Biol Invasions (2017) 19:3317–3332
DOI 10.1007/s10530-017-1503-4

FOREST INVASIONS

The role of the social sciences and economics in understanding and informing tree biosecurity policy and planning: a global summary and synthesis

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Received: 5 October 2016 / Accepted: 7 July 2017 / Published online: 12 July 2017

Abstract Increased global biosecurity threats to trees, woods and forests have been strongly linked to the upsurge in worldwide trade and the expansion of tourism. A whole range of social, economic and political actors are implicated and affected by the movement of pests and diseases along these international pathways. A number of factors affect the actions of stakeholders, and wider public, including their values and motivations, how risks are perceived and acted upon, their ability to act, as well as the existing regulatory and economic environment. Understanding these factors is key to any future attempts to improve biosecurity policy and practice, and we present available evidence on six key dimension: (1) the role of different stakeholders and the broader public within tree health; (2) levels of knowledge and awareness of tree pests and diseases amongst the variety of end-user 'stakeholder' groups, and influences on their attitudes and practices; (3) social acceptability of management approaches; (4) the impact of formal and informal governance arrangements; (5) risk communication; (6) economic analyses on the impact of tree pests. We conclude by identifying evidence gaps and emphasising the need for better integration within the social sciences and between the social and natural sciences to promote effective interdisciplinary and policy-relevant contributions to tree health.

Guest Editors: Andrew Liebhold, Eckehard Brockerhoff and Martin Nuñez / Special issue on Biological Invasions in Forests prepared by a task force of the International Union of Forest Research Organizations (IUFRO).

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Keywords Social science · Tree pests · Awareness · Acceptability · Governance · Risk communication

Introduction

Worldwide, forests and trees provide important ecosystem services such as biodiversity, carbon sequestration, timber and fuel wood, flood alleviation, air quality, landscape change, recreation, health, wellbeing and cultural values (Boyd et al. 2013). However, these benefits are under threat from increasing invasions of non-native tree pest and diseases (hereafter referred to as pests). Much of the recent literature on tree and plant health highlights the growing global movement of commodities and people that has led to introductions of pests (Brasier 2008; Hulme 2009; Hantula et al. 2014; Freer-Smith and Webber 2015). Major pathways include wood packaging (Brockerhoff et al. 2006; Ciesla 2011) and live plants (Webber 2010; Liebhold et al. 2012) with tourism and biomass markets also raising concerns (Potter and Urquhart 2017). The role of people within tree health and biosecurity is very significant and varied—consequently requiring insight from the full range of social sciences relevant to environmental management (see Bennett et al. 2017a, b).

Reliable estimates of the economic impacts and costs of biological invasions are important for developing credible management, trade and regulatory policies. It is critical to consider the differing social settings that influence (sometimes competing) values, attitudes and perceptions of risk at different geographical, political and temporal scales (Flint et al. 2009; Crowley et al. 2017). Assessing how pests and their management impact on the social values intrinsic to trees and forests is also key. Without an understanding of these and other social and economic dimensions of tree health, it is difficult to influence desired changes to attitudes and behaviours and identify which management options are more acceptable.

There is increasing interest from governments and funders worldwide in how the social sciences can contribute to addressing the crises emerging from the exponential growth in invasive pests (Boyd et al. 2013; Freer-Smith and Webber 2015). To date, however, there has been a paucity of research on the social dimensions of tree health although it has been recognised that social factors are influential in whether management outcomes are successful in invasive species (Crowley et al. 2017; see also Bennett et al. 2017a, b). This paper provides a summary and brief synthesis of current knowledge from the social sciences in the domain of tree health.

The paper organises the available evidence under six key social dimensions of tree health—stakeholder categorisation, awareness levels and behaviours, social acceptability issues around management responses, economic impacts, governance and risk communication, information and engagement. Each of these areas of knowledge is crucial to inform tree biosecurity policy and planning. We then highlight evidence gaps and the need for broadening the range of social science disciplines contributing to tree health policy.

Identifying and categorising stakeholders[1] in tree health

Often a key task of the social sciences in natural resource management has been to map out relevant stakeholders and their potential interactions with a project. Tree health issues both affect and are affected by many individuals, groups and organisations but so far very little research has been undertaken to understand this wide stakeholder landscape. Forestry sector stakeholdership is often assumed and narrowly defined in relation to professional use of, or links to, forests. Therefore interest and influence (the core dimensions of stake, see Reed et al. 2009) or lack of awareness and disinterest—have sometimes been considered relatively easy to grasp. However because of the very substantial breadth and diversity of ways in which trees and forests are valued and interacted with, along with the geographically far-reaching pathways associated with tree pests, tree health stakeholdership

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[1] There are varying definitions of a what constitutes a stakeholder (see Reed et al. 2009; Dandy et al 2017) but generally a 'stake' is created when there is a relationship of interest and/or influence between a specific phenomenon (e.g., tree pest) and individual or social group.

can quickly become very broad and diverse. The stakeholder landscape becomes more complex when you consider that tree health is nested within much larger and already established contexts (e.g., regulation of trade; sustainable forest management) that also impact on tree health.

So far stakeholder analysis has contributed to the design of policy development and operational implementation by identifying the goals and roles of different stakeholder groups, and by helping to formulate appropriate forms of engagement with these groups (Gilmour and Beilin 2007; Reed 2008; Allen and Kilvington 2010; Marzano et al. 2015). Reed and Curzon (2015) have highlighted that despite a growing number of studies considering the knowledge and actions of stakeholders, efforts to systematically identify, categorise or analyse stakeholders in the field of tree health are relatively rare. Such research can assist biosecurity policy and practice by simplifying the complex and diverse stakeholder landscape. However, recent work in the UK by Dandy et al. (2013, 2017) has attempted to map and categorise stakeholders in relation to selected pest outbreaks. Using a case-study approach to integrate stakeholder theory, pathway analysis and critical historical reflection on outbreak management practice, the research identified a core set of types of interest and influence in tree health. These include, for example, 'governors' (rule setters), 'value losers' (those who suffer reductions in economic and non-economic value through tree losses), and 'contributors' (who benefit from activities, such as trade, complicit in pest outbreaks) along with several others.

The successful management of pests relies on a range of activities that happen across different scales. Allen and Horn (2009), for example, identify three levels: strategy and policy development, local or sector-based operations, and 'peripheral' publics. Drawing on a framework developed in the field of animal health (Fish et al. 2011), Dandy et al. (2013) also identified key biosecurity actions and behaviours at three levels: strategic, tactical, and operational. Furthermore, they highlight how stakeholdership changes with time and geography, introducing a staged model. For example, at early pre-pathway and mobilisation (e.g., where a pest is mobilised into the pathway) stages, stakes focus on numerous actors in the pests 'native' range, those involved in trading activities linking the 'native' range with new areas (vectors), and those charged with regulating and observing pest pathways. During intermediate stages of pest introduction, release, establishment and spread (most frequently focused on by traditional biological models of pest invasion), stakeholdership becomes much more tightly focused on key actors such as border inspectors and outbreak managers. Vectors remain important at this stage but potentially at a different scale e.g., stakeholders that move firewood domestically. Arguably, the simplicity of the stakeholder landscape at these stages drives the concentration of governmental biosecurity action at this point. In later stages of mitigation and adaptation, stakeholdership opens up again to include a great number of individuals, groups and organisations—not to mention a variety of perspectives and values—including all those who draw value from established trees and forests.

Awareness levels of tree pest and diseases and behaviours

Much tree health literature inevitably suggests the need for better risk communication and engagement to raise awareness of tree pests and improve knowledge levels on impact and mitigation measures as this may present more varied and better opportunities for behaviour change than relying entirely on regulation. Understanding levels of awareness of tree pests is likely to be important in driving biosecure behaviours and attitudes (e.g., cleaning footwear, purchasing and growing plants, transporting woodfuel and wood packaging materials). Evidence suggests that higher awareness levels of tree pests or pre-existing knowledge can influence attitudes towards management methods and willingness to adopt biosecure behaviours (Jetter and Paine 2004; Molnar and Schelhas 2007; Chang et al. 2009; Fuller et al. 2016; Urquhart et al. 2016). However, current evidence suggests that while concern about the impacts of tree pests on our trees and forests is high, reported awareness about the presence of specific tree pests and management options is generally low. A review of available literature on stakeholder awareness of tree pest and diseases by Marzano et al. (2015) found low or superficial awareness levels amongst a variety of stakeholder groups including tree professionals (e.g., Hathaway et al. 2002; Hurley et al. 2012), landowners (e.g., Molnar et al. 2003), local residents (e.g., McFarlane et al. 2006; Flint 2006; Berheide 2012) and outdoor recreationists and tourists (e.g., Runberg 2011).

More recently, a nationally representative survey of 2000 people in the UK conducted in 2014 (Fuller et al. 2016) also discovered low public awareness of pest and disease threats and the possible range of management actions. For example, respondents stated that they 'had heard of but have no knowledge' or 'had never heard of' ash dieback (*Hymenoscyphus pseudoalbidus* 69.9%), which was particularly surprising given the high levels of media reporting when the outbreak was discovered in the UK in 2012 (see also Potter and Urquhart 2017; De Bruin et al. 2014; Tomlinson 2016). Another national survey in the UK of 1334 people was carried out in 2016 (Urquhart et al. 2016). It also found that awareness and knowledge about tree pests and diseases was generally low, with three quarters of respondents stating that they had little or no knowledge of the issues. A much broader range of tree pests and disease were presented to respondents but reported levels of awareness of specific tree pests and diseases varied greatly. The 2016 dataset was also cross-tabulated with a similar national survey conducted in June 2013, which also revealed high concern about the potential impacts of tree pests but low awareness levels of specific pests (Bayliss and Potter 2013). The 2016 results indicated a decline in reported awareness and concern between 2013 and 2016. There are exceptions to low awareness levels and this may be related to country-specific biosecurity approaches and/or the cultural significance of the tree species. For example, a survey of 2983 residents from Auckland city that were registered on a 'People's Panel' found that 82% reported awareness of kauri dieback (*Phytophthora agathidicida*) (Anonymous 2013).

It will always be difficult to build high levels of awareness among the general public so it is perhaps more useful to identify and target intermediaries who can make a difference through their behavioural actions and networking abilities. In terms of tree professionals (those with a livelihood link to trees), better levels of general awareness is expected. In their study of forestry professionals in South Africa, Hurley et al. (2012) found that general levels of awareness of tree pests was relatively high, but they were lower in relation to specific pests. A survey of 392 tree professionals across nine European countries also reported relatively modest levels of awareness of tree pests (Marzano et al. 2016). Out of the six pests listed, just over half (51.4%) stated that they had little or no awareness of these pests. The tree professionals surveyed were most aware about chestnut blight (*Cryphonectria parasitica*) (68.6%). However, in relation to Emerald ash borer (*Agrilus planipennis*), a high risk threat to Europe, 64.9% reported a lack of awareness about this pest.

There have been several surveys that have included questions about behaviours to assess that appetite and willingness to change practices. Behaviours listed mostly include actions such as plant buying habits (not importing plants, buying from accredited sources), cleaning footwear and equipment and citizen science activities. For example, 88% of tree professionals in nine European countries said they preferentially buy plants from an accredited source; 77% would avoid bringing in plants from abroad but only 65% said they would clean footwear, vehicles and bike tyres after visiting parks, gardens and woodlands (Marzano et al. 2016). Respondents from the 'People's Panel' in Auckland stated that, in addition to cleaning stations, they had cleaned boots and equipment at home (34%) and informed family and friends about kauri dieback (32%). However, 32% reported that they had not performed any other prevention activities (Anonymous 2013). Although Urquhart et al. (2016) found a decline in willingness to undertake biosecurity measures between 2013 and 2016, the UK survey still indicated a willingness to adopt measures aimed at reducing the spread of pests and diseases such as avoiding bringing plants and wood products into the UK from abroad; buying from trusted local and/or certified sources; cleaning footwear/bike tyres and citizen science monitoring schemes. However, there is a cost element to these behaviours and the study suggests that people were generally unwilling to pay extra for biosecurity such as more expensive plants from accredited sources.

Social acceptability of responses to tree pests and diseases: values and attitudes of stakeholders

Management responses to tree pests are often justified for the greater public good (i.e., saving our trees and associated biodiversity or economic returns on plantations). In this context, public interest and compliance with management actions is assumed (or hoped for) but is rarely evaluated. Although we recognise the challenges associated with more participatory forms of engagement (Porth et al. 2015; Crowley et al. 2017), social research emphasises that understanding local values and attitudes is essential to facilitate social acceptability of biosecurity operations as well as community cooperation (Marzano et al. 2015).

A broad range of studies have considered the social and cultural values of trees and forests (see for example O'Brien and Morris 2013; Dandy 2010; Nordlund and Westin 2011), but few have looked at how pests have impacted on these values. While there are studies that have indicated the severe impact of tree loss on people such as Dutch elm disease (Potter et al. 2011) and Asian longhorn beetle (*Anoplophora glabripennis*) (Porth et al. 2015) in the UK, kauri dieback in New Zealand (Anonymous 2013) and spruce bark beetles in the US (Flint 2006), some recent studies have attempted to explore directly the links between tree pest and diseases on values (De Bruin et al. 2014).

Social and cultural values associated with trees will likely influence how individuals and communities respond to pest management, particularly if they are perceived as a threat to individual or community wellbeing (Flint et al. 2009). Values are inevitably co-produced through human interaction with trees, woods and forests and we should not always assume that tree loss is negative. Flint (2006) showed in an Alaskan study that some individuals felt that a more open landscape had greater aesthetic value. Another study in a Bavarian national park in Germany surveyed 608 tourists and found that attitudes toward disturbance from native bark beetle attacks was generally positive, particularly if visitors were presented with solid arguments about pest function in the ecosystem (Müller and Job 2009). However, it can be difficult to relate evidence on social and cultural values in wooded landscapes specifically to individual trees or locations. Without this information it is not easy to assess if damages to these trees and wooded landscapes will lead to a corresponding loss of social and cultural values or to pinpoint the values that are at risk (De Bruin et al. 2014).

Until recently, much of the published evidence on public attitudes towards tree pest management came from North America and mostly in relation to native pests (e.g., Molnar et al. 2003; Flint 2006; Meitner et al. 2008; Chang et al. 2009; McFarlane et al. 2012). However, there has been a growth in social research in other countries that adds to our knowledge base. Certainly, there appears to be general support for management of tree pests. In the UK, a study of 2208 members of the public found that a 'do nothing' approach was considered unacceptable by most participants with only 11.4% stating that forests should be left alone to deal with pest and diseases naturally (Fuller et al. 2016). Similar findings were made by McFarlane et al. (2006) who presented a case study on community responses to mountain pine beetle (*Dendroctonus ponderosae*) in Western Canada where local residents surveyed (N = 1385) also felt that a 'do nothing' approach was not acceptable. Residents did have an opinion on the types of management measures preferring infested areas to be treated (such as sanitation felling) rather than the use of preventative management methods such as prescribed fire or thinning to reduce potential host species. The most acceptable management method in Fuller et al.'s (2016) study was to fell affected trees only although half of the respondents accepted the use of ground spraying of pesticides and fungicides and biological control. In their survey to assess public acceptance of tree-breeding solutions to ash dieback, Jepson and Arakelyan (2017) found little support for a 'do nothing' approach. Breeding native ash either through conventional means or accelerated breeding were the most preferred options.

In the UK survey conducted by Fuller et al. (2016), there was a suggestion that most management methods were more acceptable to the public than might be initially assumed by managers (see also Crowley et al. 2017). There are exceptions. Although the removal of (non-infected) host material may be a highly effective preventative treatment in some circumstances, this action may face intense opposition by local residents. For example, residents imposed legal action to suspend the felling and removal of host trees from a park in Nova Scotia where the infestation of brown spruce longhorn beetle (*Tetropium fuscum*) was first discovered (McLeod-Kilmurray 2009). Other studies (e.g., Mackenzie and Larson 2010; Porth et al. 2015) have attempted to unpack the primary contextual issues underlying opposition to the felling of host trees. These reveal that key components of social acceptability are trust in the agencies carrying out the management actions and the belief that such actions will be effective but social and cultural values attached to the trees and setting (e.g., gardens, parks, wooded areas) are also likely to feature.

Aerial spraying has been especially contentious. Although several chemical pesticide products have been successful in controlling incursions, few are desirable for aerial application, particularly over urban environments where there is a perceived potential for human health impacts (see for example Chang et al. 2009; Gamble et al. 2010). In New Zealand, microbial pesticides, most notably *Btk* toxins (*Bacillus thuringiensis kurstaki*), were considered to be more suitable for aerial application over urban areas than conventional pesticides and were frequently used in programs to eradicate invading Lepidoptera (Hajek and Tobin 2010) but there have been public challenges to their use (van Santen et al. 2004). Past experiences of chemical spraying can also influence attitudes. For example, a study of 507 people across New Brunswick and Saskatchewen explored attitudes towards management of two pest species—the spruce budworm (*Choristoneura fumiferana*) and forest tent caterpillar (*Malacosoma disstria*) (Chang et al. 2009). The residents of New Brunswick were less accepting of aerial application due to their living memory of mass aerial spraying programmes over parts of the province in the 1970s and high concerns about the knock-on effects of chemical on human and environmental health (Chang et al. 2009). However, there is some evidence to suggest that the public may be more accepting of control methods if they perceive a significant risk to human health from the pest. For example, Tomlinson et al. (2015) highlight how private residents in affected areas of Southeast England may have been more cooperative with management of the Oak Processionary Moth if the focus of engagement had been on the potential public health impacts of the pest. This is further supported by findings of Gustafsson and Lidskog (2012) who report that during an outbreak of Pine Processionary Moth (*Thaumetopoea pinivora*) in Sweden, residents demanded control of the outbreak due to the public health impacts.

Semiochemical-based eradication treatments, such as mating disruption and mass-trapping, are considered to have little or no effect on human health or on non-target species, but in some instances the public may fail to recognize the difference between chemical insecticide treatments and semiochemical treatments. Indeed, this was the case with the aborted eradication programme against the light brown apple moth (*Epiphyas postvittana*) in California (2007–2008). Complaints from residents (Chase 2008) led to the cancelation of the programme (Suckling and Brockerhoff 2010).

Although the survey conducted by Fuller et al. (2016) had a broader national remit, their findings suggest a greater level of support for biological control possibly as this is perceived to be a more 'natural' approach. Similar findings (support for biological control) were made by Chang et al. (2009). A study of 522 urban residents in southern California, USA also found that biological control was preferred (79% of respondents) over two other options of chemical pesticide and biorational insecticide to manage the eucalyptus snout beetle *Gonipterus scutellatus* (Jetter and Paine 2004).

While we are building a knowledge base around what management measures people find more acceptable, we still have limited understanding of factors that influence these attitudes. Demographic variables and pre-existing attitudes can be important influences on social acceptability but it is difficult to identify a pattern from existing studies. Fuller et al. (2016) for example, found that acceptance of certain management methods such as felling infected/infested trees, biological control and ground spraying increased with age but conversely acceptability of aerial spraying and taking no action decreased with age. Flint (2006) also established that respondents with high environmental values were less likely to support chemical applications.

Economic impacts of biological invasions

Biological invasions affect ecosystem goods and services and the economic activities that utilise them. Economic impact assessments attempt to estimate the monetary value of invasion damage and the costs of mitigation activities that prevent introduction, detect newly established populations, and slow the spread of established invaders. Assessments of the economic impacts of invasive species are crucial for cost-benefit analyses of biosecurity policies (see Epanchin-Niell, this volume). However, few economic impact assessments have been completed at the national scale because of the challenges of implementing the methodology and obtaining information to support it (see reviews in Born et al. 2005; Pejchar and Mooney 2009; Holmes et al. 2014). Methodological challenges include understanding and modelling the complex dynamics of invasion and damage processes (e.g., Kovacs et al. 2010; Soliman et al. 2012) and the behavioural responses of individuals, stakeholders, and producers who can affect the degree of damage (e.g., Finnoff et al. 2010). Estimating the value of damage is difficult because many ecosystem services are not traded in markets and estimates of society's willingness to pay to avoid damages to those services are not readily apparent or in some cases relevant.

However, some attempts have been made to provide an assessment of economic impacts. For example, Colautti et al. (2006) estimated the economic impacts of 16 non-native species in the agriculture, forestry and aquatic sectors in Canada. For each of the 16 invaders, they estimated the annual value of resources placed at greatest risk (e.g., hardwood timber sales, hardwood product exports) and then calculated the proportion (20–52%) of the national value of those resources that would be lost because of damage by the invader. The proportion loss was based on damages observed in local case studies, which was then scaled up and assumed to hold throughout the nation. The authors call the total value loss the invisible tax imposed by non-native species. Despite a number of challenges with this approach, calculations reveal that the seven non-native forest insects and diseases imparted an annual tax of $7.7–$20.1 billion on maple, fir, spruce, and pine timber sales and wood product exports.

Recent studies have attempted to model the complex dynamics of an invading population and the economic impacts of its damage (e.g., Kovacs et al. 2010; Soliman et al. 2012). For example, Soliman et al. (2012) estimated the potential economic impacts of the pinewood nematode (*Bursaphelenchus xylophilus*) on the producers and consumers of round wood and wood products in Europe from 2008 to 2030. The cumulative value of lost forestry stock assuming no regulatory control measures is estimated at €22 billion. Based on a model of the round-wood market, the reduction in social welfare is estimated at €218 million in 2030, whereby consumers of wood products incur a welfare loss of €357 million while producers experience a €139 million increase, caused by higher wood prices.

Our ability to assess the impacts of pests on a range of ecosystem services is limited by the scarcity of biological and economic data. Aukema et al. (2011) begin to address these issues with a study of the economic impacts of 455 non-native forest insect species known to be established in the continental United States. Of those 455, 62 species are considered to cause damage. They divided the 455 species into three feeding guilds—phloem and wood borers, sap feeders, and foliage feeders—and estimated the economic impacts of each of the guilds in five cost categories: (1) federal governmental expenditures (e.g., survey, research, regulation, and outreach), (2) local governmental expenditures (tree removal, replacement, and treatment), (3) household expenditures (tree removal, replacement, and treatment), (4) residential property value losses and (5) timber value losses to forest landowners.

These cost categories clearly relate to different stakeholder groups (e.g., homeowners and forest landowners), types of cost (e.g., mitigation cost and damage cost), and ecosystem services (e.g., aesthetic amenities provided to homeowners and timber value to forest landowners). For each of the three guilds, they identified the most damaging species to date (emerald ash borer *Agrilus planipennis*, hemlock woolly adelgid *Adelges tsugae*, and gypsy moth *Lymantria dispar dispar*), constructed spatial-dynamic models of pest spread and damage over a 10-year interval, and estimated the value of damage for each cost category. For all of the guilds studied, homeowners and local governments are bearing the greatest share of costs associated with non-native forest insects. The wood- and phloem-boring insects, including the emerald ash borer, are the species that create the greatest economic damage to urban trees, costing an estimated $1.7 billion in local government expenditures and approximately $830 million in lost residential property values every year. Of the three guilds, borers were represented by the fewest species, but a high proportion of them—20 percent—are damaging. Further, there is a 32 percent risk that a new borer that is as damaging as or more costly than the emerald ash borer will invade in the next 10 years. Across the three insect guilds, timber value losses to forest landowners are relatively small, often an order of magnitude less than local government expenditures. Timber losses are small because tree species attacked by the most damaging pests to date have relatively low value for timber products.

Aukema et al.'s (2011) cost estimates are useful for highlighting the economic importance of invasive species relative to different stakeholder groups; however, they have limitations for policy analysis. Aukema et al.'s projections of pest damages over a typical 10-year horizon ignores the long term dynamics of damages that may occur from the time of introduction and establishment to the time at which the pest has spread throughout its suitable range. The timing and persistence of damages greatly affects the present value of damages because of discounting, and the present value of damages that may occur throughout an invasion is an important gauge of the benefits of programs to prevent pests from becoming established or eradicate them after establishment (Epanchin-Niell and Liebhold 2015).

While Aukema et al. (2011) provide the most comprehensive estimates of costs of invasive pests currently available at the national level, their framework needs to be expanded to include additional species and cost categories. The most pressing need is to estimate the economic damage caused by invasive pests associated with the reduction of valuable, non-market ecosystem services (e.g., reductions in recreation, wildlife habitat, carbon sequestration, and clean water). Estimating the value of losses of non-market ecosystem services such as recreation is difficult at the national scale because of data limitations.

Governance: What are the issues and who should act?

The governance of tree health, that is the formal and informal rule-making and implementation processes that affect tree health, has received some attention from the social sciences. This work particularly focuses on formal institutional structures, at national and supra-national scales (e.g., MacLeod et al. 2010), and on particular responses to pest or disease outbreaks. Studies highlight that decision-making at different scales increasingly involve not only governments, but international organisations, transnational corporations, and non-governmental bodies.

In general, analysis of existing governance structures illustrates that actors, including governments, are constrained in how much they can act on tree health although there are exceptions such as New Zealand where biosecurity has a high priority status. As most invasive species are spread through international trade, plant scientists have called for greater trade restrictions (e.g., Brasier 2008; Webber 2010; the Montesclaros declaration 2011; Hantula et al. 2014; Roy et al. 2014). However, the openness of global trade is largely determined by rules set by the World Trade Organization (WTO), an organization for which tree health is only a minor concern. Potter (2013) explored WTO governance in relation to plant biosecurity, highlighting how WTO rules favour free trade and, amongst other things, places the burden of risk proof on importing countries wishing to stipulate phytosanitary measures for importing plants (see also Roy et al. 2014). The WTO's Sanitary and Phytosanitary (SPS) Agreement provides members with an option to restrict trade where there may be a threat to human, animal or plant health (Potter 2013). However, WTO rules only allow for the importation of a commodity to be prevented if no phytosanitary measures are available to manage its associated risk (Eschen et al. 2015). Such restrictions are hardly ever put in place, however, as appropriate measures are normally identifiable. Furthermore, trade restrictions must be justified directly by pest risk assessments based on established biological science (Pettersson and Keskitalo 2012; Pettersson et al. 2016). This can result in delays with implementing restrictions, but also that threats may be missed where scientific understanding is lacking.

Literature on the governance of tree health also identifies important issues regarding boundaries between and responsibilities of differing, sometimes competing, government bodies (Porth et al. 2015). It has been noted, for example, how decisions to devolve responsibility from central to local government contributed to poor management of Dutch elm disease in the UK in the 1970s (Tomlinson and Potter 2010). More recently, Porth et al. (2015) described how unclear boundaries between managing organizations in response to a local outbreak of Asian longhorn beetle in the UK, impacted on how local residents experienced the outbreak management. Tomlinson (2016) also notes that initial confusion about responsibilities for management of oak processionary moth (*Thaumetopoea processionea*) may have been a key factor hindering early eradication efforts. The author highlights how there was no coordinated surveillance system for tree pests and upon discovery it took some time to sort out the necessary legislative powers to act (Tomlinson 2016).

This problem is not restricted to the UK. In Sweden, responsibilities for pests and diseases, invasive species and for pathogens specifically fall under different agencies (Pettersson et al. 2016). There have been various attempts to respond to this type of problem. At the national level, Potter (2013) describes the slowly increasing integration amongst agencies in the UK, driven primarily by the need to manage pests with complex ecologies such as *Phytophthora ramorum* and ash dieback. At the supranational level, EU Regulation (1143/2014) demands increased monitoring of an extended list of risk species, but goes on to suggest that additional resources be allocated as well as increased coordination at the national level (Pettersson et al. 2016; Klapwijk et al. 2016). New EU regulations entered into force on 14th December 2016 with further emphasis on coordination (2016/2031 Regulation on protective measures against pests of plants http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R2031).

A limited number of studies have sought to understand the relationship between tree pest outbreaks and development of policy. It has been recognized that getting plant health on the political agenda often involves competition with other issues and thus requires both awareness-building and a perceived urgency (Keskitalo et al. 2016). Nelson (2007) considered the impact of the Canadian mountain pine beetle epidemic on forest policy, noting that such an event could potentially form a policy window by attracting public attention and mobilising political will. Whilst Potter (2013) describe some substantive change in policy structures and processes in response to ash dieback in the UK (see also Mackay et al. 2017), Nelson (2007) concluded that the vested economic and political interests in forestry acted to significantly constrain policy development in Canada in response to mountain pine beetle outbreaks.

Risk communication, information and engagement

Raising awareness has been acknowledged as a means of improving early detection of pests and the overall effectiveness of eradication and management measures as well as potentially preventing future outbreaks and increasing the focus on plant health (Marzano et al. 2015; Keskitalo et al. 2016). However, Marzano et al (2015) note the absence of evaluation in relation to communication and engagement efforts in tree health and call for further attention in this regard. It is essential to work with and understand affected communities and other stakeholders to help address issues of public acceptability of any biosecurity management. To illustrate, case studies from the UK (Porth et al. 2015) and Canada (Mackenzie and Larson 2010) report on community and agency engagement responses to rapid tree pest management. During the response to emerald ash borer in Southern Ontario, part of the management involved the removal of healthy ash trees as potential hosts (Mackenzie and Larson 2010). Residents felt that communication from the agencies was poor and that they were excluded even though the agency had organised community meetings. Agencies were perceived not to have taken on board community concerns and therefore people felt that management measures had already been identified beforehand.

Similar experiences are reported by Porth et al. (2015) during the Asian longhorn beetle outbreak in Kent, UK, where over 2000 potential host trees were felled in a relatively small area. Residents felt there was a lack of communication from the agencies involved when the beetle was first discovered and throughout the eradication period. Clearly there can be extraordinary circumstances when dealing with 'emergency' responses and it can be difficult to do stakeholder engagement well when rapid action is considered necessary. However, the above case studies illustrate how risk communication is important to facilitate the building of trust. Porth et al. (2015) showed that residents felt communication was needed on what the pest looked like and the impact it can have but also whether the measures implemented were likely to be effective. The authors suggested that a residents' forum during the outbreak process might have given residents a venue to voice their concerns and enable agencies to assess community responses to the management options. Mackenzie and Larson (2010) suggest that agencies develop templates for enhancing communication about scientific uncertainties and management alternatives but also examine their organisation culture to assess whether and how they can support more inclusive and participatory processes.

There is also a need to consider how the risks of tree pests and diseases are likely to be perceived when dealing with multiple scales and the broader 'general public', with the media arguably having an important role this. In their review of the ash dieback outbreak in the UK, Pidgeon and Barnett (2013) adopt the Social Amplification of Risk Framework (SARF) to explore how risks can be amplified in the media and public consciousness. The authors highlight the triggers which intensified coverage of this disease in the media: "*widespread exposure* of the tree population, *visual impact* (images of both healthy and infected trees), the possibility of *blame* for allowing a known risk to enter the UK, potential *conflict* along ideologically significant lines (e.g., between the UK and other EU governments regarding risk control measures), and high *signal value* (what does this episode portend about other threats to tree health and plant biosecurity, or about the risks from the systems for managing the natural environment?)" (p. 7). Tomlinson (2016) suggests that ash dieback was a 'focusing event' in which the intense media and public attention led to a step-change in government policy on tree health and biosecurity and moved it up the political agenda.

The format in which information is communicated is a further area to which social analysis can contribute understanding. Marzano et al. (2015) summarises much of the existing analysis. Bayliss and Potter (2013) found that the most popular source of information about tree pests and diseases in the UK was the Forestry Commission (a government agency) website (50.9%) followed by newspapers/magazines/journals (45.4%), other websites (43.2%). Another survey in Auckland, focussed on kauri dieback found that TV, newspapers and radio were the most frequent sources of information (57%) (Anonymous 2013). A UK survey in 2016 had similar findings regarding information sources (Urquhart et al. 2016), while tree professionals across Europe (Marzano et al. 2016) rated the internet as the most popular source of information (72%).

Social media is increasingly being seen by tree professionals as a medium for providing information quickly, alongside the development of recording and monitoring apps for detecting tree diseases. However, the surveys described above suggest social media is not yet a popular source of information amongst a wide variety of stakeholders. In their qualitative analysis of the role of Twitter and risk amplification of ash dieback, Fellenor et al. (2017) found that tweets about tree disease largely reflected traditional media stories trending at the time and users consisted of organisations (e.g., environmental NGOs, government agencies) and subsets of users with particular interests (e.g., horse riders, gardeners, environmentalists).

Discussion

The above summaries of social and economic research into tree health demonstrate how this relatively new research area is evolving as pest threats develop (see Table 1).

So far, this work has been pursued without a great deal of interaction between the different disciplines involved, nor has it (outside economics) brought together analyses of multiple pest outbreak 'events' (although see Flint et al. 2009; Dandy et al. 2013). There is, however, considerable potential benefit to interaction between the various social science disciplines with each area having the capacity to inform the others and develop novel perspectives and analyses that could contribute more fully to evidence-based policy-making on tree pests, an area currently dominated by the natural sciences.

The identification and categorisation of stakeholders can inform the development of communication strategies by rationalising the diverse and complex stakeholder landscape with which managers are trying to communicate and by identifying their specific communication needs. In relation to governance focused research, it can help to clarify the sectors from which institutional, political and legal drivers and constraints emerge to impact upon tree health. Another key insight from stakeholder analysis work is its characterisation of the temporal, spatial and institutional change that occurs in relation to pest outbreaks. Rather than being static in time and place, this approach highlights that significant changes occur to awareness levels, social acceptability, governance contexts, and communications needs as pests move along pathways.

Surprisingly little direct analysis has been done of the effectiveness of specific biosecurity behaviours, nor of how governance contexts may constrain their adoption. This relates not only to observable behaviours such as boot-washing and surveillance, but should also extend to analysis of how, for example,

Table 1 Summary of evidence on social dimensions of tree health

Social dimensions of tree health	Summary/key findings
Identifying and categorising stakeholders	Tree health stakeholdership is diverse and complex due to the number and scale of individuals, groups and organisations that value and interact with forests, and which are involved with relevant supply-chains and pathways;
	A framework has been developed to help simplify and categorise the stakeholder landscape;
	Stakeholdership changes over spatial, institutional and temporal scales.
Awareness levels	Awareness of tree pests and diseases and their impacts is likely to influence biosecure behaviours and attitudes towards management measures;
	Evidence suggests that awareness is generally low across a broad range of stakeholders, including key groups such as land managers or tree professional;
	While there is a stated willingness to engage in biosecure behaviours, people may not be prepared to incur extra costs (e.g., pay *more* for plants from accredited sources);
	Targeting intermediaries who can demonstrate the benefits of biosecure behaviours is likely to be more effective than building awareness amongst the general public.
Social acceptability	Understanding local values and attitudes is essential to identifying acceptable management approaches;
	There is an underlying demand for action against tree pests but acceptability varies in relation to different management measures, levels of trust in managers, past experience and perceived effectiveness of the measures;
	There is less support for aerial spraying and more support for biological control.
Economic impacts	Assessments of the economic impacts of invasive species are crucial for cost-benefit analyses of biosecurity management options;
	Assessing the impacts of pests on ecosystem services is constrained by the scarcity of economic data;
	Estimating the value of damage is difficult because many ecosystem services are not traded in markets;
	Evidence suggests that economic costs are not borne equally between stakeholders, with property and land owners (e.g., home-owners and local authorities) bearing the most costs.
Governance	While it is often state actors that take the lead, the governance of tree health necessarily includes many more non-state actors;
	Evidence suggests that management of tree pests is constrained by current governance contexts and external vested interests;
	Confusion and lack of clarity over responsibility for aspects of tree pest management can hinder effective responses.
Risk communication, information and engagement	Raising awareness of tree pests amongst stakeholders can facilitate early detection and effectiveness of management responses;
	Evidence suggests that traditional media (e.g., newspapers, TV) are still the most popular sources of information on tree pests;
	Media and public attention can push tree health issues up the political agenda;
	Communication regarding tree pest risk is more readily received if it comes from a trusted source.

historical planting strategies have promoted or suppressed pest outbreaks, or impacted upon forest resilience. Key policy constraints exist on a number of levels and include limitations in state actions that can be taken under the WTO regime, the existing coordination systems between agencies in different countries, the role and position of biosecurity within these agencies and the availability of resources (Heuch 2014). Biological invasions by their nature cross boundaries as they spread. Effective management requires coordination across political jurisdictions, different landscapes, heterogeneous populations and international borders (Knowler and Barbier 2005; Epanchin-Niell et al. 2010). Current evidence also strongly suggests that successful biosecurity management requires the on-going participation of relevant stakeholders at all stages of the biosecurity process. However, more work is needed to better understand the specific actors and motivations involved or impacted along different pathways and in 'hotspot' areas. This can underpin improved risk behaviour change strategies.

However, a number of studies reveal that awareness levels remain low. This raises questions about the possibilities of successfully promoting biosecure attitudes and behaviours in today's complex political and media landscape. Government efforts to raise public awareness and increase risk communication and engagement efforts in tree health issues are improving, but the apparent decline in attentiveness indicates the difficulty of maintaining a focus on tree health issues outside the 'peaks' of public attention. Recent work is beginning to provide a nuanced exploration of the broad range of social actors, their knowledge and awareness, attitudes and behaviours. Urquhart et al. (2016) have suggested that agencies should first target 'higher risk' and 'more willing' groups, such as those engaged in environmental activities, members of environmental groups or gardeners.

Understanding the parameters of social acceptability can inform the design and implementation of communication strategies and enable targeted economic analyses. Economic analysis can provide useful information for communication campaigns seeking to help stakeholders make tree health management decisions—for example, by illustrating high cost options. It is primarily economic impacts that spur the development of biosecurity policies but evidence is also needed on the social and cultural impacts of tree pests and this is another area where social scientists and economists can collaborate by assessing the non-market value of damage to ecosystems and assessing the tradeoffs among impacts. Programmes that are deemed economically 'cost-effective' often ignore substantive loss of value in other forms (see Pejchar and Mooney 2009; Rosenberger et al. 2012; Porth et al. 2015). For example, estimating the value of cultural services provided by ecosystems, such as inspiration, religion and cultural tradition is the most complex and under-addressed impacts of biological invasions, yet these types of services tend to resonate strongly with diverse stakeholders (Pejchar and Mooney 2009).

Many of the areas summarised in this paper constitute merely a start to a broader and more thorough understanding of the social and economic dimensions of tree health. Consequently, a number of potentially relevant areas remain absent from analysis. One example is the opportunity for learning that would be afforded by more extensive historical analyses of past tree pest outbreaks, their management and policy responses (e.g., Tomlinson and Potter 2010; Potter et al. 2011; Barnes et al. 2016). Such analyses have been limited in that most have reflected upon outbreaks only in the relatively short term or immediate aftermath (e.g., Porth et al. 2015). They do, however, enable critical reflection upon the outbreak management itself as well as the broader political and economic context. Crucially, historical analysis is less likely to be censured or opposed by policy-makers than more contemporary analysis perceived, potentially, as critical of current policy.

Bennett et al (2017a, b) highlight a number of social science disciplines involved or that could be involved in conservation and natural resource management. They list eighteen disciplinary areas ranging from environmental anthropology to ecological economics but emphasise the limited integration of social sciences into conservation practice. The social dimensions of tree health is relatively new and limited currently to involvement of what Bennett et al. (2017a, b) would term 'classic' social sciences such as environmental anthropology, economics, geography and politic science. However, other social science contributions to tree health could be made, for example, by philosophy and environmental ethics. There is little, if any, existing critical reflection on the policy and practice of forest health and biosecurity in the environmental ethics literature. This is despite the fact that biosecurity interventions have profound consequences for a range of non-humans—not only the 'pest' species and affected trees. As concern for vulnerable groups and those without a 'voice' grows amongst policy-makers, it is incumbent upon ethics scholars to clarify the moral status of non-humans and explore the ethical justifications of management actions which affect them and the environment more widely.

Psychology—and associated academic fields such as behavioural economics—has had substantial impacts on policy in various sectors (e.g., health, transport), and is beginning to be picked up in forestry (e.g., Valatin et al. 2016). Work by Allen and Horn (2009) and Surendra et al. (2009) begins to illustrate how useful psychological theories and methods could be in this field. This discipline focuses closely on the actions and intentions of individuals and may have much to contribute to understanding the behaviours related to biosecurity (e.g., inspection; phytosanitary actions; purchasing) and the management of resilient forests (e.g., species selection; forest planning; thinning regimes).

A major omission in tree biosecurity policy and practice is an understanding of the role indigenous people and how their knowledge can contribute to and frame responses to tree pests and diseases. Indigenous people have expressed concerns about the health of trees, which often hold substantial spiritual value, e.g., in New Caledonia, Mount Panié kauri (*Agathis montana*) and in New Zealand, kauri (*Agathis australis*) (Warren 1992). However, indigenous knowledge and indigenous peoples are largely under-represented or excluded in the tree health sector (although see Alexander et al. 2017). According to UNESCO, indigenous people globally manage an estimated 80% of the world's remaining healthy ecosystems and so it is vital that we understand and recognise their traditional and cultural forest preservation skills, as well as the political, psychological, cultural and environmental issues that shape their perspectives. Indigenous or traditional knowledge and cultural values are gaining some traction in biodiversity conservation (Nakashima and Roué 2002), and acknowledgement of their importance and complementary nature has steadily increased over time. Indigenous knowledge is often found in stories, songs, proverbs, folklore, laws, language and traditional practices, and can be transmitted orally from generation to generation. Such knowledge can help provide baseline information about the history and health of our tree species and offers vital complementarity rather than conflict with Western scientific approaches.

Concluding remarks

Many management initiatives are hampered just as much—or even more—by social, political and organisational constraints as they are by technical constraints. While a number of biosecurity policies and strategies can be identified, the ways in which they could be considered acceptable and successfully implemented are constrained by global trade networks and regulations, the resources available to government agencies as well as public interest in tree biosecurity. There are many contributions that social science can make to forest health and biosecurity policy, however, they are rarely integrated with other scientific evidence (largely from the natural sciences) in policy-making and research programmes. This is partly due to the ontological challenges of combining different research disciplines, but funding structures and attitudes towards different forms of 'evidence' amongst policy-makers also have considerable impact. It is critical to find ways (e.g., policy processes) in which to bring these different forms of evidence together in mutually supportive, rather than conflicting, ways.

Interdisciplinary research that effectively integrates the natural sciences with social and economic research will provide a more rounded and well-founded contribution to policy development. However, the success of an integrated approach to research depends on committed public funding for this work and long-term strategic planning to integrate social sciences insights to inform (so far) natural sciences-dominated tree health research, policy and management. Social science can significantly contribute to addressing the wide-ranging socio-ecological impacts from tree pests by, for example, understanding the diverse regulative and political structures and stakeholderships, attitudes and behaviours and identifying effective risk communications processes towards increased biosecurity. Thus, social science research is likely to become increasingly relevant to any attempt at managing current tree pest outbreaks and address future incursions.

Acknowledgements The authors would like to thank the two anonymous reviewers and editors for their constructive comments on the manuscript.

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