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Payment for multiple forest benefits alters the effect of tree disease on optimal forest rotation length

Morag F. Macpherson[a,*], Adam Kleczkowski[a], John R. Healey[b], Nick Hanley[c]

[a] Computing Science and Mathematics, School of Natural Sciences, University of Stirling, Cottrell Building, Stirling FK9 4LA, UK
[b] School of Environment, Natural Resources and Geography, College of Natural Sciences, Bangor University, Bangor, Gwynedd LL57 2UW, UK
[c] School of Geography & Geosciences, University of St Andrews, Irvine Building, North Street, St Andrews, Fife KY16 9AL, UK

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ABSTRACT

Forests deliver multiple benefits both to their owners and to wider society. However, a wave of forest pests and pathogens is threatening this worldwide. In this paper we examine the effect of disease on the optimal rotation length of a single-aged, single rotation forest when a payment for non-timber benefits, which is offered to private forest owners to partly internalise the social values of forest management, is included. Using a generalisable bioeconomic framework we show how this payment counteracts the negative economic effect of disease by increasing the optimal rotation length, and under some restrictive conditions, even makes it optimal to never harvest the forest. The analysis shows a range of complex interactions between factors including the rate of spread of infection and the impact of disease on the value of harvested timber and non-timber benefits. A key result is that the effect of disease on the optimal rotation length is dependent on whether the disease affects the timber benefit only compared to when it affects both timber and non-timber benefits. Our framework can be extended to incorporate multiple ecosystem services delivered by forests and details of how disease can affect their production, thus facilitating a wide range of applications.

1. Introduction

Forests supply a wide range of important ecosystem services such as the regulation of hydrological and carbon cycles (Carvalho-Santos et al., 2014; Cudlín et al., 2013); recreational and aesthetic values (Nielsen et al., 2007; Ribe, 1989); as well as the conservation of biodiversity (Johansson et al., 2013). They can also provide timber revenues to private forest owners and managers. However, like many other natural resources, forests are experiencing many challenges, one of which is the increasing pressure from novel pests and pathogens (Gilligan et al., 2013). Changing climate (Netherer and Schopf, 2010; Pautasso et al., 2010; Sturrock, 2012), globalisation of trade and the synonymous increase in the volume and diversity of plant species and products being traded (Gilligan et al., 2013; Work et al., 2005) are just a few of the causes of an increase in geographical ranges of pest and pathogen species. With these factors unlikely to diminish in the near future, it is very important to consider the effect of disease on multiple-output forests and how they are managed. More specifically, in this paper we consider the management decision of the time of clear-felling and ask: what is the effect of disease on the optimal rotation length of a multiple-benefit forest?

How to modify forest management to make forests less susceptible to climate change effects has become a popular theme in the literature (Millar et al., 2007), and while climate and disease risks are intricately linked (Loehle et al., 2016; Sturrock et al., 2011), there appears to be far less material on the adaptation of forest management to create greater protection against tree diseases. Some strategies that are reported in the literature are tree species diversification (Castagneyrol et al., 2014; Churchill et al., 2013; Jactel and Brockerhoff, 2007; Perry and Maghembe, 1989), alteration of spatial structure (Condeso and Meentemeyer, 2007) and adapting silvicultural practices such as thinning (Bauce and Fuentealba, 2013; D'Amato et al., 2011). More recently, Marzano et al. (2017) identified 33 disease management options applicable to combat the needle blight pathogen of *Pinus* spp. trees *Dothistroma septosporum*, ranging from increasing knowledge of the pathogen system to changes in initial forest design, such as lower initial tree stocking density. Most of these strategies are preventative and attempt to reduce the risk of initial infection. This is largely because there is little that can be done to combat most pathogens once they have arrived.

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* Corresponding author.
E-mail address: mfm@cs.stir.ac.uk (M. Macpherson).

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However, some within-rotation options include: a heavier thinning regime (for example against *D. septosporum*; Quine et al. (in preparation)); chemical sprays or biological control (for example treating stumps with urea or a biological control agent *Phlebiopsis gigantea* can help prevent germination and growth of aerial basidiospores of *Heterobasidion annosum* that causes root and butt rot of conifers; (Johansson et al., 2002) ; and clear-felling the forest early (for example in the case of widespread epidemics). All these management strategies and decisions have direct implications not only for timber production but also for the non-timber services that are produced by forests. For example in 2013–14, 575 sites in the UK were served with a Statutory Plant Health Notice requiring a total of 4.8 thousand hectares of forest to be felled in a bid to halt the progression of the pathogen *Phytophthora ramorum* (Forestry Commission Scotland, 2015). Such removal of timber not only affects the forest owner through revenue loss, but may also negatively affect the supply of non-timber benefits, e.g. through habitat loss which may disrupt wildlife (Appiah et al., 2004; Rizzo and Garbelotto, 2003). Thus, management decisions should anticipate the effect of pests and diseases on both the timber and the non-timber benefits of a forest. This is the focus of our paper.

Finding the optimal rotation length for a forest when disease is present is an economically important decision for a forest manager, since the arrival of pests and pathogens can lead to losses in market values through: reduction in tree growth, for example *D. septosporum* causes significant defoliation that can greatly reduce growth rate (Mullett, 2014); reduction in timber quality of live trees, for example *Heterobasidion annosum* decays the wood in the butt end of the log which may reduce the value of the timber (Pratt, 2001; Redfern et al., 2010); an increase in the susceptibility to secondary infection, for example *Hymenoscyphus fraxineus* and *Phytophthora ramorum* causes significant damage to the bark and cambium therefore increasing the rate of infection of wood decay fungi (Forestry Commission Scotland, 2015; Pautasso et al., 2013); or at the scale of the forest stand the disease may increase the proportion of trees that are dead and thus subject to wood decay, for example *Ips typographus* has killed trees in more than 9000 ha of *Picea abies* forest in Europe. In the case of an epidemic, large areas of monoculture forest may be felled simultaneously to try to halt disease spread (as is currently taking place in response to the *P. ramorum* infection of *Larix* spp. in South Wales and South West Scotland (Forestry Commission Scotland, 2015), thus a large influx of material to local sawmills may cause congestion and market saturation (however we do not model this scenario explicitly as that would require a reduced price for all timber independent of its infection status).

Despite the important impact of tree pests and pathogens, and the variety of analyses within the optimal rotation length literature (Newman (2002) found 313 published books and articles in over sixty journals since Faustmann's novel paper on optimal rotation length analysis), there is a lack of published work linking the effect of disease to the optimal rotation length. In Macpherson et al. (2016) we analyse the effect of disease on the optimal rotation length of an even-aged forest by creating a generalisable, bioeconomic model framework, which combines an epidemiological, compartmental model with a single-rotation Faustmann model (describing the net present value, NPV, of a forest by including a one-off establishment cost and timber revenue; (Amacher et al., 2009)). We found a key trade-off between waiting for the timber to grow and the further spread of infection over time: the optimal rotation length, which maximises the NPV of the forest, is reduced when timber from infected trees has no value, but when the infection spreads quickly, and the value of timber from infected trees is non-zero, it can be optimal to wait until the disease-free optimal rotation length to harvest. However, this set-up is representative of plantation forests where management decisions are driven by timber production only (and non-timber values are not considered).

It is, however, commonly recognised that the value of forests extends beyond timber; and Faustmann's original model has since been extended to include the benefits of non-timber goods (Hartman, 1976; Samuelson, 1976). Hartman (1976) showed that ignoring such benefits can lead to a suboptimal rotation length. Since then, the inclusion of non-timber benefits has become a cornerstone of optimal rotation length analysis, with studies examining the effect of including: the cost of maintaining the provision of recreational services (Snyder and Bhattacharyya, 1990); carbon sequestration, taxes or subsidies (Englin and Callaway, 1993; Price and Willis, 2011; Van Kooten et al., 1995); timber and carbon sequestration benefits while maintaining a given level of biodiversity in a single forest (Nghiem, 2014); and the interdependence of the provision of amenity services from adjacent forests (Koskela and Ollikainen, 2001; Swallow and Wear, 1993). These models generally depend on a function that describes the production of timber and non-timber benefits through time. It is (relatively) easy to quantify the timber value of a forest using appropriate species yield growth curves, and the timber price can be taken from market data. It is harder to do this for non-market benefits; however, recent techniques for valuing non-timber benefits have been developed (such as contingent valuation), and this can help inform the functions describing the non-timber benefits in such models (Bishop, 1999).

In this study we extend the bioeconomic model in Macpherson et al. (2016) by assuming that the forest owner has an interest in non-timber benefits such as biodiversity, carbon sequestration and/or recreation as well as timber benefits priced by the market. We do this by including a "green" payment which provides an economic incentive for the private forest owner to take into account the non-timber benefits of retaining tree cover when making decisions (the NPV of the forest is therefore similar to a single-rotation, Hartman model). This green payment could be thought of as a form of payment for ecosystem services; and we assume that it increases linearly dependent on the area of the forest. While a simplification, this allows us to investigate the effect of disease on the optimal rotation length of a multiple-output forest and undertake analysis of sensitivity to key parameters (describing the spread of infection and impact of disease on the timber and non-timber values); we also discuss how the function describing the non-timber benefits can be adapted to depend on other forest attributes (such as the age of the trees) in the Discussion section.

Traditional optimal rotation length analysis is conducted over multiple rotations where trees are perpetually planted and harvested, thus synonymously incorporating the benefit of the land (Amacher et al., 2009). In our model we analyse the effect of disease on the optimal rotation length over a single rotation, and use a 'land rent' term to include the future benefit after harvest. Including multiple rotations in our model in a more specific way would require an assumption of what happens to the level of infection between rotations (i.e. if and how the pathogen carries over to the next rotation after a harvest). This adds much complexity to the system since the carry-over of disease is very pathogen specific. Moreover, despite the use of multiple rotations to find the optimal rotation length in modelling the effects of other catastrophic events (such as fire or wind; (Englin et al., 2000)), these disturbance events have many dissimilarities with disease. These include: the speed of progression, the symptoms, the management response once detected, the potential to salvage timber and the irreversibility due to long-term persistence of many pathogens following their invasion. Therefore, we use a single rotation set-up with land rent after harvest in order to focus on the central issue of our paper: the interaction of disease with timber and the non-timber benefits.

The first key aim of this paper is to use the bioeconomic model to examine what effect disease has on the optimal rotation length of a multiple-output forest. We recognise, however, that disease can affect the provision of non-timber outputs differently. For example, a