US means that exotic pest establishment in one jurisdiction greatly increases the risk of subsequent transmission to the other region. This risk is heightened by the uniformity among certain North American forest ecosystems.

Canadian forests are of integral importance to the national psyche, a fundamental ingredient to the ecological dynamic and a major economic contributor (contributing about 3% of national GDP and employment). Forest product export revenues are the major source of domestic net export earnings. The domestic cost structure, the emergence of new forest product sources and substitute products all combine to challenge the Canadian position in highly competitive international markets. Canadian forest product trade is concentrated in three markets, the US, Japan and the EU (Figure 6). Rapidly emerging alternatives (supply and substitute) are targeting these same markets.[5] The availability of alternatives can serve to mitigate the impact of trade restrictive efforts by importing regions to reduce exotic pest exposure. The EU, Japan and the US all have substantial forest land and forest processing that warrant protection from exotic pests.

The consistently large Canada/US trade flow, border openness, and the high volume of tourist travel provide ready opportunities for the transmission of exotics that successfully establish in either country. It is also apparent that exotic establishment in any country (or region) increases the risk of subsequent transmission to a third trading partner. This risk factor rise can arise despite minimal trade with and/or phytosanitary controls on shipments from the initial source of the exotic. This risk is an inherent byproduct of market globalization.

[5] Sweden, Austria, and Finland have made major gains in whitewood lumber exports to Japan. Scandinavian exporters are also positioned for the US lumber market. Fast-growth plantation lumber has gained market share in Japanese lumber and US value-added product imports.

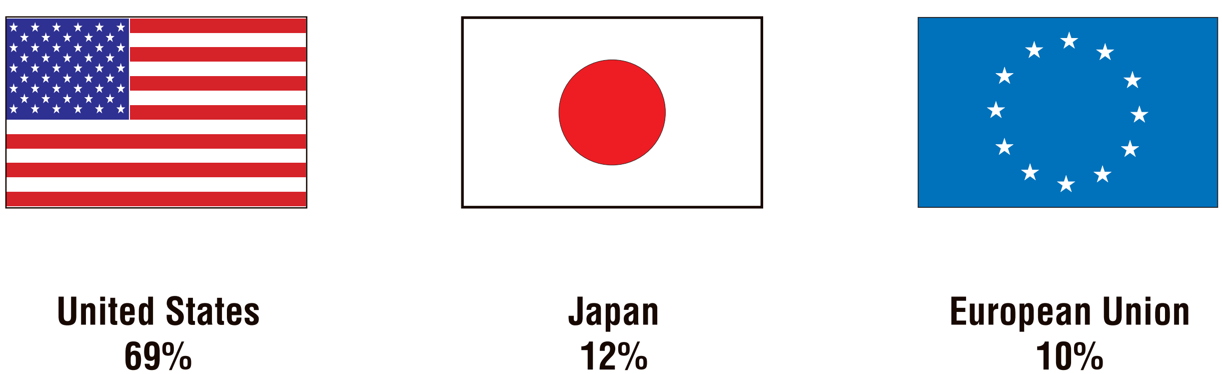

Figure 6. Distribution of Canadian Forest Product Exports

Forest Sector Impacts

Forest ecosystems are dynamic and have been adapting to natural disturbances throughout their evolution. Fire, windstorms and pests (insects and pathogens) are among the major natural disturbances that affect forests. However, there is a need to examine the ability of forest ecosystems to adapt to disturbances accelerated, aggravated or caused by human activities. Disturbances caused by the expansion of human population including harvesting, urbanization, recreation, and various kinds of pollution may contribute to the extinction of plant and animal species. Invasions by exotic species resulting from human activity are a further source of disturbance to forest ecosystems.

By 1980 more than 380 exotic forest pests (360 insects and 20 pathogens) had been introduced to North American forests (Haack and Byler 1993). Forest pests cause tree damage, reduced tree growth and increased tree mortality on vast areas of forest land. New introductions may increase the frequency of outbreaks of forest pests and the magnitude of their effects. Along with large economic impacts, some of the introduced pests have had dramatic ecological effects to forest ecosystems in terms of loss of living trees as a habitat for wildlife, loss of biodiversity and in the most extreme cases complete loss of particular species (Filip and Morrell 1996; Heywood and Watson, 1995; Heywood, 1989). Despite the apparent impacts of exotic forest pests, there is no standardized methodology for their quantification and this deficiency greatly limits any comparative analysis of various pest impacts. In order to provide an objective reference regarding the importance of an exotic species, an evaluation of economic, ecological and social consequences is required. The predictive power of this evaluation depends on many factors, including the quality and comprehensiveness of the pest data.

Economic Impact Evaluation

Costs of invasions by exotic forest pests involve direct economic losses inflicted by the pest species, the loss of recreational and amenity values, regulatory and control expenses, and any losses arising from consequent trade restrictions as other jurisdictions take market access action to reduce their risk of importing the pest. More specifically, the economic losses directly inflicted by forest pests include:

- timber losses due to growth loss, quality loss and tree mortality,
- revenue (and related jobs) lost from foregone trade, recreation and tourism,
- property value losses, and
- reduced aesthetic values.

Trade losses could include additional costs incurred as a condition of market access if quarantine measures are established. Such costs might include inspection fees, heat treatment of lumber products, and certification fees.

Regulatory, control and mitigation expenses include:

- expenses of research and risk assessment of potentially damaging exotic species,
- costs of monitoring, eradication and suppression,
- costs of mitigation (e.g., heat-treating or drying lumber to reduce pinewood nematode, or fumigation), and
- cost of replacing killed or damaged trees.

In order to estimate the total economic consequences of an exotic pest invasion all of the above costs need to be included. Available information on the economic impacts is usually limited to estimating the timber and forest product losses and/or the cost of control measures. Such estimates will significantly understate the total economic cost of the invasion.

Comparing and aggregating timber losses from different pests is often difficult because of variations in survey methods, measurements of damage intensity by individual pests, various assumptions made for each group analyzed and confounding sources for timber losses. Timber volume losses are the results of tree mortality or growth loss, as well as quality degradation. Some insects and diseases cause tree mortality. Others cause defoliation, which often does not immediately kill trees but it does decrease tree productivity. Strict comparison of economic losses between the areas affected by major defoliators is not possible. The extent of growth loss varies with damage intensity, weather condition, site condition, tree age, general forest health, and so on. Tree mortality due to defoliation depends on a succession of defoliation years, but also on the type of pest, tree species attacked, site quality, additional sources of tree stress, and environmental disturbances.

Estimates of timber losses are usually calculated on an individual pest basis.[6] Various assumptions are made for each group analyzed and different economic methodologies applied. However, the impacts of simultaneous attacks of different pest on the tree may overlap. Such an overlap will serve to overstate the total timber loss and economic cost obtained by summing up losses for each pest group. On the other hand, simultaneous attacks of various pests may weaken the tree and increase the rate of growth loss and mortality, resulting in underestimation of total losses after summation of losses for individual groups (USDA 1991; Hall and Moody 1994; CCFM 1999). All this makes summation of economic impacts from individual pest groups problematic.

The following sections contain estimates of the economic impacts of several past invasions of forest pests in North America and US Forest Service (USFS) estimates on the potential costs of controlling for invasive pests from US imports of raw logs from eastern Russia. Comparison among these results must be made with caution. Except for those studies drawn from second-order sources, the assumptions used in the various studies are presented.) Despite growing interest among the public, policy makers, regulatory agencies, media and the scientific community in an estimate of cumulative economic losses, any such estimate based on available impact estimates would be of limited use due to methodological variation among the existing studies. However, attempts have been made to provide comprehensive aggregate measures. The annual value of timber losses alone due to invasive exotic pests has been estimated at US$ 4 billion (Pimentel *et al.* 1999). There is no comparable estimate for the value of Canadian timber losses due to invasive exotic pests. However, it is estimated that the area affected by both native and exotic forest pests totals about 400 000 ha per annum (CFS 1998). The annual harvested area is about 930 000 ha. Canadian timber volume losses due to forest insects and diseases are estimated at 61 million m^3 per annum versus an annual harvest of 170 million m^3 during the 1981-95 period (CFS 1998).[7] Allowing that this timber would otherwise have been commercially harvested, the annual financial loss to provincial stumpage, royalty and rent revenues would be about $720 million.

Gypsy Moth

Wallner (1996, 1997) suggested using the gypsy moth (*Lymantria dispar*) history as a template for estimating the economic consequences of forest pest invasions. A detailed examination of the North American history, impacts and control of this alien forest pest is provided in the case studies section below. The losses due to the gypsy moth invasion provide an order of magnitude of the possible consequences of an invasive pest establishment (Table 4). Timber losses reported are due to the European strain of the insect, since the Asian strain has not yet successfully established in North America. There have been a number of introductions but these have been controlled and eradicated. Preventing the establishment of the Asian gypsy moth is a considerable challenge due to the flying ability of the female.

The US Forest Service assessed the risk of an Asian gypsy moth introduction on logs imported from Russian Siberia (USDA 1991). However, the moth arrived in Pacific Northwest ports on Russian grain ships. The introduction resulted in US$ 14-20 million in eradication and monitoring costs (OTA 1993). Another overlooked pathway of Asian gypsy moth introduction was on US military equipment returned to North Carolina from Germany. Inspection and eradication of this introduction involved costs totaling US$ 30 million (Wallner 1997). It is interesting to note that the Asian gypsy moth was introduced into Germany from eastern Russia.

[6] Work by the British Columbia Ministry of Forests estimates $72 million in net benefits from efforts to control the mountain pine beetle (annual costs are $4.5 million). Average annual timber mortality and growth loss in British Columbia were estimated at 28 million m^3 for the 1988-92 period.

[7] Hall and Moody (1994) report that Canadian timber losses due to insects and diseases averaged about 100 million m^3 over 1982-87.

Table 4. Economic costs due to the gypsy moth (*Lymantria dispar*) invasion in the US and Canada

Country/state/ Province	Period	Area infested (mil. ha)	Timber losses (US$ million)	Control costs[a] (US$ million)	Source
European gypsy moth					
Pennsylvania	1981	> 6	>72	>9	Wallner (1996)
Pennsylvania	1969-88	–	219	–	Gottschalk (1990)
US (average annual)	1980-94			11[b]-30[c]	Pimentel *et al.* (1999) Wallner (1996)
US	1995			8[d]	Wallner (1996)
Canada[e]	1982-92	0.553[f]	–	–	Hall and Moody (1994), Hall 1994; Moody 1993a, b, 1990 Nealis and Erb (1993)
Asian gypsy moth					
Pacific Northwest	1992			25	Wallner (1996)
North and South Carolina	1994-95			9	Wallner (1996)

a. Control costs include research, eradication and suppression.
b,c. Estimates refer to average annual control costs. Wallner (1996) estimate is in 1995 dollars.
d. Total trapping costs were US$ 20 per trap (for both European and Asian gypsy moths).
e. Ontario and Quebec are where the gypsy moth is established in Canada.
f. Cumulative area infested.

It is important to note that the gypsy moth mainly slows timber growth and that tree mortality only occurs after defoliation over successive growing seasons. Rather than tree mortality, the major impacts of the gypsy moth are in lost growth, reduced recreation, aesthetic losses, human health (allergies) and nuisance terms. The costs of these effects are not included in the studies summarized in Table 4.

Dutch Elm Disease

The impacts of another exotic forest pest, Dutch elm disease, are relatively well documented.[8] Dutch elm disease is caused by the fungus *Ophiostoma ulmi* (also known as *Ceratocystis ulmi*) and was introduced into the US in 1930 from Europe. Its vector, the European elm bark beetle, rapidly spread the disease across the country. While most of the American elm trees died years ago, the presence of Dutch elm disease is still evident throughout forests in the eastern US. About 46 million elm trees out of 70 million in total have been killed since the introduction of the disease (Wallner 1996). The estimated value of US$ 430 per tree (USDA 1991) equates into a total loss of about US$ 20 billion (in 1991 dollars) just for the lost elms. Additional millions of dollars have been spent on removal of dead trees (US$ 215 per tree), replacement costs (US$ 40-100) and efforts to protect surviving elm trees. In 1945 Dutch elm disease was introduced to Quebec from the US. It has killed 600 000 elm trees in Quebec and in one year alone killed an estimated 80% of the 35 000 elm trees in Toronto (Hubbes 1999). The disease is now established in all Canadian provinces except Alberta and British Columbia.

The estimated impacts of Dutch elm disease are summarized in Table 5. Given the heavy urban presence of American elm, the loss of these shade trees along boulevards and in urban parks created considerable social costs on numerous communities and frustration with the obvious inability of government and scientific research to control or eradicate Dutch elm disease.

[8] The 'Dutch' connection relates to the Dutch scientists who identified the pathogenic agent.

Table 5. Impacts of the Dutch elm disease invasion in the US, Canada and England

Country/province	Period	Trees killed ('000s)	Timber losses (Billion)	Control costs[a] (Billion)	Source
US	1930-76	46 000	US$20.2	US$11.7-14.5	Wallner (1996)
Quebec	1945	600			Hubbes (1999)
Toronto	–	28			
Manitoba	1975-96	2.5 -5%[b]		C$0.01.5b	Westwood (1991)
Southern England	1960-80	17			Hubbes (1999)

a. Control costs include research, eradication, suppression and tree replacement.
b. Annually.

The American elm population in Canada is estimated at 700 000 with an estimated value in excess of $2.5 billion (Hubbes 1999; Westwood 1991). Hubbes (1999) also reports that rate of annual elm tree loss in Winnipeg due to Dutch Elm disease increased from 2.5% in 1975 to nearly 5% in 1996, despite all mitigation measures.

A new form of Dutch elm disease reached Southern England in the late 1960s. It was caused by a different type of fungus supposedly introduced to England on logs imported from Canada (Gibbs and Wainhouse 1986; Gibbs 1978; Wallner 1996). About 17 million of the region's 23 million elm trees were killed by mid-1980.

Pinewood Nematode

One example of a pest invasion which has directly affected the country of origin is the pinewood nematode (*Bursaphelenchus xylophilus*). The pinewood nematode (PWN), native to North America, has caused dramatic timber losses in Japan's red pine (*Pinus densiflora*) stands and given the species mix and age profile of Japanese forests, the timber losses due to PWN can be expected to increase considerably. By a complex and only partly understood mechanism, PWN causes pine wilt disease, which stresses and eventually kills the trees.

PWN was introduced into Japan on North American log imports in the early 1900s. Until 1984, PWN infested about 25% of Japan's total forest area of 25.2 million ha. Timber losses reached 2.4 million m^3 per year during the peaks of pine wilt disease spread. In the early 1990s annual timber losses still averaged about one million m^3 (McNamara and Smith 1993).

In 1984 PWN was found in wood shipments from North America to Europe. European countries responded with the introduction of various import restrictions. In 1988, the European and Mediterranean Plant Protection Organization designated the PWN and its vectors a high risk quarantine pest. This decision produced a non-tariff barrier to the importation of green lumber products from North America and resulted, at least in part, in significant reductions in softwood exports from Canada to the United Kingdom and other EU countries (Berghdal 1988). In 1999, Portugal listed a PWN establishment located near a tidewater port and has placed restrictions on the movement of wood products outside this region. It is believed that the PWN was introduced in shipments from China. Trade restrictions such as those arising from the PWN threat have led to international disputes under the ambit of the World Trade Organization/General Agreement on Tariffs and Trade (WTO/GATT) (McNamara and Smith 1993).

International trade of green or raw wood is considered a major pathway of exotic forest pest introductions, such as that of PWN, that can threaten the host country forest ecosystems. Several USDA risk analysis studies on US importation of green wood (USDA 1991, 1992, 1993, 1994, 1998a,b,c) have demonstrated that the risk of negative financial impact is of a considerable magnitude.

Impacts of Log Imports

In 1993, the Northwest Forest Plan (i.e., Option 9) was introduced by the Clinton Administration in the US Pacific Northwest in response to the mounting environmental challenge to the commercial logging of federal timber. This

Table 6. Potential timber losses from forest pests due to US importation of Russian logs, 1990-2040
(Source: USDA 1991)

Pest	Affected area (millions of ha)	Total economic costs (US$ millions 1990) Best Case	Worst Case
PWN[a]	10.8	33	1,670
Larch canker[b]	0.3	25	241
Annosus root disease[c]	3.9	84	344
Defoliators[d]	31.2	35,049	58,410
Spruce bark beetle[e]	3.3	201	1,500

a. Best case assumes mortality rate of 2 % and worst assumes of 100%.
b. Best case assumes low rate of infestation and no rehabilitation costs; Worst case assumes high rate of infestation and high rehabilitation costs.
c. Best case assumes mortality of 2.3 billion board feet per year and worst case assumes mortality of 8 billion board feet per year.
d. Best case assumes 15% net loss in growth per decade and worst case assumes 25%.
e. Best case assumes mortality of 25% of the spruce resource in the first 30 years and the worst case assumes the spruce resource is completely killed in first 7 years.

served, among other things, to greatly reduce the timber harvest on these contested lands. Indeed the timber volume harvested has been reduced by about 80%. One consequence of this dramatic reduction in timber supply has been a vigorous industrial interest in developing imports of both logs and chips. The US Forest Service has approved the importation of chemically treated radiata pine (*Pinus radiata*) chips from Chile and small volumes of Russian sawlogs on a test basis. The predominant industrial interest has been the importation of Russian sawlogs.

The importation of sawlogs was quickly seen as a source of exotic pest introduction and the USDA has undertaken to define the character of the exotic pest risk and to quantify the financial impacts from consequent timber losses. The cost of eradication of any resulting exotic introduction would be considerable. Table 6 summarizes estimates on the financial impacts to western US commercial timber stands over the period 1990-2040 resulting from timber pests arising from the importation of larch from Siberia and Russian Far East regions (USDA 1991). In addition to timber losses, costs include control costs due to eradication and suppression, foregone recreation and tourism, loss of national and international reputation, aesthetic and reductions in property values. The analysis was limited to estimating the impact on timber.

Environmental /Ecological Impact Evaluation

Insects and pathogens are a normal part of a forest ecosystem, even when their populations increase during outbreaks or remain high over a prolonged period. In those cases, insects and pathogens can become destructive to ecosystems. This generally happens when some ecological constraint on the pest population is removed. This removal can be the result of natural events or anthropogenic activity. The lack of any effective ecological counterbalance can afford a competitive advantage to an exotic over native species. Examples of exotics becoming major pests have proved that introductions of new organisms carry considerable ecological risk.

Exotic pests are more destructive than native species, even more so today than in the past (Liebhold *et al.* 1995; Haack and Byler 1993; Niemela and Mattson 1996). First, exotic insect pests operate in new ecological conditions where there are no natural enemies and no established defenses by the trees. In addition, forest ecosystem stresses associated with human activities often make modern forests more vulnerable to both native and exotic pests. However, successful invasions of undisturbed systems are also common. Among important stresses are human population growth, air pollution, changing climate and global warming, habitat modification and fragmntation of ecosystems due to land management. Finally, increasing rates of international travel and trade exacerbate the incidence of accidental or purposeful introductions of non-native organisms.

Ecosystems of low diversity have proven to be relatively more susceptible to the invasion by exotics. Exotic (and native) insects and diseases have often successfully attacked monoculture plantations. This is not peculiar to agricultural crops. Canada's boreal forests are considered susceptible to exotic pests because of their limited species diversity. Vulnerable ecosystems have a relatively simple ecological structure, limited intra-system competition, and soil and climatic conditions similar to the invasive exotic's native conditions. Radiata pine plantations, with their standard limited genetic diversity, are particularly vulnerable to exotic pest attacks (Bright 1998). In India, the *Cercosspora* needle blight, a prime pest in radiata pine plantations, has also infected the native pine species forests. Uruguay completely abandoned radiata pine plantations because of pests and the threat of exotic pathogens is a major challenge to the established softwood plantations in New Zealand and Chile (Hammond 1995).

The effects of invasive species to biodiversity include:

- suppression or replacement of native species by introduced species,
- potential local elimination of native species (e.g., chestnut blight virtually eliminated the American chestnut and a similar fate is proceeding for the elm), and the
- threat to rare and endangered species in direct and indirect ways.

The ecological impacts of potential pest introduction are difficult to assess because of the complexity of forest ecosystems and because potential ecological impacts vary with the introduced pest. However, general concepts can be applied (USDA 1991) based on:

- the adundance and distribution of the host in the ecosystem,
- the role of the host in the ecosystem, and
- the adaptability, aggressiveness and spread of potentially introduced pests.

If the risk of spread of the pest is high, then large-scale infestation and tree mortality are more likely to occur. Ecological impacts of large-scale infestations include short- and long-term impacts. Long-term impacts are more important from the ecological perspective and they depend on how quickly and completely the system recovers. Depletion of forests may influence changes in food and habitat for wildlife species, and forest fundamentals such as regional hydrology, forest fires regimes and nutrient cycles.

Social Impact Evaluation

In the technical and scientific literature dealing with bio-invasions, social impacts are usually held to be implicit or at best within economic analyses under a category of "other costs". Social impacts are often limited to inclusion in a note that additional costs of past or potential impacts have not been taken into account (USDA 1991, 1998a,b,c; Wallner 1996). In contrast, community stability and spiritual values of forests are favorite topics of the popular media and the emergence of costly and high profile introductions are creating pressure on governments to address the problem of exotic pests.

The social effects of bio-invasion identified in April 1999 at a Canadian Forest Service workshop titled *A Strategy on Exotic Forest Pests* included:

- losses of aesthetics and spiritual values,
- impacts on human health,
- public perception and support to forestry,
- international relations,
- credibility of federal, provincial and municipal governments,
- federal and provincial relations,
- forestry related jobs, and
- community stability and well-being.

Case Studies

Harvesting, fire and forest pest attacks are the major sources of natural disturbance in Canadian forests. The CFS provides reports on disturbances classified by the type and region affected. Data are compiled into annual reports including *The State of Canada's Forests* (CFS 1999c, 1998 and 1997). Forest depletion refers to timber losses due to mortality and unrealized growth. Forest depletion is measured in terms of volume and value of timber losses. Although considerable, the losses in terms of amenity, recreational, aesthetic and in conservation and biodiversity values are not included in the CFS forest depletion estimates. Table 7 illustrates the order of magnitude of depletion of Canada's forests. It is estimated that the annual timber depletion in Canada's forests over 1982-87 period was nearly 300 million m^3. This figure includes natural depletion (forest insects, diseases and fire) and human induced disturbance (harvesting).

The National Forestry Database Program (CCFM 1999) keeps track of data on the areas of Canada's forest affected by major forest insects and diseases. The CFS Forest Health Network compiles information on the defoliated areas and forest losses due to insects and diseases.

Measured in terms of area affected, the dominant insect pests in Canada's forests, with one exception, are primarily native species. These are the spruce budworm, jack pine budworm, hemlock looper, mountain pine beetle and forest tent caterpillar. The exotic exception, the European gypsy moth, has certainly proven to be a formidable pest. In 1991, the gypsy moth defoliated about 350 000 ha of Ontario hardwood and the speed of the infestation spread has been startling. Within about twenty years of its establishment in Canada, it became a widespread forest pest in eastern Canadian hardwood species, particularly oak and aspen (Figure 7).

Comprehensive data about the introduction and establishment of exotics to Canada is not currently available and it is unknown how many exotic species have entered. It is simply not feasible to track the almost daily introductions of exotic pests. A list of important forest insects and diseases introduced into Canada contains 36 entries (Montreal Process Liaison Office 1997). This listing along with the estimated year of introduction and the primary host is provided in the Appendix.

Despite many uncertainties about exotics, there are some common features. In an effort to illustrate the main features of introduction, establishment, spread and impacts, case studies of two significant domestic forest pests are provided in this report. The case studies are the European gypsy moth and native ambrosia beetle. A study of indigenous species does help predict the potential magnitude of the economic consequences of recent introductions of non-indigenous wood boring beetles to British Columbia.

Table 7. Annual depletion of Canada's forests, 1982-1987 (millions of m^3)

Losses from insects	51.6
Losses from diseases	51.2
Losses from fires	36.0
Harvest	160.0
Total depletion	298.8

Source: Hall and Moody, 1994

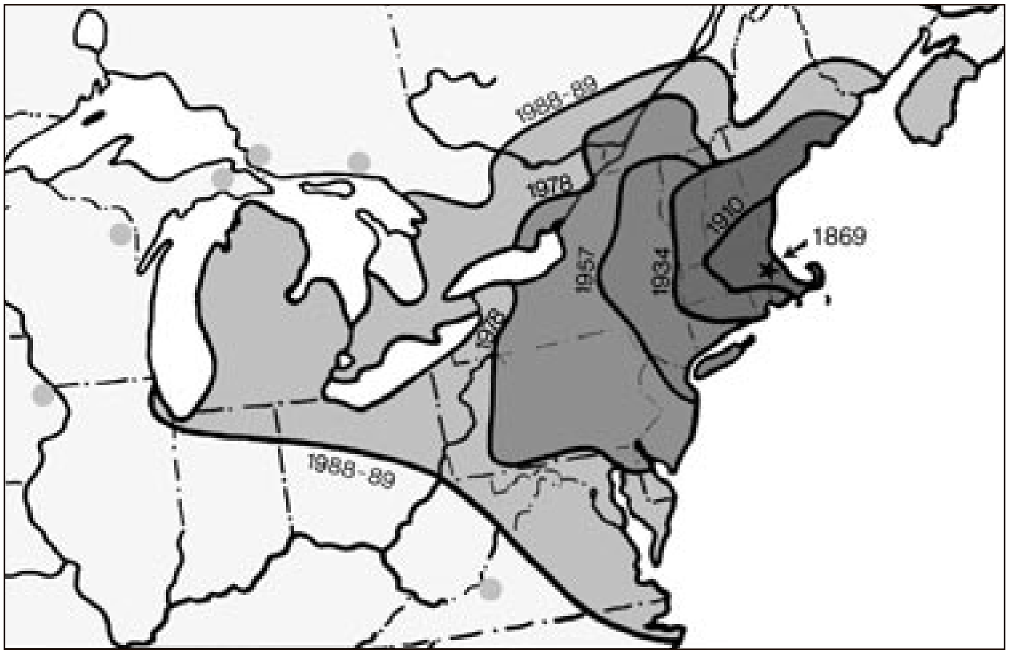

Figure 7. Establishment and spread of the gypsy moth in North America. *(Source: Nealis and Erb 1993)*

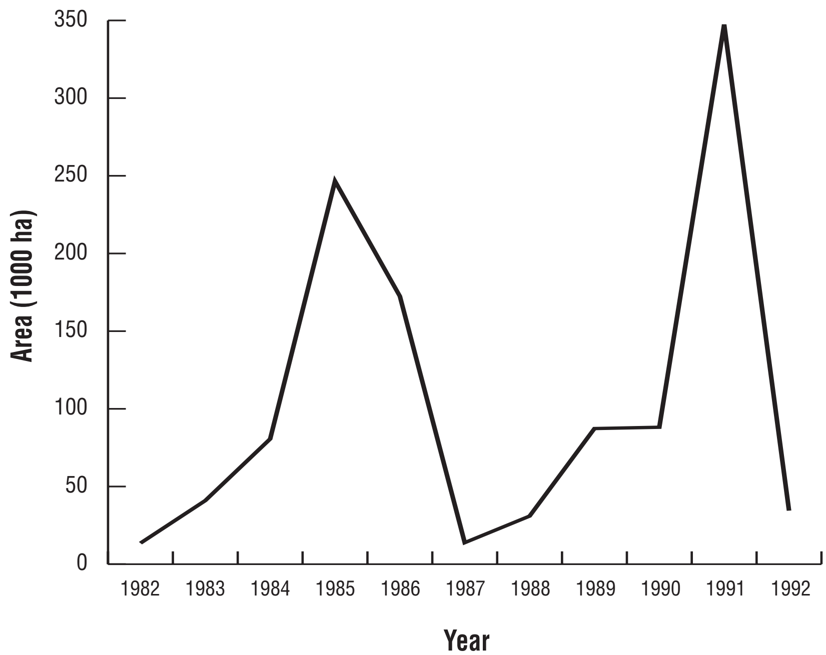

Figure 8. Area of defoliation in Ontario and Quebec, 1982-1992 (*Source: Hall and Moody 1994; Hall 1994; Moody 1993a, b; Hall 1992; Moody 1990*).

Gypsy Moth

The gypsy moth case study has become a denominator of every North American study on exotic pests. Some of the reasons why the gypsy moth has achieved this role are:

- international significance,
- wide range of ecological zones infested,
- large time span,
- comprehensive documentation, and
- variety of pathways of introduction.

Canadian sources focus on the gypsy moth situation in Ontario because this is the region where the most severe outbreaks have occurred but data have been collected for Quebec and sporadic infestations in the Maritimes and British Columbia.

The European gypsy moth was introduced from Europe to eastern North America in 1869. Introduced purposefully as a potential source of silk production, the moth accidentally escaped and has successfully established through most of the hardwood forests in eastern North America. There have also been isolated infestations in the western US and Canada and in the southern US. The gypsy moth prefers all types of oak, but many other hardwood species will be attacked as the number of caterpillars increases (Nealis and Erb 1993; Wallner 1996, 1997). The rapid spread and broad impacts were warning signs for Canada to begin monitoring for gypsy moth introductions from the US. The 100-year time span between the US escape and the first defoliation in Ontario is the product of decades of control efforts in the northeastern US and the relatively slow natural rate of spread for this particular insect. Since the Canadian introduction, the area of infestation has increased rapidly. The gypsy moth was established throughout Ontario by 1992. Figure 8 provides a summary of the area of defoliation in Ontario and Quebec caused by the gypsy moth.

Impacts of the Gypsy Moth
Nealis and Erb (1993) have provided a comprehensive and well-documented list of the various impacts of the gypsy moth (Table 8). However, there are few scientific publications which contain actual measurements and analyses of the impact of the gypsy moth. Much of the information in Nealis and Erb (1993) was collected from public information brochures and handbooks.

Table 8. Impacts of the gypsy moth infestation

Short-term impacts	Long-term impacts
Defoliation	*Economic*
Nuisance	losses due to reduced growth
allergic reactions	losses due to tree mortality
	impacts on domestic trade an domestic traffic
	Ecological
	species conversion
	deforestation
	wildlife habitat destruction
	degradation of riparian communities
	increased fire hazard
	loss of biodiversity

Source: Nealis and Erb 1993, USDA 1991, 1992

The Canadian Forest Service uses the area of defoliation and its severity and duration as a basis for estimating tree mortality and growth loss. Area data are used in Geographic Information System based methodology to estimate timber losses (Power 1991). A five-year report on forest depletion (Hall and Moody 1994) contains information on loss estimates for specific pests. For gypsy moth, total timber losses due to growth loss and mortality in Ontario for the 1982-87 period of were estimated at 325 000 m^3 (Gross *et al*. 1992).

Management

Management of the gypsy moth can be classified into short- and long-term measures (Table 9). Short-term measures are oriented toward an immediate reduction of impacts of established gypsy moth infestations. These measures address the issues of eradication (i.e., forced extinction of a pest [Liebhold 1995]) and suppression (limitation of the spread of a pest). Long-term control measures are intended to prevent introduction, establishment and spread of the gypsy moth into additional areas. The control options for both eradication and suppression are listed in Table 9.

Table 9. Control measures

Short-term	Long-term
Scrapping and destroying egg masses	Monitoring and inspection of travelers
Mass-trapping	Monitoring and inspection of commodities
Barriers	Silvicultural control methods
Insecticides	Biological control
Release of sterile life stages	Research
Biological control	Education
	Media support

Bark and wood-boring beetles in British Columbia

Economic Effects of Exotic Beetles

Recent introductions and establishment of exotic bark and wood-boring beetles in British Columbia warrant close attention. Table 10 provides a list of 19 species of bark and wood boring beetles known to have been introduced recently (post 1992) to western Canada. Six of these beetles are now established in British Columbia.

A collaborative research program between the CFS and the CFIA detected a series of introductions of exotic bark and wood-boring beetles into British Columbia since 1992. One of the known sources of entry for exotic wood boring beetles is through wood packaging material (both containers and support material) used in the shipment of heavy commodities. This includes items such as cable drums used to ship wires from China, packaging for granite shipped from Europe and South America, and green dunnage (Allen 1999).

Pests introduced in untreated shipping dunnage can find their way to forests near ports of entry or anywhere in the country where the containers are opened. Inter-modular shipping links tidewater container ports with land-locked destinations. A particularly disturbing fact is that one of the recently introduced species actually originates from the subtropics (Humble *et al*. 1999). The subtropical introduction is testimony to the unpredictable dimension of introduction pathways and pest establishment, which are inherent to global commerce.

Four species of exotic long-horned boring beetles and five species of bark and ambrosia beetles were intercepted in British Columbia between 1992 to 1994. An additional nine non-indigenous bark and wood-boring beetles were recorded between 1995 and 1999. Six of those species have already established in western forests (Humble personal communication). Humble *et al*. (Humble, L.A., Allen, E.A., Duncan, R.W., and Bell, J.D. 1999. Distribution and abundance of non-indigenous bark- and wood-boring beetles in British Columbia. Unpublished

Table 10. Bark and wood-boring beetles introduced or intercepted in Canada after 1992.

Bark or wood-boring beetles	Year of introduction / establishment
Long-horned beetles (Cerambycidae)	
Anoplophora glabripennis	1992
Anoplophora nobilis	1992
Arhopalus sp.	1994
Tetropium castaneum	1994
Bark and Ambrosia beetles (Scolytidae)	
Pityogenes chalcographus	1994
Pityogenes saalasi	1994
Hylurgus ligniperda	1994
Xyleborus affinis	1994
Cyrtogenius brevior	1994
Long-horned beetles (Cerambycidae)	
**Phymatodes testaceus*	1997
Trichoferus campestris	1997
Bark and Ambrosia beetles (Scolytidae)	
Euwallacea validus	1997
Cyrtogenius brevior	1997-98
Xylosandrus crassiusculus	1997
**Trypodendron domesticum*	1997-98
**Xyleborinus alni*	1995-98
**Xyleborus perforans*	1995-97
**Xylosandrus germanus*	1995-98
**Xyloterinus politus*	1997-98

* Denotes species established in Canada when discovered.

Source: Humble et al. 1999;
Humble, L. Canadian Forest Service, Victoria, personal communication;
Humble, L.A., Allen, E.A., Duncan, R.W., and Bell, J.D. 1999. Distribution and abundance of non-indigenous bark- and wood-boring beetles in British Columbia. Unpublished manuscript. Natural Resources Canada, Canadian Forest Service. Victoria, B.C.

manuscript. Natural Resources Canada, Canadian Forest Service. Victoria, B.C.) found that three of the newly introduced ambrosia beetles will attack both deciduous and coniferous hosts. The number of non-indigenous bark and ambrosia beetles known to occur in British Columbia has doubled since 1995 (Humble *et al*. 1999). Indeed, at some locations the exotic component comprises more than 97% of the total bark and ambrosia beetle fauna attacking dead and dying deciduous trees.

Economic Effects of a Native Ambrosia Beetle

Research on the potential impacts of recently introduced bark and wood-boring beetles has been initiated by the CFS. The potential effects and magnitude of new introductions is illustrated by examining the impacts of the native ambrosia beetle. The impact of two native species of ambrosia beetle (*Trypodendron lineatum* and *Gnathotrichus sulcatus*) on the economy of coastal British Columbia are well-documented (McLean 1985, 1992; Orbay et al.1994). These studies provided estimates of annual timber losses due to the beetles in British Columbia's coastal forest industry. [9]

It was estimated that on average 30% of the 18 million m^3 of wood traded through the Vancouver log market in 1980/81 had been attacked by ambrosia beetles (McLean 1985). After applying the specific beetle degrade parameters to the proportions of volumes damaged by beetles, an estimate of 1.38 million m^3 per year of the volume of infested wood was obtained. This equates to an aggregate loss to the forest industry in 1980/81 of about $64 million (in 1981 Dollars) at a degrade value of $46 per m^3 (McLean 1985).

A recent study found that 14% of the logs sampled in coastal British Columbia between October 1990 and September 1991 were infested (Orbay *et al.* 1994) It was estimated that 80% of attacks occurred in the forest during the spring flights of the beetles. The degrade losses in lumber caused by the ambrosia beetle infestations range from $8.17 per m^3 for gang hemlock logs to $77.40 per m^3 for high-grade hemlock logs. The estimate of degrade losses due to attacks of one species of ambrosia beetle (*Trypodendron lineatum*) to MacMillan Bloedel Ltd., a major coastal forest products company in British Columbia, was $11 million in 1991.[10] Because pests have different effects on timber quality, growth and mortality these estimates cannot be extrapolated for the forest industry. The impact measured in these studies was limited to log degrade due to beetle boring. In contrast, exotic wood-boring beetles known for tree mortality would produce greater timber and economic damage.

An additional potential economic impact of forest pests is the disruption in market access as importing jurisdictions move to reduce pest importation risk on green lumber or wood chips. Australia, for example, is considering the potential efficacy of restrictions on green lumber imports from Canada and other exporting countries in an effort to reduce exposure to the introduction of alien ambrosia beetles.

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[9] This analysis is specific to old-growth timber (i.e., mature trees that are of large diameter). The impact on second-growth timber is not known.

[10] In 1999 a US company, Weyerhaeuser Ltd., purchased MacMillan Bloedel Ltd.

Decision Making For Management of Exotic Pests

Risk and Uncertainty

The magnitude of the potential impacts of exotic pest introductions does suggest the need for systematic and careful decision making on how to manage for the control of exotic pests (Norton and Mumford 1993). Uncertainty is one of the critical factors affecting decisions with respect to exotic pest introductions and their impacts. According to Goodwin and Wright (1991), any decision usually contains the following elements.

- multiple objectives
- uncertainty in its broadest sense including randomness, imprecision, vagueness, lack of data, human error, uncertainty of introduction, establishment, spread and potential impacts of the exotic pest. Available data are imprecise due to different (and often non-existing) methods to measure and evaluate losses. On the other hand, there is an inherent uncertainty in risk perception among different decision makers and stakeholders,
- complex structure
- sequence of decisions to be made
- multiple stakeholders

The theory of decision-making usually distinguishes between two classes of incomplete information: “risk” and “uncertainty”. An event is considered to involve risk if all possible outcomes along with the probability of its occurrence are known. If any of these conditions is not satisfied, then an event is considered to involve uncertainty. This paper uses the term “uncertainty” in its broad meaning: including both risk and uncertainty. Uncertainty characterizes each stage of a bio-invasion, but its magnitude varies from stage to stage. The highest level of uncertainty accompanies introductions of non-native species, in terms of what can arrive, when and where.

Many researchers would agree that the exotic pest invasions and their impacts are characterized more by uncertainty than by risk. Nevertheless, risk analysis is the option of choice in the context of studying bio-invasions. One possible reason for this methodological selection is that the existing literature related to decision-making and economic analyses tends to employ risk rather than uncertainty (Perrings 1995).

In one of its earliest uses within decision-making methodology, the term risk was defined in a context with the level of certainty about the state of nature. This study adopts a definition of risk as a measure of probability and severity of harmful effects (Lowrance 1976; Haimes 1998). This definition addresses both the likelihood that something can go wrong and the severity of its consequences. The same concept of risk is accepted and used in the pest risk assessment studies by the CFIA (1999) and USDA (1991, 1992, 1998a) (Orr *et al*. 1993).

Risk analysis must be incorporated in a decision making process rather than performed as a separate analysis. The purpose of risk analysis is to identify all potential sources of risk, known as well as unknown, identify all potential impacts (including but not exclusive to those which previously occurred) and evaluate these impacts. Highlighting the risks and their impacts allows for development of policies to deal with the threat and measures to reduce or prevent losses.

Two groups of questions are apparent within a risk analysis process. One group, referred to as risk assessment, addresses events that can go wrong, their likelihood and consequences. Risk assessment is a set of well-defined activities that provide the decision-makers with an identification, quantification and evaluation of the risk associated with certain natural phenomena or man-made activities (Haimes 1998).

The second group, synthesized under the term risk management, deals with management alternatives to prevent or control consequences of risk. Risk management may be defined as searching for an optimal balance between uncertain benefits and uncertain losses (Haimes 1998). Risk management in the context of exotic pest introductions should promote measures to minimize the risk of introductions and establishment and their potential harmful impacts to the economy, environment and health, but at the same time protecting international and domestic flows of trade and people. This objective is consistent with a general purpose of environmental analysis seen as promoting sustainable management to balance benefits, risks and costs to "both people and environment" at present as well in future (National Research Council 1993). A summary of the questions posed in risk assessment and management are presented in Table 11.

There is an overlap between risk assessment and risk management, but a distinction can be made between these two aspects in order to assess and evaluate different steps of risk analysis in the context of exotic pest introductions.

The challenging portion of every risk analysis includes both quantification of environmental impacts and people's attitudes toward risk (perceptions of risk). Traditional decision analysis has widely accepted the decision making approach based on expected value of risk (Goodwin and Wright 1991). Expected value of adverse effects is calculated as the probability that a harmful impact occurs multiplied by the severity of that impact (Kim 1983). Hence, the expected value of risk refers to average risk. However, expected value of risk, when used as the sole criterion for risk assessment, can lead to erroneous conclusions.

Even traditional decision analysis emphasizes the importance of incorporating decision-maker attitudes toward risk into the process of selecting the course of action. People in general are not risk neutral. This becomes apparent when dealing with environmental threats of potentially disastrous consequences. Neither risk averse nor risk taking decision-makers would be willing to accept a decision alternative selected by a method based on expected value of risk (Haimes 1998). Recent risk assessment studies regarding importation of raw wood and wood products to the US (USDA 1991, 1992, 1993, 1994, 1998a,b,c) have taken a conservative approach to decision making, using maximum rather than average risk approach.

The value of pest risk analysis lies in the quality and comprehensiveness of the biological and ecological information on target pest species and their economic significance. However, obtaining necessary data is very expensive and time-consuming. The costs of recent USDA pest assessment studies regarding the import of raw wood into the United States ranged from $28 000 for a 1992 study of New Zealand wood to $500 000 for the 1991 study on imports from Siberia (USDA 1991, 1992). These costs do not include government agencies' staff salaries. However, given the estimated potential impacts of exotic transfers these study expenditures are prudent investments.

Table 11. Questions raised in risk analysis

Risk Assessment[a, b]	Risk Management[b]
What can go wrong?	What can be done?
What is the likelihood that it would go wrong?	What options are available? What are the trade-offs in terms of costs, benefits and risk?
What are the impacts and their consequences?	What are the impacts of current management decision?

Source: a) CFIA (1999), b) Haimes (1998), Orr et al. *(1993)*

Analysis of Exotic Pest Invasions

As indicated above, the spread of exotics is usually the point at which an invasion can be observed. For that reason, spread has drawn the major attention of professional foresters and scientists. Historically, measures have been developed and implemented to mitigate the negative effects of spread. When successful these measures have slowed the invasion spread and reduced negative economic, ecological and social impacts. With the continued increase in exotic introductions the human and financial resources available to mitigate the effects of exotics will be greatly challenged.

The ability to respond to exotic invasions is further challenged by increasing limitations on the response options available.[11] Chemical and biological control options are rapidly being eliminated due to increased costs of registration, improved information on efficacy, collateral damage to other organisms, and public acceptance.[12] Work continues on control agents, silviculture options, and genetic selection.[13] This increasing limitation in response options is occurring at the same time as the risk of exotic transmission is increasing due to world trade and travel trends, transportation speeds, inter-modal transportation, transportation vehicles, and efforts to increase urban green space. A necessary response to this combination of increased exposure to exotic pest invasions and reduced control/eradication options is to focus on preventing new introductions.

The most rational response option to bio-invasions is to move toward control or eradication at the source of the introduction. Exporters will be required to ensure that packaging and shipping materials are treated to control exotic transmission. These requirements will not eliminate the potential for transmission but will serve to greatly reduce the number of pest transmissions. Any reduction in pest introductions will permit a more effective allocation of scarce resources when transmission does occur. Multi-lateral development will minimize the deployment of non-tariff barriers and serve to create a financial equity among traders.

Measures against exotic pest invasions can be classified according to their relationship to the three stages of any invasion. Table 12 summarizes bio-invasion processes, the level of accompanied uncertainty, potential preventive and mitigation measures along with their level of success and costs. Although, these estimates are in qualitative terms, the use of such qualitative estimates has proven valuable in pest risk assessment (Orr *et al.* 1993; USDA 1998a).

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[11] The range of control options includes: baits and attractants; fumigants, repellants and barriers for use in physically constrained spaces; traps; poisons; biological agents; bounties and commercial exploitation; and mechanical removal. The latter includes tree harvesting.
[12] For example, under the Montreal Protocol, the use of methyl bromide as a pesticide must be phased out by 2005.
[13] The recent spate of strident public challenges to genetically modified organisms and direct action on various tree nursery stock signals a problematic future for the genetic selection and manipulation options (see Hogan and Wilson 2000).

Table 12. Classification of fighting measures by the invasion stages.

Stage in a bio-invasion	Level of uncertainty/risk	Measures against bio-invasion	Success	Costs
Introduction	Very high uncertainty	Prevention	(relatively) high	(relatively) low
Establishment	High uncertainty	Eradication	Moderate	moderate
Spread	High risk	Suppression, control	Low	High

Treaties and Conventions

A successful identification, impact estimation and response to the threat from exotic pests will require a multi-disciplinary approach and the involvement of many stakeholders. Modern international agreements have produced a variety of regulatory mechanisms in response to various environmental concerns. Since the first environmental treaty, signed in 1902, there have been about 175 environmental treaties. Bright (1998) provides a list of 23 global or regional agreements that explicitly refer to exotics. Unfortunately, these treaties have dealt with exotic invasion in a circumspect and limited manner.[14] As a consequence the international regulation of exotic species transmission is weak. The relevant international treaty is the 1951 International Plant Protection Convention (IPPC). This treaty was intended to serve as a phytosanitary mechanism for protecting agriculture from pests and is aimed at quarantine pests, a very narrow class of alien invasive species. Amendments were made in 1997 to make the IPPC consistent with the World Trade Organization (WTO) in terms of phytosanitary standards. The IPPC provides a framework for international cooperation on agricultural pest control; standardizes terminology and methodologies; establishes quarantine dictates and practices; and provides a mechanism for dispute resolution. The wide disparity in national commitment to IPPC delivery and the availability of implementation funds have combined to limit the effectiveness of the treaty in reducing potential pests in shipments. A more fundamental shortcoming to the IPPC as a comprehensive control vehicle is the explicit focus on commercial plants. There is no similar international effort to protect non-commercial indigenous plants nor is there any comparable fauna convention.

A treaty which has been noted as a potential model to improved international control of the transmission of exotics is the 1973 Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). This treaty focuses on the international movement of endangered plants and animals. CITES has been successful in saving species from extinction but there are a number of design features which detract from it as model for regulation of the transmission of exotics. For example, CITES excludes non-commercial pathways, includes an “opt-out” provision, includes abundant opportunity for strategic behavior in exporting countries, and lacks effective enforcement provisions. One additional fundamental limitation is that CITES explicitly addresses identified species. However, one of the characteristics apparent from an examination of identified bio-invasions is the difficulty in predicting which exotics will successfully relocate and become pest species. Despite these and other limitations, effective regulation of exotic invasions will require international commitment, cooperation and legally binding vehicles intended to prevent the transmission of various species among trading partners (and more importantly across ecological zones).

In addition to the various international treaties, many with legally binding agreements, there are other international legal vehicles that attempt to regulate the movement of organisms around the globe. Some of these vehicles include codes regulating fishery, forestry and agricultural sectors and other industries. Dealing with exotics will require preventative measures from the international to local levels. Public education and information of potential impacts of deliberate or accidental introductions are essential. This will include electronic communication. For example, the rising numbers of web sites devoted to exotics will contribute to more effective international efforts against exotics.

Information Resources

Information on exotics is scattered in technical newsletters and publications, in professional discussion groups, and among regulators. This is inefficient and inhibits a more timely dispersal of information and response to the issue of exotics. There is a need to create a comprehensive information base on exotics which is regularly updated and readily accessible. Several government and academic institutions have already developed well designed, but limited electronic databases (NBII 1999, CERES 1999). One regional example is the Exotic Forest Pest Information System for North America developed by the North American Forestry Commission (NAFC 1998).[15]

[14] Multilateral treaties with potential to affect transmission of exotics are the International Plant Protection Convention, The Convention on Biological Diversity and The Convention on the Law of the Sea. The “Law of the Sea” has not taken effect because the required minimum number of countries has not ratified the treaty. The Convention on Biological Diversity has only vague provisions on this issue.

[15] A second example is the effort of University of British Columbia students to maintain a website on forest pests, including a section dealing with exotics (UBC 1999).

Conclusions

Canada's economic performance is highly dependent on international trade and the largest source of net export earnings is forest products. This trade dependence carries with it the risk of exotic bio-invasion and the impacts of such invasions are especially threatening because of the abundant forestlands and the commercial contribution of these forests. The non-commercial contributions of domestic forest ecosystems, which are considerable, are also threatened by exotic bio-invasions. Many exotic organisms are transported with raw wood and wood products, including shipping and packaging material. These organisms can survive in transit, they have the potential to establish with a suitable host near ports of entry and to subsequently spread. Spread of exotic forest pests beyond the infested area can produce severe adverse economic, ecological and social consequences to Canadian forest resources. Such spread will also threaten access to international markets as trading partners seek to reduce their exposure to transmission of the exotics.

The available estimates of the impacts of exotic invasions are limited, both in scope and methodology. However, the research estimates that have been completed do provide a reasonable illustration of the potential magnitude of invasive exotic pest impacts. An example in terms of ecological impacts is the threat to native species due to invasive exotics. The Canadian Committee on the Status of Endangered Wildlife estimates that 25% of endangered species and 31% of threatened species in Canada are in some way at risk because of exotic species. US timber losses due to exotic pests are estimated at US$ 4 billion annually (Pimentel *et al*. 1999). Annual Canadian timber losses to forest pests are estimated at 61 million m^3 or about one-third of the annual commercial harvest (CFS 1999c, 1998 and 1997). An equivalent reduction in the timber harvest results in reduced government timber stumpage, royalties and rents estimated at $720 million per annum. The social costs of exotic pest invasions include increased public frustration with the limited ability of government and science to respond with acceptable control measures, aesthetic and spiritual losses, impacts on human health, and disruptions in trade flows.

The available information suggests that the potential for exotic introduction and consequent spread will continue to increase as trade volume and the list of trading partners increases. It is expected that the rate of exotic invasion will be further augmented by the expansion of emerging industries such as aquaculture. Climate change is expected to reinforce the positive trend in exotic invasion (OTA 1993). It is also expected that a number of the invasive exotics will prove to be pests.

Risk analysis profiles similar to those for epidemics of human diseases, nuclear catastrophes and various environmental threats need to be developed for those pests with the greatest potential risk to North American forests. In addition, before suggesting and applying mitigation procedures, standard procedures for estimating economic impacts need to be developed. Improved detection methods and effective deployment of these methods are necessary components in a comprehensive program to reduce the risk of and impact from invasive exotic pests.

A multilateral commitment to reduce the rate of transfer at source is a critical leading ingredient to any efficient control regimen. This will also require a financial commitment to communicate and train emerging trading nations on how to control for point source introduction in order to reduce the potential for pest transmission.

Finally, the institutional setting for domestic control of exotic pests needs to be objectively assessed to ensure that national programs are effectively positioned to complement the natural barriers (e.g., geographical scale and biological complexity) that exist within Canada to the spread of exotic pests.

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Appendix

Table A1. Important forest insects introduced into Canada

Insect	Year of introduction	Primary host
Chestnut blight (*Cryphonectria parasitica*)	post-1904	American chestnut
Dothichiza canker (*Cryptodiaporthe populea*)	pre-1900	poplar
Larch sawfly (*Pristiphora erichsonii*)	1882	larch
Browntail moth (*Euproctis chrysorrhea*)	1902	deciduous
Poplar sawfly (*Trichiocampus viminalis*)	1904	poplar, trembling aspen
Larch casebearer (*Coleophora laricella*)	1905	larch
Late birch leaf edgeminer (*Heterarthus nemoratus*)	1905	birch
Balsam woolly adelgid *(Bedelges piceae)*	1908	balsam fir, grand fir, subalpine fir, Pacific silver fir
White pine blister rust (*Cronartium ribicola*)	1910	white pine
Satin moth (*Leucoma salicis*)	1920	poplar
Winter moth (*Operophtera brumata*)	1920s	oak, maple, willow
European spruce sawfly (*Glipinia hercyniae*)	1922	spruce
Gypsy moth (*Lymantria dispar)*	1924	oak, birch, larch, linden, willow, Manitoba maple, speckled alder
European pine shot moth (*Rhyacionia buoliana*)	1925	red pine, scots pine, jack pine
Willow blight (*Venturia saliciperda*) ca	1925	willow
Mountain-ash sawfly (*Pristiphora geniculata*)	1926	mountain-ash
Birch leafminer (*Fenusa pusilla*)	1929	birch
Introduced pine sawfly (*Diprion similis*)	1931	pine
Birch casebearer (*Coleophora serratella*)	1933	birch, alder, elm
Spruce bud moth (*Zeiraphera canadensis*)	1938	spruce
European pine sawfly (*Neodiprion sertifer)*	1939	scots pine, red pine
European spruce needleminer (*Epinotia nanana*)	1940	Norway spruce, white spruce
Elm leaf beetle (*Pyrrhalta luteola*)	1945	elm
Smaller European elm bark beetle (*Scolytus multistriatus*)	1946	elm
Ambermarked birch leafminer (*Profenusa thomsoni*)	1948	birch
Apple ermine moth (*Yponomeuta malinella*)	1957	apple
European pine needle midge (*Contarinia baeri*)	1964	Scots pine, red pine
Early birch leaf edgeminer (*Messa nana*)	1967	birch
Pear thrips (*Taeniothrips inconsequens*)	1989	sugar maple, red maple
Pine shoot beetle (*Tomicus piniperda*)	1993	pine, spruce

Source: Montreal Process Liaison Office (1997); CFS (1999d).

Table A2. Important forest diseases introduced into Canada

Disease	Year of introduction	Primary host
Dothichiza canker (*Cryptodiaporthe populea*)	pre-1900	poplar
Chestnut blight (*Cryphonectria parasitica*)	post-1904	American chestnut
White pine blister rust (*Cronartium ribicola*)	1910	white pine
Willow blight (*Venturia saliciperda*)	ca 1925	willow
Dutch elm disease (*Ophistoma ulmi*)	1944	elm
Scleroderris canker (*Gremmeniella abietina*)	1978	pine
European larch canker (*Lachnellula willkommii*)	1980	larch
Beech bark disease (*Nectria coccinea var. faginata Lohm.*)	1980	American beech
Beech scale (*Cryptococcus fagisuga*)	1980	American beech
Butternut canker (*Sirococcus clavigignenti juglandacearum*)	1991	butternut

Source: Montreal Process Liaison Office (1997); CFS (1999d).