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Climate change and forest diseases: using today's knowledge to address future challenges

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Abstract

The health of the earth's forests and urban green spaces is increasingly challenged by the outcomes of human activities, including global climate change. As climate changes, the role and impact of diseases on trees in both forest ecosystems and in urban settings will also change. Knowledge of relationships between climate variables and diseases affecting forest and urban trees is reviewed, with specific emphasis on those affecting foliage, shoots, and stems. Evidence that forest diseases are already responding to the earth's changing climate is examined (e.g., Dothistroma needle blight in northern British Columbia) as are predicted scenarios for future changes in impact on forests by other tree diseases. Outbreaks of tree diseases caused by native and alien pathogens are predicted to become more frequent and intense – this and other general predictions about the effects of climate change on forest and tree diseases are discussed. Despite the uncertainty that accompanies such predictions it is imperative that researchers, forest and urban tree managers, and policy makers work together to develop and implement management strategies that enhance the resilience of the worlds' forests and urbanized trees. Strategies discussed include monitoring, forecasting, planning, and mitigation.

Key words: tree diseases; forest pathogens; forest health; urban forests; plant disease management.

Resumen

Cambio climático y enfermedades forestales: uso de los conocimientos actuales para hacer frente a los retos del futuro

La salud de los bosques y los espacios verdes urbanos está cada vez más cuestionada por los resultados de las actividades humanas, incluyendo el cambio climático global. Así como el clima cambia, también cambiarán el papel y el impacto de las enfermedades en los árboles en los ecosistemas forestales y en las zonas urbanas. En este artículo se revisa el conocimiento de las relaciones entre las variables climáticas y las enfermedades que afectan a los árboles forestales y urbanos, con especial hincapié en lo que afecta al follaje, los brotes y los troncos. Se examina la evidencia de que las enfermedades forestales ya están respondiendo al cambio climático (por ejemplo, el tizón de la hoja de Dothistroma en el norte de la Columbia Británica), como prevén escenarios de futuros cambios en el impacto sobre los bosques por otras enfermedades de los árboles. Los brotes de enfermedades causadas por patógenos de árboles nativos y exótico se prevé que sean cada vez más frecuentes e intensos – se discuten esta y otras predicciones generales sobre los efectos del cambio climático sobre los bosques y las enfermedades de los árboles. A pesar de la incertidumbre que acompaña a tales predicciones es imperativo que los investigadores y los responsables de la gestión de los bosques y árboles urbanos cooperen para desarrollar e implementar estrategias de manejo que mejoran la capacidad de recuperación de los bosques y los árboles urbanos. Las estrategias analizadas incluyen el monitoreo, la previsión, la planificación y la mitigación.

Palabras clave: enfermedades de los árboles; patógenos forestales; sanidad forestal; bosques urbanos; gestión de enfermedades vegetales.

Introduction

The health and extent of the earth's forested land base is increasingly challenged by the outcomes of human activities, including global climate change. Boreal forests, occupying about 10% of the earth's land cover, are expected to experience some of the most extreme climate change-induced effects while the areas

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of temperate and tropical forests may actually expand (Krankina *et al.,* 1997). Although the beneficial effects of increased atmospheric CO_2 concentrations on tree productivity through enhanced photosynthesis will be realized in some locations, elsewhere they are likely to be offset by the negative effects of temperature-induced water stress on trees and increased incidence and interactions between biotic disturbances such as pathogens and insects and abiotic agents such as fire (McCullough *et al.,* 1998; Lewis and Lindgren, 2000; Parker *et al.,* 2006; Tubby and Webber, 2010).

The benefits that urban forests and treed greenspaces provide to community well-being are also at risk under climate change (Tubby and Webber, 2010). These 'urban ecosystems' (Bolund and Hunhammar, 1999), which often include non-native 'plants for planting', may act as 'sentinel plantings' and be some of the first settings where both climate change effects and new, native and/or introduced pathogens are seen (Tubby and Webber, 2010).

Although this is often not recognized, the ecological importance and economic impact of native tree diseases in forests and urban settings is significant (Castello *et al.,* 1995; McCarthy, 2001; Brandt *et al.,* 2003; Cruickshank *et al.,* 2011). These diseases play fundamental roles in shaping forest structure and composition and can have a profound effect on the ability of forests to provide ecosystem services such as carbon sequestration. However, where their natural patterns of disturbance are altered by human activities such as monoculture timber production or fire exclusion, native tree pathogens may grow and spread unrestricted by coevolved limits to their population growth, conflicting with human-desired outcomes with enormous negative economic consequences (Singh, 1993). Non-native tree pathogens have even greater negative impacts, which are often very difficult to stop or even mitigate.

The purpose of this brief review paper is to improve understanding and management of diseases impacting forest and urban trees under a changing climate. Information on climate factors affecting several forest and tree foliage, shoot, and stem diseases is summarized along with predictions about how these relationships might change or are already changing. Several strategies for the imperative of managing forest and urban trees and their health under a changing climate are discussed.

There are several recent reviews from a few different perspectives on the topic of 'climate change and forest and tree diseases and/or pests' (e.g., Ayres and Lombardero, 2000; Boland *et al.,* 2004; Desprez-Loustau *et al.,* 2006; Sturrock, 2007; La Porta *et al*., 2008; Moore and Allard, 2008; Dukes *et al.,* 2009; Kliejunas *et al.,* 2009; Tubby and Webber, 2010; Sturrock *et al.,* 2011). These review papers make many common predictions about what to expect from hosts and pathogens and their interactions under future climate changes and the uncertainties associated with these predictions; all emphasize the importance of changes in interactions between biotic diseases and abiotic stressors (e.g., temperature and moisture), as these may represent the most substantial drivers of increased disease outbreaks.

Today's knowledge

At a basic level, healthy forests can perhaps be defined as those comprised of trees that are not limited by the availability of water or nutrients (e.g., nitrogen, phosphorus, sulphur, micronutrients), light or suitable temperatures, and which occur and interact with a complement of other biotic and abiotic factors in a dynamic, sustainable manner. Forest pathogens, which have similar basic requirements, regularly interact with trees and cause disease when their occurrence coincides with the presence of a susceptible host and a favourable environment - a relationship often visualized as the 'disease triangle' (Agrios, 2005). Since the 19th century, forest management practices, the introduction of several invasive species, and other factors have disrupted the natural equilibrium of many tree host-pathogen interactions; climate change will redefine the shape of the disease triangle and the worlds' forests even further.

Using today's knowledge to predict what might happen under climate change

It is probably safe to say that there is a high level of uncertainty about how to profile fungal tree pathogens into a 'climate-changed future' because 1) generally less is known about their occurrence, incidence, and impact compared with other disturbance agents such as fire and insects and 2) many have complicated life cycles (e.g., rusts with four types of spores), exhibit pleomorphy (Tubby and Webber, 2010), or little is known about their life history and epidemiology. Despite this uncertainty it is necessary to assess the likelihood of possible outcomes for tree diseases under climate change (Dukes *et al.,* 2009). In general, it appears that canker/dieback pathogens of trees are likely to be favoured in areas where host stress is increased, especially by drought; the incidence and impact of foliar pathogens will be enhanced in areas that become both warmer and wetter (Sturrock *et al.,* 2011). Researchers and modellers are working together to prepare such assessments, starting with identification of the environmental variables most influential on pathogen and host interactions. Such information is summarized here (Table 1) for several foliage, shoot, stem and root diseases on their 'present-day status and predicted future status under climate change', including: Dothistroma needle blight (*Dothistroma septosporum* (Dorog.) Morelet and *D. pini* (Hulbary)), Cytospora canker of alder (*Valsa melanodiscus* G.H. Otth), Pine wilt disease (*Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle), Chestnut blight (*Cryphonectria parasitica* (Murr.) Barr.), Armillaria root rot (*Armillaria ostoyae* (Romagnesi) Herink), Phytophthora root rot (*Phytophthora cinnamomi* Rands), and sudden aspen death.

Managing forest diseases under climate change

Tree mortality, whether it is caused by climate alone, a single pathogen, or a whole suite of disturbance agents, must be expected and planned for now and in the future. This seems a straightforward task but in reality is a significant challenge because of the complexities around first understanding and then predicting changes to biological systems and how and why society should respond to these changes (Stenlid *et al.,* 2011). Also, many of the world's forests will have to adapt to climate change without the aid of humans (Spittlehouse 2009) and the care of urban trees may take second place to other priorities in cities, towns and villages. Despite these realities, trees can be managed to mitigate the undesirable effects of projected increases in their mortality that will be driven by biotic and abiotic phenomena (Sturrock *et al.,* 2011).

Forest managers, urban planners and local to regional authorities must think proactively and embrace a modified suite of forest management approaches because current management strategies will not protect forest values under a changing climate (Moore and Allard, 2011; Sturrock *et al.,* 2011). The best management approaches for tree diseases under a changing climate will be those that enhance the diversity of tree species in both urban plantings and in forested settings. This could include planting and/or regenerating with mixes of both deciduous and coniferous tree species: the phenotypic plasticity of conifers means that they are generally better adapted to drought than broadleaved species (Rohde and Junttila, 2008) while deciduous trees (Brisson and Levrault, 2010) are thought to generally return more water to the environment than do conifers (Hasselquist *et al.,* 2010). Clearly, decisions about the kinds and numbers of trees to be deployed on any landscape should be tailored to the location and its predicted future condition.

Monitoring

The forest sector and agencies responsible for the health of urban greenspaces need effective monitoring and detection protocols and tools to allow even the possibility for quick action in the face of changing or increasing pathogen impact (Moore and Allard, 2008). Systematic surveys of overall tree health should be conducted regularly by experienced people. Urban trees and areas of 'plants for planting' should be given special attention because of their 'ability' to act as early warnings or sentinels to changing pathogen conditions and their high potential to 'receive' invasive species. Monitoring activities should be coordinated across all levels of jurisdictional boundaries and results communicated to experts, policy makers, and the public in language they each understand. Such coordination is essential for the detection of new diseases or epidemics, which are expected to increase as the earth warms and global trade intensifies. In many instances 'news' about the importance of existing or new tree diseases may receive more supportive responses from society if they are described in quantifiable economic terms (Stenlid *et al.,* 2011).

Forecasting

Models can be good predictive tools and development of those that integrate the best available information about disturbance, vegetation, and climate dynamics will help to reduce the often significant uncertainty around their forecasts. There are an increasing number of models available to project future distribution of forest pathogens using both climate variables and retrospective data. For example, CLIMEX, which was developed to predict the potential geographical distribution of weed species, at least initially, has been used to look at the potential distribution of tree pathogens such as *Phytophthora ramorum* Werres, De Cock & Man in`t Veld (Venette and Cohen, 2006).

Table 1. Selected tree diseases: a summary of present-day status and predicted changes in future impact on trees due to climate change

Disease	Present-day status &/or factors affecting disease	Predicted future impact by disease	References
Dothistroma needle blight ~ *Dothistroma septosporum* & *D. pini*	Native to temperate forests of North America but only since late 1990s has had significant impact there on *P. contorta* var. *latifolia* and also in Great Britain and France on mostly *P. nigra* ssp. *laricio*; prior to that time was especially damaging to *P. radiata* plantations in S. hemisphere; Affects over 80 *Pinus* species worldwide plus *Pseudotsuga menziesii*, *Larix decidua*, & five *Picea* spp.; Damage from defoliation usually limited to reduced growth but effect increases and mortality may occur with crown infection and/or if infection occurs over successive years; As with most needle pathogens, the life cycle of *D. septosporum* is very sensitive to temperature and moisture conditions – temperatures between 15 and 20 °C during extended periods of moisture are optimal for *D. septosporum* infection.	In general, damage from Dothistroma needle blight is expected to continue or increase wherever it currently occurs and where springs &/or summers become warmer and moister and suitable host species are present. Disease intensity may decrease if summer rainfall decreases.	Bradshaw, 2004; Woods *et al.,* 2005; La Porta *et al.,* 2008; Watt *et al.,* 2009; Woods, 2011
Cytospora canker ~ *Valsa melanodiscus*	Has caused dieback and mortality to *Alnus tenuifolia* since late 1980s in Colorado and since about 2002 in Alaska; also damaging alders in British Columbia, northern New Mexico, & southern Wyoming; Cankers, which may girdle tree branches or stems, are more successful if alder hosts are suffering from temperature-induced drought stress (i.e., temperatures high, humidity low).	Projected increases in temperature where the disease currently occurs will likely cause it to continue and increase in severity.	Trummer, 2006; Worrall, 2009; Worrall *et al.,* 2010a
Pine wilt disease ~ *Bursaphelenchus xylophilus*	Caused by pine wilt nematode (PWN), vectored by *Monochamus* beetles, disease originated in North America, now also found in European locations (e.g., Portugal, Spain), and East Asia (e.g., Japan, China, Korea); Disease rare if mean July temperature < 20 °C, even if nematode present; high summer temperatures and low precipitation accelerate tree damage by enhancing vector activity, nematode reproduction and stress of infected trees.	Under elevated summer temperatures and seasonal moisture stress, PWN has potential to cause increased and more severe damage where currently occurs and to spread and cause damage to other parts of Europe and Asia.	Rutherford and Webster, 1987; Enda, 1989; Mota *et al*., 1999; Kiritani and Moromoto, 2004; Pérez *et al*., 2008; Abelleira *et al*., 2011
Chestnut blight ~ *Cryphonectria parasitica*	Introduced to North America from Asia in late 1800s; likely spread from USA to Europe in 1920s; devastated *Castanea* spp. trees in both regions; Hypovirulent strains that arose and infected virulent strains in Europe have reduced epidemic but this has not occurred in North America; Both strains have optimum growth range of 27-32 °C.	Warmer temperatures in Europe may enhance 1) exchange of dsRNA (cause of hypovirulence in this fungus) and 2) activity of chestnut endophytes antagonistic to *C. parasitica* and therefore may contribute to decrease in disease. Epidemic of chestnut blight expected to continue in North America to extent that suitable host is available and temperatures not lethal to *C. parasitica*.	See La Porta *et al.,* 2008

Table 1 (cont.). Selected tree diseases: a summary of present-day status and predicted changes in future impact on trees due to climate change

Disease	Present-day status &/or factors affecting disease	Predicted future impact by disease	References
Armillaria root disease ~ *Armillaria ostoyae*	Armillaria species cause root and butt rot in forests worldwide; *A. ostoyae* is a primary pathogen in many parts of the Northern hemisphere including western North America and Europe; Disease can cause significant mortality and growth reduction in affected stands; infected trees more susceptible to bark beetle attack; Factors such as drought, extreme temperatures, soil compaction etc. reduce host resistance to *A. ostoyae* infection; aboveground symptoms of infection are more evident in dry regions than in moist, wet regions.	Incidence of root disease and butt rot caused by *A. ostoyae* is likely to increase as temperatures increase and precipitation decreases, resulting in increased direct and indirect tree mortality and larger impacts on tree growth.	Kile *et al*., 1991; Cruickshank *et al*., 1997; Goheen and Otrosina, 1998; Morrison *et al*., 2000; La Porta *et al.,* 2008; Dukes *et al*., 2009; Kliejunas, 2011
Phytophthora root rot ~ *Phytophthora cinnamomi*	One of the most destructive species of *Phytophthora* affecting woody plants; occurs in most temperate and subtropical regions of the world; Infection by *P. cinnamomi* results in root rot and cankering and often mortality; Droughts and floods generally considered triggers of *P. cinnamomi* epidemics with temperature, moisture and pH all affecting pathogen growth and reproduction.	Increased incidence and/or range expansion of *P. cinnamomi* and other *Phytophthora* spp. causing root rots is expected in temperate world forests where seasonal temperatures and precipitation increase whereas a reduction is predicted across the tropics and subtropics.	Brasier and Scott, 1994; Jung, 2009; Sturrock *et al*., 2011.
Sudden aspen death ~ abiotic and/or biotic agents	Disease damage first noted starting late 1990s in parts of USA (Utah then Arizona, Colorado, Wyoming) and Canada (Alberta, Saskatchewan, Ontario); is characterized by rapid, synchronous branch dieback and stem mortality of trembling aspen. Disease associated with several factors, including drought and secondary pathogens and insects.	Incidence and impact of this kind of 'multi-factor' tree death is predicted to increase in all world forests.	Worrall *et al.,* 2008, 2010b; Hogg *et al.,* 2004, 2008

Other models designed to predict future distributions for tree pathogens include one for pine wilt disease (Evans, 2007), one for Dothistroma needle blight (Desprez-Loustau *et al.,* 2007), and one for *Diplodia* shoot blight (Fabre *et al.,* 2011), all in Europe, and one for Swiss needle cast in the Pacific Northwest of the USA (Manter *et al.,* 2005). Efforts are underway to improve modelling of climate change and forest diseases and this should include their ongoing evaluation and adjustment.

Planning

As climate changes so too will the effects of tree diseases and other disturbance agents on forest and urban tree ecosystems and society must plan for these changes. Forest health programs already in place must be maintained and funded. Policies and legislation pertinent to all aspects of tree health should be reviewed to ensure that problems can be quickly responded to (Sturrock *et al.,* 2011). Despite the existence of global plant health legislation and standards for the movement of a wide range of plants and forest products around the world, many professionals feel that gaps and weaknesses in enforcing the legislation may result in major biosecurity problems (Brasier, 2008). Clearly, this issue must be addressed. Risk assessments and related rating systems are also valuable planning tools and coordination and sharing of these systems would likely be very beneficial to managing disease problems as they emerge.

Mitigation

The establishment and maintenance of a diversity of tree species in forests and urban plantings can help them maintain resilience to mortality and the other adverse effects that may be brought on by diseases and climate change. Other effective mitigation strategies include tree breeding programs that promote genetic diversity, disease resistance and tolerance to environmental stresses (Sturrock *et al.,* 2011). Also proposed is the practice of assisted migration (AM), where humans deliberately move tree species and seed sources (populations). Assisted migration is envisioned to be practiced at three increasingly aggressive and 'riskier' scales: the first, *assisted population migration*, involves the translocation of genotypes within their existing range, the second, *assisted range expansion*, is translocation just beyond species' range limits, and the third, *assisted long-distance migration*, involves translocation over long distances (Winder *et al*., 2011). Forest managers should use AM "within a framework that allows for flexibility, uses best available science and predictive tools, considers risk and uncertainty, and evaluates and monitors results to ensure that unintended consequences are minimal" (Leech *et al*., 2011).

Conclusions

Outbreaks of diseases caused by native and alien tree pathogens are predicted to become more frequent and intense as international trade increases and as abiotic stressors and drought are amplified under climate change. These outbreaks will drive change in forests and urban greenspaces as will the convergence of human needs for key goods from forests such as food, fuel, and fibre and for essential ecosystem services (Sampson *et al.*, 2005). Activities under the key strategies of monitoring, forecasting, planning, and mitigation must be implemented to deal with these emerging problems.

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