Forestry Commission

Research Note

Biodiversity and rotation length: economic models and ecological evidence

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This Research Note presents the findings of a study which examined how biodiversity changes with stand age, with a view to incorporating it into optimal forest rotation length modelling. The study reviewed relevant literature and analysed Forestry Commission Biodiversity Assessment Project data. The review revealed no simple or universal response of biodiversity to stand age. However, there was more evidence of biodiversity increasing with stand age than falling (or not changing) and, with regard to habitat requirements for birds and mammals in British forests, there is evidence that after a brief initial increase, biodiversity declines until around 20 years and thereafter increases again. While only a limited number of economic models were found which linked biodiversity and rotation length, two distinct approaches to such work were identified: first, a direct approach which accounts for biodiversity values when estimating net present values and, second, an indirect approach which employs biodiversity management constraints in the modelling. The data analysis also revealed, in most cases, no evidence of significant changes in biodiversity with stand age. Upland Sitka spruce stands were an exception, where biodiversity levels were higher in young forests and again in more mature forests and at a minimum at around 40 years old. Overall, the study found that both the ecological evidence linking biodiversity and stand age and the economic modelling accounting for that linkage are limited. Therefore, a substantial challenge remains to incorporate biodiversity into rotation length models, and recommendations are made to address this.

Forest Research

Introduction

Biodiversity is a major focus of international environmental policy and practice. Its vital role in sustaining life on Earth and underpinning the provision of all ecosystem services has become increasingly recognised, including in the Convention on Biological Diversity (CBD) signed by 150 governments at the 1992 Rio Earth Summit and the Millennium Ecosystem Assessment (MEA, 2005), with the UK National Ecosystem Assessment (UK NEA) (2011, p. 64) adopting similar views.

It is widely recognised that biodiversity in woodlands varies across different biogeographical zones and depends upon the tree species mix, forest management approach and stand structure. Although biodiversity value is sometimes particularly ascribed to mature old-growth forests, the relationship between stand age and biodiversity may be complex, as some species may thrive when trees are younger, or prior to canopy closure. Furthermore, the relationship with stand age may also be influenced by geographical location (e.g. related to limits in the range of particular species, soil quality), land-use history (e.g. continuity of woodland presence), tree species present, origin of the forest stand (natural regeneration versus planted) and climate change impacts.

This study explores links between biodiversity and stand age with a view to including it in stand-level optimal rotation length models and associated forest management tools. The investigation is conducted through literature reviews and re-examination of Forestry Commission Biodiversity Assessment Project data.

Background

Biodiversity can be conceptualised and measured in a variety of ways. The CBD states that biological diversity is 'the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems'. This study focuses primarily on the total numbers of different species ('species richness').

Biodiversity is a complex concept that can be particularly difficult to incorporate in economic analyses. This is due in part to it having system properties where the whole is more than the sum of its parts. It is also partly due to the benefits being widely spread across time and space, often being characterised as a public good (see Box 1) that is both 'intergenerational' – benefiting more than one generation, and 'global' – benefiting everyone more or less worldwide (Helm and Hepburn, 2012). In addition to its direct role in the delivery of 'final goods' such as recreation and tourism, it also has an indirect role in the production of others, such as timber production and carbon sequestration, through its contribution to 'intermediate' ecosystem services such as soil fertility and pest control (EFTEC, 2011; UK National Ecosystem Assessment, 2011).

What is the UK approach to biodiversity?

The current approach to achieving UK forest biodiversity objectives tends to be primarily in terms of regulation (e.g. conservation of areas associated with protected species and habitats) and application of specific measures (e.g. for habitat restoration, landscape connectivity, structural and tree species diversity), but less often through routine forest management practices (e.g. rotation length decisions). However, there may be potential both for the Forestry Commission and other woodland owners to adopt a more nuanced approach based upon a wider 'ecosystem services' approach, taking account of evidence linking biodiversity to stand age and forest structure. There is also potential for accounting for changes in biodiversity in modelling forest management at stand level (including continuous cover forestry) and/or at a landscape scale, as well as in appraising forestry policy options more widely.

The economic value of biodiversity

Estimating aggregate economic values for biodiversity, as opposed to valuing marginal changes, can be theoretically problematic (Helm and Hepburn, 2012, p. 6). However, it is notable that biodiversity values estimated in economic studies are relatively large compared to most other woodland ecosystem service values. For example, the non-use value (see Box 1) of biodiversity for British forests has been conservatively estimated (leaving almost 2.2 million hectares, or 81% of British forests, with no assigned biodiversity value; an aggregation of marginal values, reflated to 2013 prices) at £500 million per year (Willis *et al*., 2003). This is more than double the estimated current annual standing sales value from UK timber production, for which analysis for the UK NEA (Valatin and Starling, 2011) for instance, reported a maximum of over £190 million in 1995 at 2010 prices. Valuing the 10 million green tonnes of softwood and 0.5 million green tonnes of hardwood produced in the UK in 2012 (Forestry Commission, 2013) at an average price for Forestry Commission coniferous standing sales of £14 per cubic metre over bark (approximately £17 per green tonne) (Forestry Commission Timber statistics, www.forestry.gov.uk/statistics), would suggest a current annual revenue of UK softwood production of the order of £170 million. The estimate for woodland biodiversity is at a similar order of magnitude to the value estimated for recreational visits to British woodlands, the highest of the non-market values estimated in the study (Willis *et al*., 2003), although below the social value of net carbon sequestration estimated in analysis for the UK NEA of around £700 million during 2002 (Valatin and Starling, 2011, Fig. 17, p. 33).

Box 1 Definitions

Public good is a good that is both non-excludable and non-rival in that individuals cannot be effectively excluded from use and where use by one individual does not reduce availability to others.

Non-use value is the value that people assign to goods/services even if they never have and never will use them. Non-use values are associated with knowledge that environmental resources continue to exist (existence value), or are available for others to use now (altruistic value) or in the future (bequest value).

Hartman optimal rotation. Richard Hartman in 1976 (Hartman, 1976) considered how the optimal rotation length changes if one also considers other ecosystem services provided by forests that depend on the age of the forest. These 'amenity services' of forests are considered to include recreation, wildlife, wilderness, visual amenity, water quality, carbon sequestration and biodiversity. It is Hartman's assumption that these services depend only on forest age.

Ecological resilience is the amount of disturbance that an ecosystem could withstand without changing self-organised processes and structures (defined as alternative stable states), that is before flipping into a different stable state (Gunderson, 2000).

Aims and objectives

The aim of the study was to examine links between forest or woodland biodiversity and stand age with a view to exploring how biodiversity could be incorporated in an optimal rotation length model. This is part of a wider agenda of accounting for the multiple benefits provided by woodlands in decision-making frameworks for sustainable forest management. An optimal rotation length model currently under development by Forest Research covers two ecosystem services (carbon and timber) as well as accounting for specific risks (windthrow) that may be affected by climate change. Extending such traditional models from a focus on timber production to the wider benefits of woodlands will allow more comprehensive comparisons between management alternatives such as leaving stands unmanaged, or with minimal harvesting intervention.

Three specific objectives are:

1. To review approaches taken in previous work incorporating biodiversity in rotation length models.

2. To review evidence of how biodiversity varies with the age of woodlands and between woodland types, using woodland biodiversity indicators and considering different forest management approaches (mixed age/single age stands, mixed species/single species, coppice rotations) and climatic conditions.

3. To provide recommendations on approaches to incorporating biodiversity when modelling optimal rotation length.

Methodology

The study was primarily based on literature reviews first covering ecological evidence and then economic evidence in line with the Government Social Research Service Rapid Evidence Assessment guidance and re-analysis of ecological data from the 52 stand plots of the Forestry Commission Biodiversity Assessment Project established in 1993 (Humphrey, Ferris and Quine, 2003). Ecological and economic evidence is summarised separately, before drawing together these strands in discussing broader underlying issues, overall study conclusions and recommendations. Although no attempt is made to account for uncertainties of future climate change and consider the extent to which existing relationships between biodiversity and stand age may be expected to continue to hold – we bear these issues in mind in drawing our recommendations.

Results

We present the results below in six sub-sections, starting with ecological evidence for influence of stand and management type on biodiversity as this would underpin any economic analysis. The last two sections review the economic evidence. A full list of references consulted can be obtained from the authors.

Evidence from the literature

This sub-section reviews evidence from the literature of how biodiversity varies with stand age and between woodland types using woodland biodiversity indicators.

Although our search for relevant literature was not restricted to particular methods of assessing biodiversity, changes in biodiversity were most frequently reported in the literature in terms of species richness. Biodiversity indicators (e.g. coarse woody debris, stand structural diversity) were also sometimes assessed.

A high proportion of the studies focused on arthropods (invertebrates such as insects, arachnids and crustaceans). Approximately half of the arthropod studies investigated beetles. Ground vegetation and lichen also featured frequently with fewer studies on birds, mammals and fungi.

The studies found mixed results for many of the taxa on the relationship between biodiversity and stand age with variation between studies and species group. For example, for arthropod species there were 18 cases where biodiversity increased with stand age, 12 cases where it fell and 3 cases where stand age had no effect. A clearer trend was observed for lichen, where the majority of studies (*n*=15) revealed a positive effect of stand age on species diversity, with many of these following a linear positive relationship with rotation age. Coarse woody debris is a biodiversity indicator that, unsurprisingly, also generally increases with stand age.

From the wide range of responses found in the studies, a relationship between biodiversity (or even taxonomic groups) and stand age is not easily identified. The variety of responses is likely to be due in part to the many extraneous influences on woodland biodiversity, such as site history, tree species composition, topography and climate.

Overall there was more evidence of an increase in biodiversity with stand age. Of the studies with significant results, 66 indicated an increase in species richness with stand age, 33 a decrease and 10 were neutral. These results are summarised in Figure 1.

Birds and mammals

A separate analysis was undertaken for birds and mammals, as these often feature prominently in management objectives.

The response of birds and mammals to stand age, in terms of species richness and relative abundance was assessed from evidence of habitat requirements reported in the literature (Fuller, 2003; Harris and Yalden, 2008). Use of each age class was scored 0–3 representing the frequency of use for each species (0 none; 1 occasional; 2 moderate; 3 high). In total 73 bird species and 49 mammal species were considered.

The results for both birds and mammals relative abundance indicated a small peak in the use of young stands with a small decline in the thicket stage, followed by an increase in the relative use of mature stands (Figure 2).

The results point to diversity generally increasing with rotation length, with a dip in early mid rotation (at around 20 years) and the greatest value in mature stands (Figure 2). These changes reflect the broad changes in vegetation structure accompanying stand ageing, namely the initial establishment of herb and shrub layers followed by replacement by thicket and then a mature tree canopy.The development of a mature stand is typically associated with partial recovery of ground and shrub vegetation as well as increasing amounts of dead wood and canopy depth.

The response of species richness to stand age was much weaker than for relative use, suggesting that age-related changes affect habitat suitability for many species but the overall number of species remains relatively constant.

Evidence from re-examining Forestry Commission Biodiversity Assessment Project data

The Biodiversity Assessment Project was established by the Forestry Commission in 1993 in response to a growing awareness of the value of forests for wildlife, and the need to develop management practices suited to its promotion. The project involved an assessment of presence and abundance of species in 52 even-aged forest stands distributed across GB, and included sites encompassing a range of tree species, site types and plantation ages (Humphrey, Ferris and Quine, 2003). The data obtained from the project represents the most extensive data on biodiversity for GB forests that currently exists.

Figure 1 Number of studies from the literature with significant results indicating an increase, decrease or neutral response to stand age by taxonomic group/biodiversity indicator.

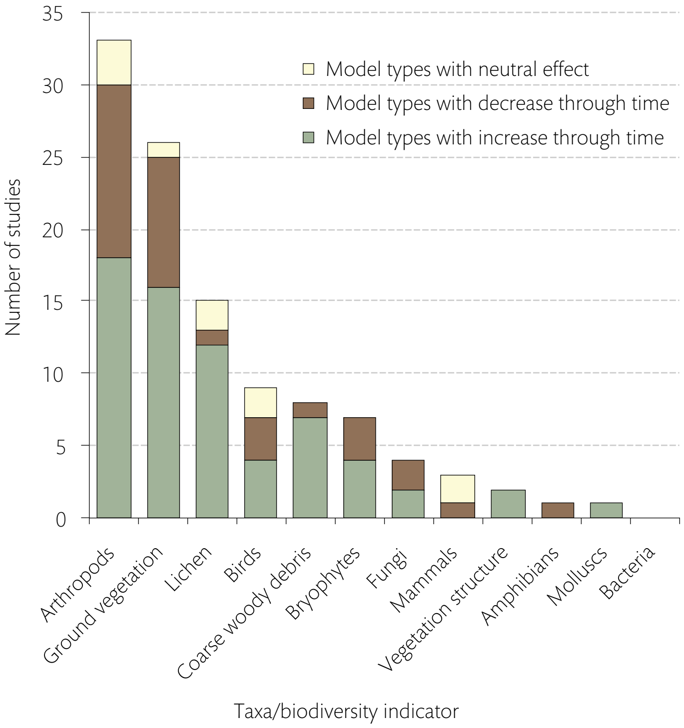
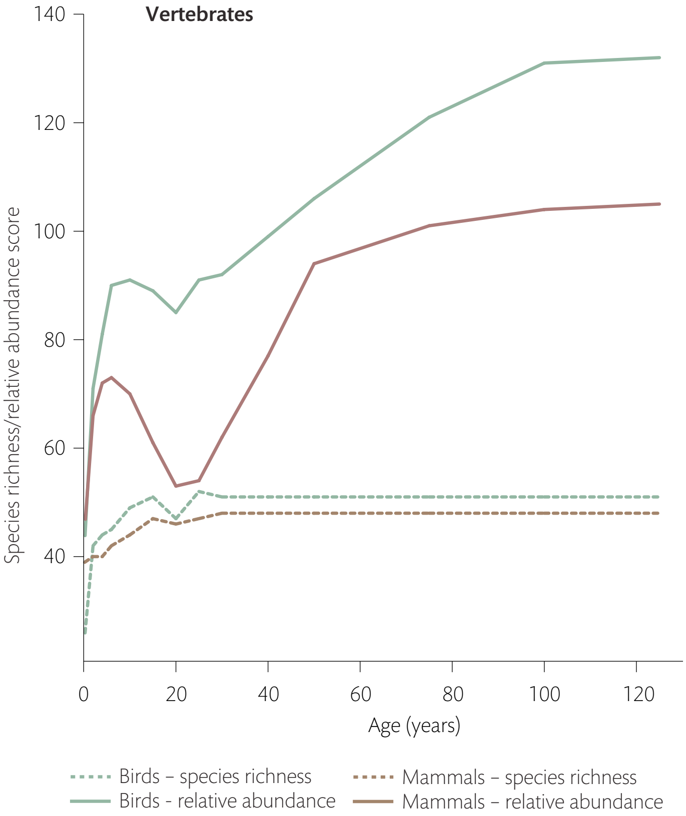


Figure 2 Relationship between vertebrate species richness and relative abundance and stand age in British forests.

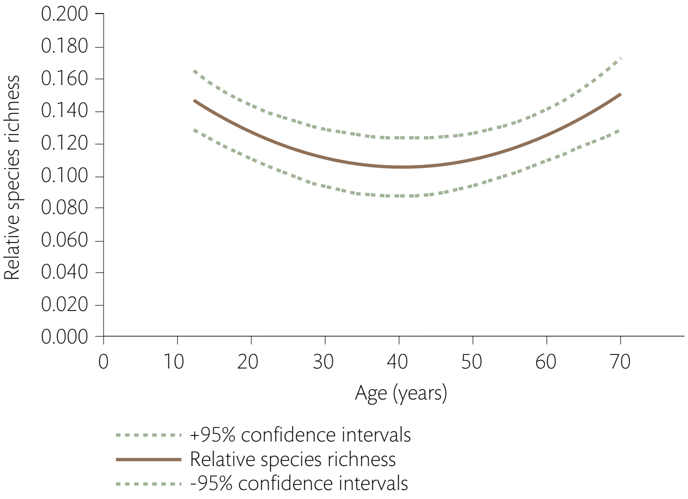


For each tree species and elevation class (lowland, foothills and upland) the dataset includes two sites considered similar ('replicates') with up to four different stand ages at each site, representing different stages of development from pre-thicket to over-mature. Thus, the dataset contains a maximum of eight observations for each tree species.

We re-examined the data with a view to obtaining evidence of the functional relationship between biodiversity and stand age. However, it proved impossible to obtain a full chrono-sequence of stands for some tree species and elevation classes, with the result that there was limited scope for determining a general relationship between biodiversity and stand age.

However, it proved easier to obtain chrono-sequence of comparable stands of Sitka spruce in upland sites. These revealed a clear trend, with biodiversity lowest in mid-rotation than in young and mature stands (Figure 3). Sitka spruce trees are particularly efficient at light interception, with the result that forest vegetation is forced through acute structural change as the under-storey is almost entirely eliminated during transition from young-mid rotation phases.

Figure 3 Biodiversity response through the stages of forest growth from pre-thicket to mature, in Sitka spruce upland forests.



Woodland type and management and biodiversity

This sub-section reviews the evidence of the influences of woodland type and forest management on how biodiversity varies with stand age.

Identifying impacts of different interventions on biodiversity under differing management systems proved very difficult. The most substantial problems identified were:

- Timescales of studies are often too short to determine an effect.
- Species choice for study is selective or not sufficiently representative of biodiversity as a whole.
- Results are often contradictory and different species respond in different ways.
- Site conditions are often not truly comparable.
- The scales of studies are rarely equivalent.
- Measuring species richness is limited and can favour early successional species at the expense of the woodland specialist species (e.g. birds such as woodpeckers which are highly dependent on woodland) most under threat.

The difficulties associated with comparing studies meant that there was insufficient evidence in the literature to identify the best interventions for biodiversity. These would depend on individual site conditions and on a multi-scaled approach: incorporating multiple stands and the broader landscape.

The literature did reveal certain characteristics of specific management systems that are beneficial or detrimental to aspects of biodiversity and these are summarised in Table 1.

Table 1 Management systems and biodiversity.

Silviculture	Characteristics identified as positive for biodiversity	Characteristics identified as detrimental to biodiversity
Clear cut	• Large open spaces • Refuge for grassland species in intensively managed arable landscapes • Provision of edge habitat • Provide horizontal diversity on a landscape scale	• Even-aged structure • Lack of horizontal and vertical stand complexity • Structure favours generalists and excludes woodland specialists • Management technique precludes many species • Lack of natural regeneration • Lack of tree species diversity
Coppice	• Permanent and temporary open space • Standard trees • Varied ground flora • Structural diversity • Deadwood in abandoned coppice	• Lack of deadwood in active coppice • Lack of tree species diversity • Lack of structural diversity associated with abandoned or over-mature coppice
Selection felling	• Stand continuity • Structural complexity • Standing biomass • Tree age distribution • Gap release and open areas • Horizontal diversity	• Few refuges for species susceptible to disturbance • Open areas can be too small to benefit a full suite of open habitat species • Absence of large veteran trees
Shelterwood	• Structural diversity in mid-storey • Canopy trees • Seedling regeneration	• Lack of open space, ground flora and microhabitats • Lack of horizontal diversity • Even-aged structure and lack of mature forest

Consideration of the factors in Table 1 could help inform management decisions as they also broadly equate to the indicators that are widely recognised as proxies for biodiversity (e.g. deadwood, structural diversity). Such indicators have obvious limitations – they indicate rather than determine – and they do not take account of rare species or species with particular cultural value. Nevertheless, they can be used to inform principles of management that increase the potential for biodiversity (e.g. high tree species diversity, diverse age distribution of trees, areas of open space). However, as responses to management differ within taxonomic groups, conservation of particular species of ecosystem service interest (e.g. butterflies, wood ants, earthworms) would require a more individually targeted approach taking specific site, species and landscape characteristics into consideration.

Valuation of biodiversity

This sub-section reviews the evidence of how biodiversity can be reliably monetised and the influence of spatial and landscape scale issues.

A number of examples of monetary valuations of forest biodiversity (though not linked directly to rotation length) exist (Garrod and Willis, 1997; Hanley *et al*., 2002; Horne, Boxall and Adamowicz, 2005; Nijkamp, Vindigni and Nunes, 2008; Czajkowski, Buszko-Briggs and Hanley, 2009; Christie *et al*., 2011; Thiene, Meyerhoff and De Salvo, 2012; Tyrväinen, Mäntymaa and Ovaskainen, 2014). There are unresolved issues related to eliciting value from the public for a concept as complex as biodiversity. For example, in survey-based economic valuation studies hypothetical bias can occur with respondents overstating values if they do not expect to have to pay the costs. Additionally, there can be large differences between values expressed in such surveys for willingness to accept payment in exchange for damages and willingness to pay in order to avoid damages. These have led to continuing debate in the literature about the robustness and validity of existing valuation methods.

An interim conclusion, in line with UK NEA follow-on (2014, Work Package Report 3, p. 13), is that some valuations of use values of some aspects of biodiversity (e.g. watching birds and wild animals) could be sufficiently robust to be included in modelling work. However, for wider biodiversity considerations, especially including non-use values, a conservation approach, which adopts some set of management constraints to deliver a non-decreasing biodiversity level, should be adopted given the lack of robust valuations. Even this approach is difficult to implement due to absence of developed woodland biodiversity metrics. The existing metrics are often based on criteria for condition (e.g. diverse tree age and structure; deadwood over 20 cm diameter is present) of semi-natural woodland and do not take into consideration the structure of plantation or commercially managed forests that represent a larger group of more than a quarter of the UK woodlands.

Biodiversity in economic models of rotation length

This sub-section presents results of a review of studies incorporating biodiversity in economic models of rotation length. None of the papers reviewed were for UK woodlands. All the papers use bespoke datasets and estimated functional relationships for their particular study areas. Thus, although the studies illustrate how linking biodiversity and rotation age could be tackled in principle, the results are not easily transferable to a UK context.

Only two studies reviewed incorporate values for biodiversity directly in modelling optimal rotation length. Both studies (Koskela *et al*., 2007; Miettinen *et al*., 2014) incorporate biodiversity in the objective function (net present value). The value of biodiversity is determined from a separate contingent valuation study.

The first study (Koskela *et al*., 2007) applied the extended Hartman rotation (see Box 1) framework and ran a simulation based on Finnish data for a pine stand in southern Finland. Biodiversity conservation was modelled through the volume of green tree retention (GTR) at final felling. GTR differs from conventional shelterwood or seed systems in that retention trees are left permanently uncut to attempt to mimic and restore natural disturbance regimes. In order to maximise the combined net present value of timber and biodiversity the study suggested longer rotation periods by comparison with the standard Faustmann model and a higher volume of GTR (volume depends positively on biodiversity valuation).

The second study (Miettinen *et al*., 2014) examined alternative whole-tree and stem-only harvesting regimes when water quality, biodiversity conservation and carbon sequestration ecosystem services are included in the analysis on drained peatland forests. However, due to data problems the study could not estimate optimal rotation age or the biodiversity conservation impact.

Other studies have analysed the impact of biodiversity on rotation length indirectly through adopting constraints or specific forms of management. Examples of the types of biodiversity conservation measures included were:

- not disturbing growth in key areas;
- selective or shelterwood felling;
- maintaining at least 30% of the woodland as old forest;
- maintaining a 20% share of the woodland as deciduous forest;
- 10 retention trees per ha;
- increasing the rotation cycle by 50%;
- not thinning;
- using only natural regeneration;
- bird density indicator, which depends positively on stand age and size, being equal to or exceeding a minimum viable population threshold;
- volume of GTR at final felling;
- maintaining a minimum area of 'good' wildlife habitat quality for a chosen set of vertebrate species.

The inclusion of these measures was shown to affect the net present value of the optimal rotation length. Three studies found that inclusion of a biodiversity constraint leads to an increase in the optimal rotation length and a lower net present value (by up to 43%) compared with unconstrained optimisation.

A more general European study linking different forest management alternatives, economics and biodiversity (Duncker *et al*., 2012) illustrates how high management intensity (productive forests for timber and biomass) can negatively impact on biodiversity indicators (woody debris, tree size distribution and number of tree species). The study simulated forest management units representing Central European forest ecosystems in the submontane vegetation zone under a humid–temperate climate with acidic soils. This supports the common perception that a trade-off often exists between maximising the economic value of timber production and the preservation of biodiversity at stand level.

Although a single-stand perspective is the traditional approach in forest economics, some recent studies suggest adopting a broader-scale approach that views the forest as comprised of a number of stands of differing characteristics (e.g. age, species, amount of open space, canopy structure). Given the habitat requirements for different species, optimisation with biodiversity benefits included may be best accomplished in a multi-stand model rather than with the current well-developed and widely applied single-stand approaches of Faustmann and Hartman. Such models can be developed to cover a number of stands but are more complex and tend to have a fixed time horizon (unlike Faustmann type models, which consider an infinite series of rotations).

Support for the multi-stand approach also comes from the fact that some forestry production processes are non-linear. For example, the relationship between profit and production of ecosystem services such as timber and biodiversity. Such non-linear behaviour may arise, for example, from fixed forest management costs and administration constraints. In this situation it may be optimal to spatially separate management objectives for different stands in some cases (Noack *et al*., 2010; Robert and Stenger, 2013). Thus one stand may be best managed for optimal timber production while another is optimised for biodiversity or the delivery of ecosystem services such as carbon sequestration and recreation.

Conclusions

The study reached the following conclusions on quantifying biodiversity and its links to stand age:

- The concept of biodiversity is complex with no consensus at present in either the ecological literature or the economic literature on how best to quantify it. A consequence is the difficulty of encompassing all the aspects of interest in a single metric suitable for incorporation into rotation length models.

- There is no universal (or simple) response to stand age, with variations between taxa and sites (as might be expected). In the published international literature there is more evidence of increasing species richness with stand age than of a fall or of no change. However, the literature on habitat requirements for birds and mammals in British forests suggests that after a brief initial increase in species richness and relative abundance with stand age, these both then fall in the thicket stage (with a minimum at around 20 years), thereafter increasing again. Some of the increase is only obtained at ages beyond typical rotation lengths. Re-analysis of data from the Forestry Commission Biodiversity Assessment Project showed very little change in overall biodiversity levels with stand age. Upland Sitka spruce stands were an exception, where biodiversity levels were highest in young forests and mature forests with a minimum for 40 year-old stands.

- There is no clear evidence on the impact of alternative forest management approaches such as continuous cover forestry and how these differ from traditional even-aged stands with respect to biodiversity.

The review found that economic literature linking biodiversity and rotation length is sparse. In particular economic aspects of biodiversity and rotation length are very rarely adequately treated in research papers or their relationship investigated in any depth. Nevertheless, some strands of research were identified as potentially helpful to progress investigations into links between biodiversity and rotation length:

- Where robust estimates of biodiversity values are available a direct approach to including biodiversity in optimal rotation modelling is possible if there is knowledge of how biodiversity (or its proxy) changes over a rotation. However, such circumstances are rare at present.

- When the biodiversity value is unknown it may still affect the net present value of the optimal rotation length model through a set of management constraints required for biodiversity conservation. In this case an indirect approach is possible. This involves incorporating these constraints and associated costs into the optimisation problem.

- Optimisation with biodiversity benefits included may be best accomplished in a multi-stand model rather than the more common single-stand approach as different taxa/species respond differently to forest age and structural characteristics (canopy closure) and optimal management may vary within the multi-stand forest.

- It may be optimal to spatially separate management objectives for different stands in a forest for some forestry production processes. For example, the relationship between profit and production of ecosystem services such as timber and biodiversity is non-linear.

- Some argue (Perry, 2013) that in the presence of climate change uncertainties and still largely unknown ecological interactions among species, the pursuit of objectives based on optimisation approaches may be misguided. Instead, they suggest the focus should be on increasing ecosystems ecological resilience (see Box 1) and functional diversity based on the precautionary principle. However, empirical evidence demonstrating the superiority of forestry management approaches based upon maximising ecosystem resilience appears to be lacking at present.

- There are examples of economic valuations of forest-related biodiversity but the contingent valuation approach often used for this is still fraught with many unresolved issues, which means that estimated values should be used with great caution.

Recommendations

As a result of our study the following recommendations are proposed:

- Further work on multi-stand forest modelling and the nature of the relationship between timber, biodiversity conservation and the provision of different ecosystem services by UK forestry is needed. This would permit the identification of conditions under which it is optimal to separate the management of stands by forestry objective, and where biodiversity objectives are best pursued in isolation rather than as part of a multi-objective optimisation approach (as implicit in sustainable forest management).

- Given the presence of climate change uncertainties and still largely unknown ecological interactions among species, empirical work is needed to investigate conditions under which it is optimal to maximise ecosystems ecological resilience rather than biodiversity. This will minimise the risk of errors associated with assuming that future relationships will be based on those from the past.

- Where vertebrates are considered most important, adopting the shape of response to stand age estimated from the habitat requirements of vertebrates in British forests (see Figure 2) is recommended.

- Foundational work on developing methods to provide robust estimates of woodland biodiversity values is still needed, including taking account of insights from behavioural economics: concerning factors (e.g. loss aversion) driving divergence between willingness to pay and willingness to accept estimates, hypothetical bias, as well as other cognitive influences on values.

- Where reliability of existing monetary biodiversity estimates is in doubt, consider ranging estimates to reflect existing uncertainties, or incorporating biodiversity in optimisation models using other approaches, such as multi-criteria analysis. Where mandatory forest management measures to preserve biodiversity are incorporated as costly constraints in forestry optimisation, the impact of these costs on the net present value may serve as a proxy for the value society places on woodland biodiversity conservation in the region of study.

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