The analysis demonstrates how forest management could change at the stand level if a carbon value is included in economic appraisals for a range of planted and managed forest systems worldwide, leading to the following conclusions.

- A forest management system that increases tree growth rates would reduce the extending effect of a carbon value on optimal rotation age.
- When carbon values are considered, adding in residue (bioenergy) income and carbon benefits from fossil fuel substitution makes optimal rotation ages shorter. This incentive to reduce rotation age is particularly profound in forest stands that are currently producing sawlogs of relatively low market value. The preliminary focus on extending rotation age as a carbon-related policy tool should therefore be on forests currently producing low-value wood.
- Over long timescales, an extension of rotation ages for carbon value will likely increase the production of sawlogs at the expense of small roundwood, causing more carbon to be stored in long-lived HWPs. The most profitable end-use of small roundwood produced locally would likely be for woodfuel (owing to the fossil fuel substitution effect) rather than panels and paper.
- Plantation of additional forest areas is a necessary measure when mitigation is achieved by extending rotation age.

BETTER MANAGEMENT OF PESTS AND DISEASES

Insect, pest and disease outbreaks have significant effects on forest carbon storage and sequestration rates because of their influence on growth, mortality, decomposition rates and other ecosystem processes (Ellison *et al*. 2005; Albani *et al*., 2010; Hicke *et al*., 2012; Boyd *et al*., 2013; Ghimire *et al*., 2015). Tree mortality from catastrophic outbreaks reduces forest carbon uptake and increases future emissions from the decay of killed trees (Kurz *et al*., 2008). These impacts must be accounted for in forest carbon projects and in large-scale carbon modeling (Box 15).

Insect pest attacks, like forest fires, can be regarded as natural factors in forest dynamics. However, in recent years both the number and scale of damaging forest pest and pathogen outbreaks have increased with rising world trade in trees, wood and wood used in packaging and impacts of climate change (Aukema *et al.*, 2010, Santini *et al*., 2013; Freer-Smith and Webber, 2015). Insect pest and pathogen damage may continue to increase in the future, since the most responsive pest species are those with short life spans and rapid regeneration rates, which are likely to be boosted by climate change, especially relative to their long-lived hosts (Ayres and Lombardero, 2000).

The scale of losses from some recent outbreaks underlines the potential of pest and disease damage to release CO_2 and methane into the atmosphere. Kurz *et al*. (2008) estimated that the forest in British Columbia, Canada affected by bark beetle between 2000 and 2020 will release 73.6 Mt CO_2e (9.8 g CO_2e per square metre annually over 34.7 million hectares) (Figure 19). Thus, during and immediately after an outbreak, the forest is transformed from a small net carbon sink to a large source of carbon.

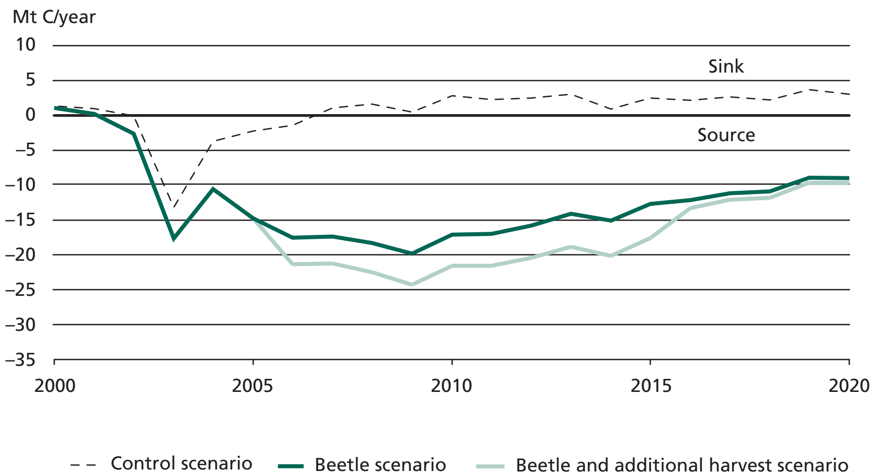
Effective continuous management of insects and diseases can improve the ability of forests to fix and store carbon and thus needs to be integrated in sustainable forest management, particularly where carbon removal from the atmosphere is a major forest objective.

BOX 15
Estimating potential carbon losses from woodlands

Under a recently developed model for estimating potential carbon losses from woodlands accredited under the United Kingdom's Woodland Carbon Code (Davies, 2014), 3 to 10 percent of carbon sequestered in projects must be set aside as a buffer against future carbon losses due to pest and disease problems over 50 to 100 years. Recent verification work in the forest suggests that the actual losses at current risk levels are likely to be at the lower end of this range. Pest and disease risk varies considerably according to the tree species and regional and local factors. These relatively low carbon loss estimates apply to well-managed and certified woodlands.

The risk-based approach to carbon storage, and particularly the adoption of management practices to mitigate such risks, is important to sustainable forest management planning, forest restoration, carbon sequestration management in forest ecosystems and the design of forest carbon schemes.

FIGURE 19
Total ecosystem carbon stock change for three scenarios



Note: The control simulation was run with no beetle outbreak, and with base harvest and fires. The beetle simulation added insect impacts to the control scenario. The additional harvest simulation added the management response of increased harvest levels from 2006 to 2016 to the beetle simulation. Negative ecosystem carbon stock change values represent fluxes from the forest to the atmosphere (net source of carbon). The source in 2003 was in part the result of the large area burnt (2 440 km^2 in the study area), which was included in all three scenarios.

Source: Kurz *et al.*, 2008

BOX 16

Managing tree disease to prevent additional emissions: the case of *Phytophthora ramorum* in the United Kingdom

Phytophthora ramorum causes sudden oak death or ramorum blight and has a broad host range. In the United Kingdom, *P. ramorum* infection has resulted in dieback of Japanese larch (*Larix kaempferi*). Spread of the disease has been rapid under wet weather conditions, and by the end of October 2014, 17 485 ha had been infected, with impacts for the landscape and the wood processing sector (P. Freer-Smith, personal communication).

To limit the further spread of *P. ramorum*, 10 673 ha of infected forest have been felled, representing some 2.2 million cubic metres of roundwood, which has been processed in the normal way without significant impacts on end use. Felled areas are being replanted with productive species. In this way it has been possible to avoid the increase in carbon emissions that would have occurred if trees had been "felled to waste", that is, if the wood had remained on site to decay (King, Harris and Webber 2015; Forestry Commission, 2016b).

P. ramorum has also killed millions of oak and tanoak trees in the United States of America (California). It is likely spread through the movement of infected or contaminated plant material, growing media, nursery stock, and soil carried on vehicles, machinery and footwear (Brasier and Webber, 2010).

Outbreaks are better understood in hindsight and are difficult to forecast. Outbreaks are frequently associated with changes in host distribution or density, which are often a legacy of land-use policies or management practices. Since it remains unclear which pathogens or insect pests are most likely to benefit from climate change, diversifying plantations would be wise. Given the inherent risks associated with selecting species while the environment is in flux, monitoring needs to be increased, at a resolution that will capture changes in forest insect pest and pathogen behaviour while the damage levels are low (field experiments, modelling), so that management efforts can be adapted effectively and efficiently (Metsaranta *et al*., 2011). An adaptive management approach is needed, where forest managers are trained to expect the unexpected (Millar, Stephenson and Stephens, 2007).

In the case of outbreaks, additional carbon emissions can be avoided through sanitation felling and replanting with productive species (Box 16). A lack of intervention, with trees left to die and decay on site (more likely with pests that kill a small proportion of individual trees spread throughout a forest stand, such as the pine processionary moth in central Europe), will result in a relatively rapid return of CO_2 to the atmosphere.

IMPROVING FIRE MANAGEMENT

Over the past decade, climate change impacts (droughts and lengthening fire seasons), combined with other factors such as land management and land-use change, have altered