



Continuous Cover Forestry: A Selected Bibliography 2011-2018

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Continuous Cover Forestry: A Selected Bibliography 2011 – 2018

Sam B. Manning & James D. Walmsley

Continuous Cover Forestry Group



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Forestry Group**

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This report intends to collate and review papers from a broad range of research subjects within the area of Continuous Cover Forestry and aims to be as thorough and representative as fully possible, however it is understood that some research may have been unintentionally omitted; such omissions rest solely with the author and not the CCFG.

S. B. Manning

May 2018

Front cover: A mixed species, un-even aged stand at Stourhead Western Estate, Wiltshire. Photo: © Sam Manning 2018

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Introduction

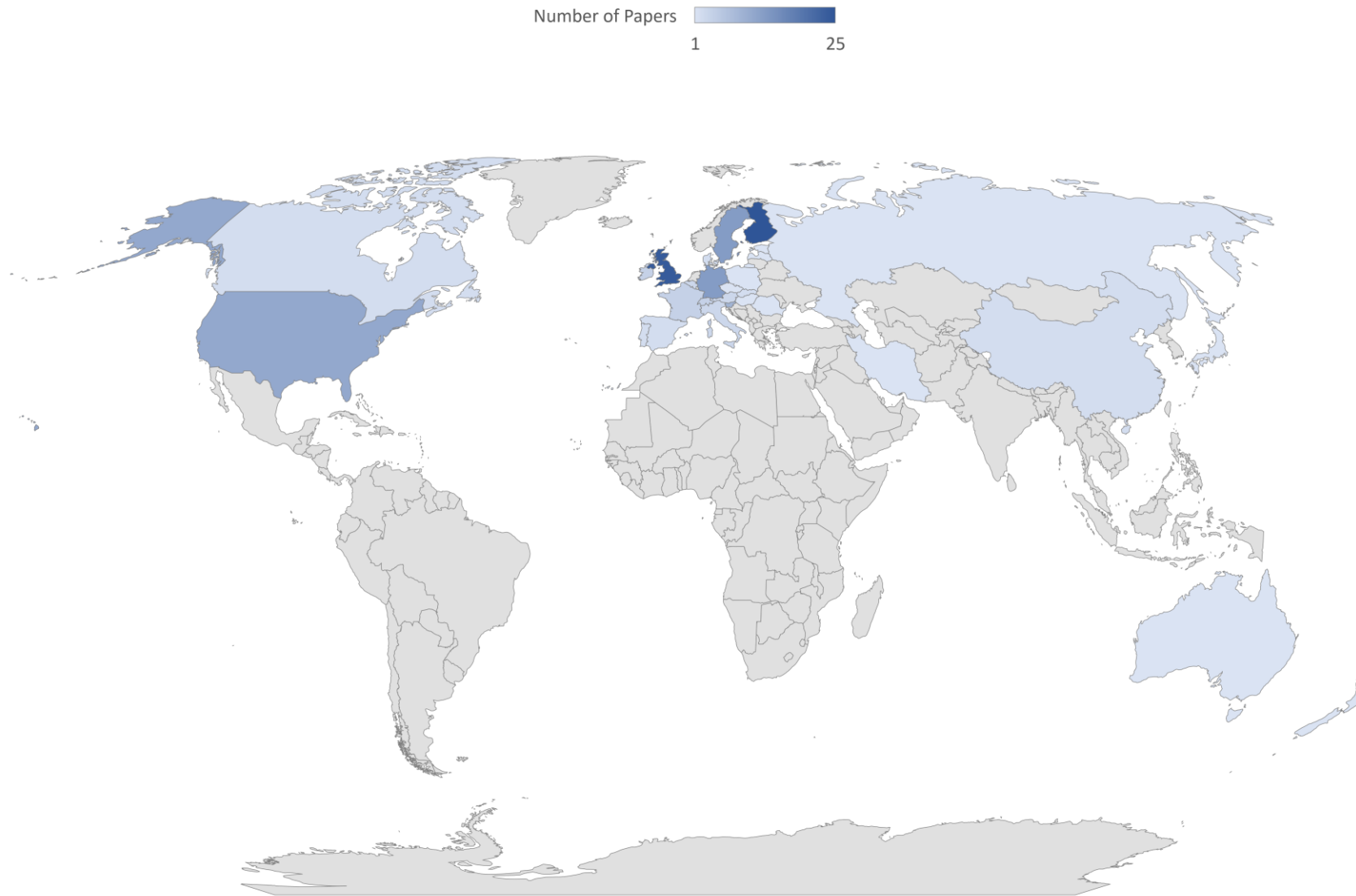
This bibliography builds on from Sharon Rodhouse and Edward R. Wilson's two previous bibliographies published in 2006 and 2010 respectively, which compiled research published in the subject area of CCF, (Rodhouse, S., & Wilson, E. R., 2006; 2010). It features a selection of peer reviewed research papers, reviews and text books published between January 2011 and May 2018, authored by academics and forest professionals from across the world. Papers written in the English language only were included, with a predominant focus on the northern hemisphere, however a few notable exceptions from Australia and New Zealand have been included. Search terms used included, 'continuous cover', 'un-even aged', 'multi-aged', 'dauerwald' and 'close-to-nature', all paired in various combinations with keywords, 'forestry', 'forest', 'woodland', 'silviculture' and 'management'. In addition to providing a list of references and abstracts, the bibliography also features a small number of analyses into the global provenance of research papers (Map 1), the proportional distribution of research subject areas (Figure 1), number of papers on CCF published each year (Figure 2), and the temporal trend of research across from 2011 – 2018 (Appendices, Figure 3). A short literature review for a selection of papers has also been included.

References:

Rodhouse, S., and E. R. Wilson. (2006) '*Continuous cover forestry: a selected bibliography*'. Forest Research Report 2. National School of Forestry, Newton Rigg. 68 pp.

Rodhouse, S., & Wilson. E.R. (2010). '*Selected Scientific and Technical Publications in Silviculture with Relevance to Continuous Cover Forestry*'. Continuous Cover Forestry Group. 7pp.

Map 1: Global distribution of published papers by location of lead author



Map 1 illustrates the geographical areas that have produced the most CCF research in the years between 2011 and 2018. With western Europe, particularly the UK and Finland, publishing the most by a considerable margin, 24 and 25 papers respectively.

Subject Class & Species Codes

Subject Class

Table 1: Key to subject classes identified for cross-referencing in the bibliography

Code	Subject Area
C	Concept, philosophy and approaches to continuous cover forestry, including social and political science
E	Economics, financial appraisal and economic modelling
H	Habitat, biodiversity, environment and amenity
M	Management and inventory of forest stands and working groups
P	Pests, diseases and other damaging agents, including impact of wildfire and deer/ other browsing animals
R	Light and regeneration, including natural regeneration
SiS	Silvicultural systems and stand dynamics, including timing, planning and intensity of designed stand interventions, tree development in forest stands, natural patterns of stand development, competition and response of stands to natural and human disturbance
W	Wind effects
CC	Carbon sequestration and climate change, including resilience to changing environmental conditions.
G	Genetics, wood science, timber quality and tree biology

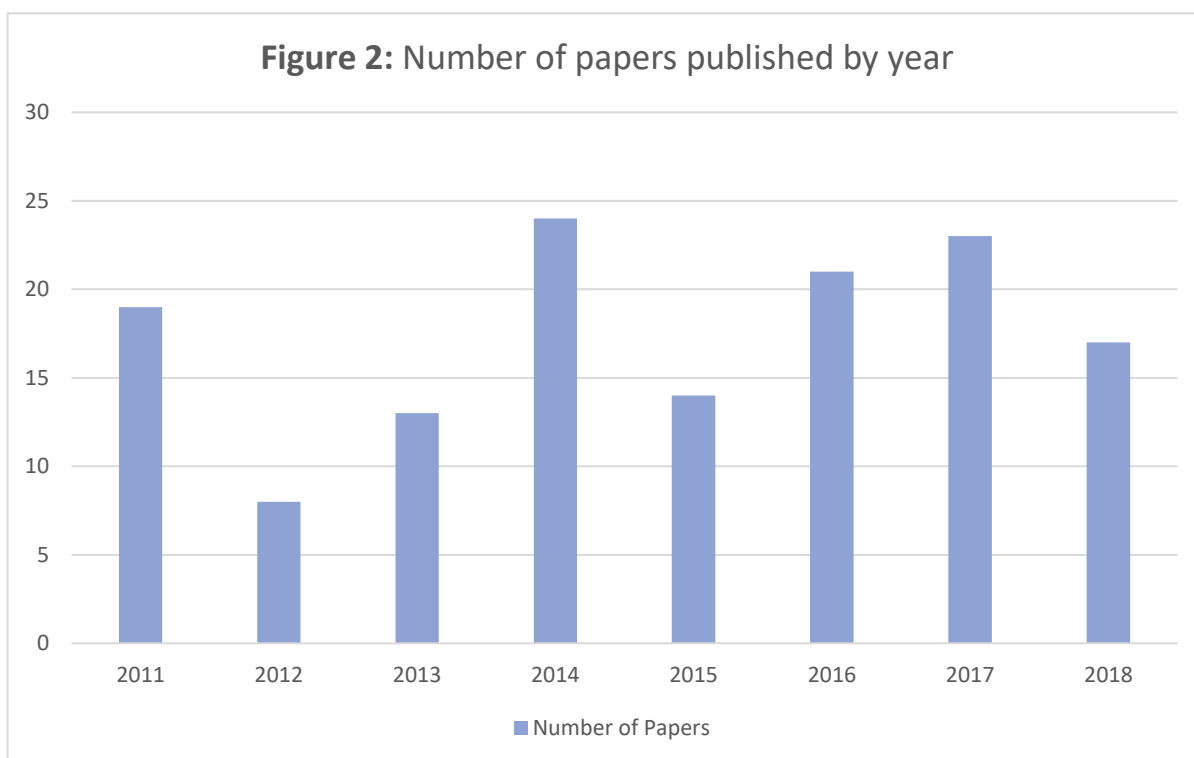
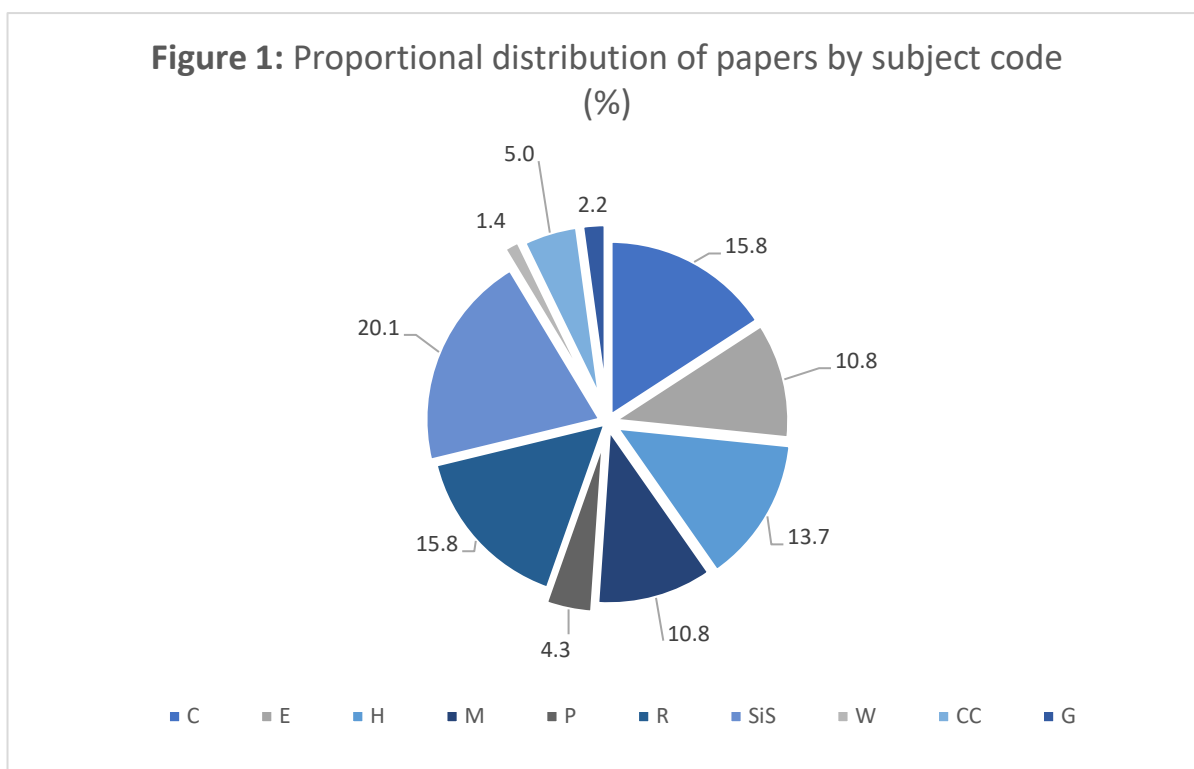


Figure 1 (above), illustrates which areas of research have received most attention by the research community, with the most popular subject areas being silvicultural systems (20.1%), concept (15.8%) and regeneration (15.8%). Areas such as genetics (2.2%), wind effects (1.4%), climate change (5%) and pests/ diseases (4.3%), have received decidedly less attention. Figure 2 shows the fluctuation in the amount of research published on CCF each year since 2011.

Species Codes

The list of 2-letter (sometimes 3-letter) species codes is adapted from Forestry Commission Management Codes (Table 1). Where the code xxx is given, it implies that the paper is of a general nature dealing with a large number of species and/or the species discussed are not commonly found in UK or Ireland.

Table 1. Species names and codes.

Scots pine <i>Pinus sylvestris</i>	SP
Sitka spruce <i>Picea sitchensis</i>	SS
Norway spruce <i>Picea abies</i>	NS
European larch <i>Larix decidua</i>	EL
Japanese larch <i>Larix kaempferi</i>	JL
Hybrid larch <i>Larix eurolepis</i>	HL
Douglas fir <i>Pseudotsuga menziesii</i>	DF
Western hemlock <i>Tsuga heterophylla</i>	WH
Silver fir <i>Abies alba</i> Mill.	SF
Other conifer	XC
Oak <i>Quercus spp.</i>	OK
Pedunculate oak <i>Quercus robur</i>	POK
Sessile oak <i>Quercus petraea</i>	SOK
Beech <i>Fagus sylvatica</i>	BE
Ash <i>Fraxinus excelsior</i>	AH
Sweet chestnut <i>Castanea sativa</i>	SC
Other broadleaves	XB
Mixed broadleaves	MB

Continuous Cover Forestry ‘Top 10 Hot List’

Following on from a tradition started by Gary Kerr in the original 2006 bibliography, a ‘hot list’ of ten papers (in alphabetical order) that aim to provide an overview of the last 8 years of CCF research has been identified by the author. This list is subjective; however, it is designed to serve as a broad sample of the subject areas for the benefit of forestry practitioners or students who have little or no prior knowledge of the subject, or for more experienced individuals seeking an update on the most recent CCF research. A short list of text books about CCF published between 2011 – 2018 has also been included.

1. **Alder, D.C., Fuller, R.J. & Marsden, S. J. (2018)** ‘Implications of transformation to irregular silviculture for woodland birds’, *Forest Ecology and Management*, 422, pp. 69–78.
2. **Davies, O. & Kerr, G. (2015)** ‘Comparing the Costs and Revenues of Transformation to Continuous Cover Forestry for Sitka Spruce in Great Britain’. *Forests*, 6(7), pp. 2424–2449.
3. **Hjältén, J., Joelsson, K., Gibb, H., Work, T., Löfroth, T & Roberge, J. (2017)** ‘Biodiversity benefits for saproxylic beetles with uneven-aged silviculture’, *Forest Ecology and Management*, 402, pp. 37–50.
4. **Kerr, G & Mackintosh, H. (2012)** ‘Long-Term Survival of Saplings during the Transformation to Continuous Cover’. *Forests* (MDPI open access journal). 3, pp. 787 – 798.
5. **Ligot, G., Balandier, P., Courbaud, B., Jonard, M., Kneeshaw, D. & Claessens, H. (2014)** ‘Managing understory light to maintain a mixture of species with different shade tolerance’. *Forest Ecology and Management*, 327, pp. 189–200.
6. **Lundmark, T. Bergh, J., Nordin, A., Fahlvik, N., Poudel, B. (2016)** ‘Comparison of carbon balances between continuous-cover and clear-cut forestry in Sweden’. *Ambio*, 45, pp. 203–213.
7. **Mason, W. (2015)** ‘Implementing Continuous Cover Forestry in Planted Forests: Experience with Sitka Spruce (*Picea sitchensis*) in the British Isles’. *Forests*, 6(4), pp. 879–902.

8. **Pretzsch, H., & Rais, A. (2016)** 'Wood quality in complex forests versus even-aged monocultures: review and perspectives'. *Wood Science and Technology*, 50(4), pp. 845-880.
9. **Pukkala, T., Laiho, O., & Lähde, E. (2016)** 'Continuous cover management reduces wind damage'. *Forest Ecology and Management*, 372, pp.120–127.
10. **Pukkala, T. (2016)** 'Which type of forest management provides most ecosystem services?'. *Forest Ecosystems*. 3(03), pp.190–205.

Text Books on Continuous Cover Forestry

1. **Helliwell, R. (2013).** *Continuous Cover Management of Woodlands: a brief introduction*. DOI: 10.13140/2.1.2044.7046
2. **O'Hara, K.L., (2014).** *Multiaged silviculture: managing for complex forest stand structures*. Oxford University Press. Oxford.
3. **Pukkala, Timo & Gadow, Klaus Von. (2012).** *Continuous Cover Forestry*. 2nd ed., Dordrecht: Springer.
4. **Süsse, R., Allegrini, C., Bruciamacchie, M. & Burrus, R. (2011).** *Management of Irregular Forests – Developing the Full Potential of the Forest*. Association Futaie Irrégulière. Besançon, France.

‘Top 10’ Hot List Literature Review

This short literature review will explore ten pieces of new research that encompass the main subject areas outlined in this bibliography. It functions as a small sample of the diversity of research currently being produced on the subject of CCF. Alder et al. (2018) explore spring and winter woodland bird densities in mixed broadleaf stands under three different management types in Lowland Britain; non-intervention, traditional coppice and continuous cover forestry. The paper found that ten out of the twenty bird species surveyed had higher population densities in the CCF managed woodlands, significantly higher than areas with non-intervention employed as a management strategy. In a similar study by Hjältén et al. (2017) non-intervention, old growth and CCF stands were compared for beetle biodiversity in Northern Sweden. The results showed that the species compositions of beetle communities were similar between CCF and old growth stands, with species richness and abundance being consistently lower in non-intervention stands. The implications of the emerging body of research in this area may suggest that CCF management can offer significant benefits to biodiversity conservation in a woodland context.

New areas of research also include the impacts of CCF management on ecosystem services provision and carbon storage. A study by Timo & Pukkala, (2016) used data from forests in Finland to model the provisioning of ecosystem services such as carbon sequestration, berry forage productivity, aesthetic value and habitat for biodiversity in two types of management system, CCF and even-aged, clear-cut. The study found that CCF was able to deliver ecosystem services far more effectively than an even-aged system. However, Lundmark et al., (2016) modelled the carbon balance of Norway Spruce (*Picea abies*) forests in Sweden, comparing CCF and clear-cut systems. They found site productivity was more important for determining carbon sequestration than management type, suggesting little difference between clear-cut and CCF stands when variables such as wood product use, growth and extraction levels were assumed to be the same.

Other studies have focused on subject areas more applicable to production forestry, such as economics. Davies & Kerr (2015) compared the costs and revenues of various different silvicultural scenarios. The study found that if natural regeneration is successful during transformation from an even-aged forest to a complex structure, CCF could be more cost-efficient than clear-felling and restocking. However, the study highlighted that the net present value of a forest stand may be lower over the long-term in a CCF system than a clear-fell scenario. Another important area of research to silviculturalists is natural regeneration of seedlings in un-even aged stands. Kerr & Mackintosh (2012) analysed data from a 50+ year study at the Glentress trial area, Scotland. They found that the survival rate in seedlings of a variety of tree species were significantly lower than predicted, and showed high variation between different site conditions, with an overall survival rate of 37%. Ligot et al (2014) compared the regeneration success of various species under different cutting and thinning scenarios in the Belgian Ardennes. The most significant finding revealed that removing less dominant, lower quality trees, (a practice characteristic of CCF management) provides a larger area favourable to light-demanding species. The paper also studied the effect of different combinations of cutting practice, and varying levels of canopy openness on the regeneration success of different shade-tolerant and light demanding tree species.

A review paper by Pretzsch & Rais (2016) explored the effect of CCF and even-aged, monoculture silviculture systems on timber quality. The review found that 'morphological plasticity', a characteristic higher in shade-tolerant species was more important than management type in determining wood quality. It was determined that there was little consensus amongst academics on whether CCF produces more or less timber strength than even-aged, and that the different growth strategies of individual trees had a large effect on timber quality, knottiness, distortion and stem shape. Pukkala et al (2016) investigated wind damage in CCF and even-aged stands using computer modelling techniques. The study concluded that greater structural complexity resulting from selection thinning reduced the incidence of wind damage, with losses highest in even-aged stands with repeated low-thinnings.

Lastly, Mason (2015) conducted an extensive review into the transformation of Sitka spruce (*Picea sitchensis*) even-aged monocultures to CCF systems in the British Isles. This review offers insights into a broad range of areas including single-tree growth models for *P. sitchensis*, costs and revenues of transformation, wind stability and a conceptual analysis of the status CCF currently holds in British forestry.

List of References

No.	Reference	Subject Class	Species Code
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2	Alder, D.C., Fuller, R.J. & Marsden, S. J. (2018) 'Implications of transformation to irregular silviculture for woodland birds', <i>Forest Ecology and Management</i> , 422, pp. 69–78.	H	xxx
3	Assmuth, A. & Tahvonen, O. (2018) 'Optimal carbon storage in even- and uneven-aged forestry'. <i>Forest Policy and Economics</i> , 87, pp.93–100.	CC	xxx
4	Assmuth, A., Rämö, J., & Tahvonen, O. (2018) 'Economics of size-structured forestry with carbon storage'. <i>Canadian Journal of Forest Research</i> , 48(1), 11-22.	CC	NS
5	Axelsson, R. & Angelstam, P. (2011) 'Uneven-aged forest management in boreal Sweden: Local forestry stakeholders' perceptions of different sustainability dimensions', <i>Forestry</i> , 84(5), pp. 567–579.	C	xxx
6	Basche, A. & DeLonge, M. (2017) 'The Impact of Continuous Living Cover on Soil Hydrologic Properties: A Meta-Analysis', <i>Soil Science Society of America Journal</i> , 81(5), p. 1179.	H	xxx
7	Baudry, O., Charmetant, C., Collet, C. & Ponette, Q. (2014) 'Estimating light climate in forest with the convex densiometer: Operator effect, geometry and relation to diffuse light', <i>European Journal of Forest Research</i> , 133(1), pp. 101–110.	R	BE, OK
8	Bayat, M., Pukkala, T., Namiranian, M. & Zobeiri, M. (2013) 'Productivity and optimal management of the uneven-aged hardwood forests of Hyrcania', <i>European Journal of Forest Research</i> , 132(5–6), pp. 851–864.	SiS	BE
9	Berrill, J. P. & O'Hara, K. L. (2016) 'How do biophysical factors contribute to height and basal area development in a mixed multiaged coast redwood stand?', <i>Forestry</i> , 89(2), pp. 170–181.	SiS	XC

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| 12 | Bianchi, S., Hale, S., Cahalan, C., Arcangeli, C & Gibbons, J. (2018) 'Light-growth responses of Sitka spruce, Douglas fir and western hemlock regeneration under continuous cover forestry', <i>Forest Ecology and Management</i> . Elsevier, 422(April), pp. 241–252. | R | SS, DF, WH |
| 13 | Bílek, L., Vacek, S., Vacek, Z., Remeš, J., Král, J., Bulušek, D. & Gallo, J. (2016) 'How close to nature is close-to-nature pine silviculture?', <i>Journal of Forest Science</i> , 62(1), pp. 24–34. | C | SP |
| 14 | Boncina, A. (2011) 'History, current status and future prospects of uneven-aged forest management in the Dinaric region: an overview'. <i>Forestry</i> . 84, (5) pp. 467-478. | C | xxx |
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| 17 | Brockway, D. G. & Outcalt, K. W. (2017) 'Influence of reproduction cutting methods on structure, growth and regeneration of longleaf pine forests in flatwoods and uplands', <i>Forest Ecology and Management</i> , 389, pp. 249–259. | R | XC |
| 18 | Calladine, J., Bray, J., Broome, A. & Fuller, R.J. (2015) 'Comparison of breeding bird assemblages in conifer plantations managed by continuous cover forestry and clearfelling'. <i>Forest Ecology and Management</i> , 344, pp.20–29. | H | xxx |

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Abstracts

1 Ahlström, M. & Lundqvist, A. (2015)

Long term effects of partial harvests were studied in seven uneven-aged *Picea abies* (L.) Karst stands in northern Sweden, by reconstructing stand development from increment cores. All stands had been subjected to partial harvests 16–57 years before the inventory. Two 1000 m² circular plots were established in each stand. All trees with a diameter at breast height (1.3 m above ground) P5 cm were mapped and calipered. Historic stand development was reconstructed backwards in five-year intervals to the year of the previous harvest, using increment cores taken from randomly chosen sample trees in each 2-cm diameter class. The pre-harvest stem density was restored in all stands but one, at the time of the inventory. Average ingrowth of survived trees was 13 stems ha⁻¹ yr⁻¹, but no relation was found between annual ingrowth and standing volume. Only four stands had inversely J-shaped diameter distributions after harvest, but all seven stands did at the time of the final inventory. Standing volume was 34–88 m³ ha⁻¹ after harvest and 126–207 m³ ha⁻¹ at the final inventory, with an average volume increment around 3 m³ ha⁻¹ yr⁻¹ for the whole observation period. Volume increment increased with standing volume in all stands but one. The shapes of the diameter–height curves were similar for all stands, irrespective of the time elapsed since the harvest. In conclusion, the results from this study indicate that the selection system is a sustainable silvicultural system in uneven-aged sub-alpine Norway spruce forests. These forests have high resilience and a capacity to recreate stable diameter distributions after rather harsh treatments.

2 Alder, D.C., Fuller, R.J. & Marsden, S. J. (2018)

Woodland birds in Britain have undergone significant long-term declines since the late 1960s, associated in particular with the changes in woodland structure in general and loss of early successional. Irregular, continuous canopy broadleaf management is a form of selective logging, very recently adopted in UK that produces woodlands with open canopies and substantial mid- and understory growth. We examined spring and late winter bird densities, estimated using distance sampling, at 310 points in irregular, transitional (that being managed toward irregular), limited intervention, and coppice stands within a large working broadleaf woodland in lowland southern Britain. Almost all understory and canopy vegetation measures differed significantly across stand types. Ten of 20 species had highest spring abundance in irregular woodland, five in coppice, three in transitional, and just two in limited intervention. In winter, 5-6 species preferred each of limited intervention, irregular and transitional, while no species preferred coppice. Densities differed little across seasons except in *Paridae* where abundances increased in late winter during which limited intervention stands were more used by this group. Birds generally occupied similar niche positions and had similar breadths. Compared to under-managed woodlands, irregular silviculture in the UK's broadleaf woodlands is likely to enhance habitat quality for woodland birds including several species of conservation concern e.g. marsh tit *Poecille palustris* which was twice as abundant in irregular stands as in any other stand type.

3 Assmuth, A. & Tahvonen, O. (2018)

We study the effects of forest carbon storage on optimal stand management by applying a model where optimal harvests are partial cuttings, implying uneven-aged forestry, or both partial cuttings and clearcuts, implying even-aged forestry. Optimal carbon storage postpones partial cuttings and increases stand volume along the rotation. Carbon pricing may shorten or lengthen the rotation period depending on interest rate and speed of carbon release from wood products. If the carbon price is high, the shadow value of forest biomass is negative, implying that a higher interest rate leads to higher stand density. In empirically realistic examples, carbon pricing causes a switch from clear-cuts to continuous cover management rather than vice versa.

4 Assmuth, A., Rämö, J. & Tahvonen, O. (2017)

We study the economics of carbon storage using a model that includes forest size structure and determines the choice between rotation forestry and continuous cover forestry. Optimal harvests may rely solely on thinning, implying infinite rotation and continuous cover forestry, or both thinning and clear-cuts, implying finite rotation periods. Given several carbon prices and interest rates, we optimize the timing and intensity of thinnings along with the choice of management regime. In addition to the carbon storage in living trees, we include the carbon dynamics of dead trees and timber products. Forest growth is specified by an empirically validated transition matrix model for Norway spruce (*Picea abies* (L.) Karst.). The optimization problem is solved in its general dynamic form by applying bilevel optimization with gradient-based interior point methods and a genetic algorithm. Carbon pricing postpones thinnings, increases stand density by directing harvests to larger trees, and typically yields a regime shift from rotation forestry to continuous cover forestry. In continuous cover solutions, the steady-state harvesting interval and the diameter distribution of standing and harvested trees are sensitive to carbon price, implying that carbon pricing increases the sawlog ratio of timber yields. Additionally, we obtain relatively inexpensive stand-level marginal costs of carbon storage.

5 Axelsson, R. & Angelstam, P. (2011)

To implement policies on sustainable forest management (SFM), there is a need to satisfy economical, ecological and socio-cultural sustainability objectives. Due to a long history of sustained yield wood production to satisfy the needs of the forest industry, clear-felling management systems are used in ~96 per cent of managed forests in Sweden. To satisfy the intentions of contemporary forest and land use policies, uneven-aged forest management systems as a complement are currently debated. We interviewed local forestry stakeholders in the Swedish boreal forest region's north and south about their views on and attitudes towards different forest management systems' contribution to SFM. Most stakeholders were generally negative to the use of uneven-aged system for sustained yield wood production but saw advantages for ecological and socio-cultural dimensions of SFM. To encourage the use of even-aged cohort and uneven-aged systems to satisfy all dimensions of SFM, there is a need for improved communication, education and public awareness. This could ultimately lead to a more constructive and less heated debate. In addition, there is a need of more empirically based knowledge about uneven-aged and cohort forest management systems' pros and cons when it comes to satisfying economical, ecological and socio-cultural objectives.

6 Basche, A. & DeLonge, M. (2017)

Increased rainfall variability due to climate change threatens the efficacy of critical soil ecosystem services. One strategy to negate effects of too much or not enough rainfall is to improve soil water properties. Practices that offer "continuous living cover" can enhance soil water storage and other soil hydrologic properties relative to annual crop systems, but to what extent such benefits can accrue, under different conditions, remains under-quantified. To address these uncertainties, we conducted a meta-analysis that included 27 studies representing 93 paired observations measuring two soil hydrologic properties: porosity and the water retained at field capacity. All experiments compared the impact of continuous living cover practices (cover crops, perennial grasses, agroforestry and managed forestry) to annual crop controls. Continuous living cover significantly increased total porosity ($8.0 \pm 2.2\%$) and the water retained at field capacity ($9.3 \pm 2.7\%$). There was some evidence indicating improved effects in relatively drier environments (<900 mm annual rainfall) and in regions with sandier soils. There was no evidence of publication bias, and a sensitivity analysis indicated that overall effects were robust. The similar direction and magnitude of improvements in both properties could be evidence of similar physical and chemical processes impacted by the continuous presence of living roots. Overall, our findings suggest that continuous living cover practices may be a potential adaptation strategy to combat rainfall variability. Furthermore, properties such as porosity and field capacity may serve as proxies to determine how management influences soil water and health more broadly.

7 Baudry, O. et al. (2014)

Although light is a key factor in forestry, it is surprisingly seldom measured in day-to-day management of European forests. The spherical convex densiometer is a simple instrument that allows to evaluate the canopy openness (CO) by counting the number of 'canopy' dots on a grid lying on a convex mirror reflecting the canopy. In this contribution, we compared the performances of this instrument in mixed oak–beech hardwood forests spanning the lower end of the light gradient [1–17 % above canopy photosynthetically active radiation (PAR)] to two reference techniques: PAR measurements and fish-eye photography, based on a detailed analysis of its functioning. Discrepancies between the densiometer and the fish-eye estimates of CO were due to a combination of differences in dot resolution, dot counting, and portion of the hemisphere considered. By contrast, the various effects of operator on densiometer estimates, including the influence of conformation on the angle of view, were found to be relatively minor. Densiometer readings were closely related to the relative light intensity assessed by PAR sensors in overcast conditions, which suggests that the use of this inexpensive tool should be expanded.

8 Bayat, M. et al. (2013)

Hyrcania is a productive region near the southern coast of Caspian Sea. Her forests are mostly uneven-aged beach-dominated hardwood mixtures. There is increasing willingness to treat these forests without clear-felling, following the ideas of continuous cover management. However, lack of growth and yield models have delayed this endeavour, and no instructions for uneven-aged management have been issued so far. This study developed a set of models that enable the simulation of stand development in alternative management schedules. The models were used to optimize stand structure and the way in which various initial stands should be converted to the optimal uneven-aged structure. The model set consists of individual-tree diameter increment model, individual-tree height model, survival model, and a model for ingrowth. The models indicate that the sustainable yield of the forests ranges from 2.2 to 7 m³ ha⁻¹a⁻¹ in uneven-aged management, depending on species composition. Better ingrowth would substantially enhance productivity. The optimal stand structure for maximum sustained yield has a wide descending diameter distribution, the largest trees of the post-cutting stand being 80–100 cm in dbh. If cuttings are conducted at 30- or 40-year intervals, they should remove 20–40 largest trees per hectare. Despite moderate growth rate, uneven-aged management.

9 Berrill, J. P. & O'Hara, K. L. (2016)

We studied biophysical (biotic and abiotic) factors correlating with dominant height and basal area (BA) development within 110 ha of evergreen mixed conifer forest dominated by coast redwood (*Sequoia sempervirens* (D.Don)Endl.) in north coastal California. Various descriptors of species composition, topography, soil properties and moisture, light and harvest disturbance were assessed in a grid of 234 permanent sample plots. Within the study area characterized by heterogeneous topography and variable species composition, site descriptors alone were poor predictors of stand volume production in multiple linear regressions. Multivariate canonical correlation analysis revealed that redwood height growth was related to a different suite of biophysical variables than BA growth. Greater stand volume production was measured in areas with less hardwood, more Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirbel) Franco), higher soil pH and at lower slope positions. Sheltered lower slopes were more amenable to red wood height growth. Exposed upper slopes and ridges receiving more light favoured BA over height growth in redwood. Our analysis provides a framework for refining estimates of forest growth, yield and carbon stocks in natural forests in accordance with divergent dimensions of productivity and allied biophysical gradients.

10 Bertin, S. et al. (2011)

Continuous cover forestry (CCF) aims at enhancing stand structural diversity and favouring natural regeneration. To give guidance on how to manage a CCF stand to achieve seedling growth below canopy, an estimate of light transmittance is required. So far, in the UK, only

stand-level parameters have been used by managers to predict the understorey light in CCF stands. We assessed a UK Sitka spruce stand undergoing transformation to CCF and measured canopy transmittance using hemispherical pictures. Stand-level characteristics were found to be highly stand specific and not appropriate to predict seedling growth in CCF stands. We parameterized a detailed light model (4C-A-RTM) and a simple one-layer turbid medium model (BL). A sensitivity analysis was performed to test the effect of key stand structural parameters on the modelled transmittance. Measured transmittance from hemispherical photographs was used to validate the models. Both models tended to underestimate canopy transmittance but were positively related to current-year growth of the below canopy seedlings ($R^2 = 0.92$, $P < 0.001$). Comparison of the two models showed that the 4C-A-RTM provided a better estimation of light transmittance across observed canopy structural differences. Furthermore, the inclusion of stand characteristics in the 4C-A-RTM is likely to confer greater applicability across stands.

11 **Benneter, A. et al. (2018)**

Mixed-species forests can have higher productivity, in terms of wood volume, than monospecific forests. In addition, higher tree species richness has been found to positively correlate with multiple ecosystem services and functions. Surprisingly, stem quality as one of the most important factors regarding the economic value of forests has rarely been formally studied in diverse forests. This paper aims at investigating how tree species richness influences stem quality and which factors may drive quality development in these stands. Stem quality, understood here essentially as the suitability of a particular stem for particular end-uses, is influenced by a tree's ability to capture sufficient resources for growth and is influenced by neighbouring trees, e.g. through shading and physical crown interactions. We collected data on crown size, stem form and tree health for over 12,000 trees in 209 study plots in six European regions (Finland, Germany, Poland, Romania, Italy and Spain) within naturally diverse forests to assess the impact of tree species richness on these characteristics. Results showed that quality variability between regions, stands and individual trees was high across species. At the stand level, there was a slight tendency towards lower stem quality with increasing diversity. However, individual trees of high quality were present at all diversity levels and for all target species. Tree species richness could not be confirmed as a primary influence on stem quality at the stand level. Rather, stand and individual tree properties such as structural composition, competition, tree size and crown characteristics were identified as the main factors for stem quality development, even in mixed stands. Many of the factors identified in this study can be directly or indirectly influenced by forest management strategies tailored to produce high-quality timber in mixed-species forests. Our findings suggest that diverse stands are not inferior regarding stem quality, while at the same time being able to provide various other ecosystem services.

12 **Bianchi, S. et al. (2018)**

Natural regeneration is crucial for silvicultural approaches based on the continuous presence of a forest cover, or Continuous Cover Forestry (CCF). Light is considered one of the most important factors affecting regeneration growth under canopy cover. Sitka spruce, western hemlock and Douglas fir are important forestry species both in Europe and in North America with potential to be used together under CCF management. Our aim was to develop predictive early-growth models for these species growing beneath forest canopies, and to investigate species differences in terms of shade tolerance. We sampled regenerating trees growing under canopy cover at multiple sites in the UK. We compared alternative asymptotic non-linear models as a function of light availability to simulate the height growth for all species and the diameter growth for Sitka spruce and western hemlock only. We included tree size and intra-regeneration competition as predictors, which affected the asymptotic growth at full light and/or the growth rate at which such asymptote was reached. We also calibrated models of apical dominance ratio (ADR, for all species) and live crown ratio (LCR, for Douglas fir and Sitka spruce only) as a function of light availability, tree size and intra-regeneration competition. Species-specific non-linear models best simulated the light-growth responses (3-points Logistic for Sitka spruce, Michaelis-Menten for western hemlock, asymptotic with offset for Douglas fir). Tree size in all cases increased the asymptotic growth and in two cases also the growth rate. Competition significantly reduced the growth for Sitka spruce and

western hemlock, with the diameter growth reduced more than height growth. Both the ADR and the LCR increased with light availability, with species-specific differences for LCR but not for ADR. For Sitka spruce an apical dominance ratio of 1.5 can be used in the field to identify adequate growing conditions. An increasing shade tolerance ranking was found as Douglas fir < Sitka spruce < western hemlock. We conclude that modelling light-growth requires species-specific non-linear functions and that predictions are improved by including size and competition. The developed predictive models for height and diameter growth will allow accurate modelling of the study species in CCF management.

13 Bílek, L. et al. (2016)

Structural parameters of Scots pine stands (129–191 years) on their natural sites (270–600 m a.s.l.) are described on 6 permanent research plots (PRP; 3 in managed stands using near-natural silvicultural practices and 3 in stands without active forest management for 3 decades at least) in areas of western, central and eastern Bohemia and in the Polish part of the Krkonoše Mts. In the framework of the study structural and growth parameters, horizontal and vertical structure and biodiversity were evaluated on the plots. A comparison of the plots, and of managed and unmanaged plots showed a relatively high variability in different parameters. Nevertheless, the results document that managed stands, compared to forest stands without management, mostly have significantly higher standing volumes (1.5 times in total and 1.7 times in pine), which is caused by more extreme sites. An opposite trend was found out in dead wood volume, which is distinctly higher in unmanaged stands. Differences in the other parameters are not so pronounced, probably because small-scale management is used and because a relatively short time since the stands were left to spontaneous development has elapsed (30–52 years).

14 Boncina, A. (2011)

The development of uneven-aged forest management in the Dinaric region (north-west Balkans) is reviewed. Un-even aged silviculture has been the major silvicultural system in the region since regular forest management began in the second half of the nineteenth century. Regular forest management in former virgin forest areas began as selection forest management mainly because of the awareness of the importance of multi-layered continuous forest cover for preventing soil erosion on carbonate substrate. The observed period of more than 100 years has seen several changes to uneven aged forest management ranging from the complete domination of rigid selection forest management to the gradual acceptance and eventual domination of the irregular shelterwood system and finally to the acceptance of freestyle forest management, which is presently practiced in the Slovenian part of the Dinaric region. Freestyle silviculture combines practices of different silvicultural systems. By using this system, consideration for site conditions and heterogeneous stand dynamics at small spatial scales is possible. In the observed period, some stand parameters of Dinaric forests have changed substantially. Growing stock has increased significantly, the number of large-diameter trees has increased and alternation of the main tree species (silver fir and European beech) has occurred. The development of uneven-aged forest management is described, and its prospects are discussed.

15 Boncina, A. et al. (2014)

Long-term dynamics of selection (plenter) forests and corresponding virgin forests in NW Balkan countries (Slovenia, Croatia, Serbia, Bosnia and Herzegovina and Montenegro) were examined by assessing changes in diameter structure, stand volume and tree species composition. The parameters were aggregated at the landscape spatial scale, and the intensity of changes in diameter structure and tree species composition was measured by the index of dissimilarity. It was hypothesized that structure and composition of selection forests and virgin forests remained rather stable over several decades. Our study revealed pronounced dynamics in the observed parameters. However, these changes were divergent; in most study areas, increases of stand volume and large-diameter trees were observed, and in selection forests, the proportion of silver fir in the total stand volume decreased in three study areas and increased in two. Changes in diameter structure and tree species composition of the virgin forests were relatively less pronounced. In selection forests, an

increasing proportion of mid-shade-tolerant Norway spruce and a constant proportion of light demanding sycamore, which is almost absent in virgin forests, were observed. The great capacity of the selection system to create stands of different structure and composition may be an important advantage in increasingly unpredictable economic, social and environmental conditions.

16 Brang, P. et al. (2014)

In many parts of Europe, close-to-nature silviculture (CNS) has been widely advocated as being the best approach for managing forests to cope with future climate change. In this review, we identify and evaluate six principles for enhancing the adaptive capacity of European temperate forests in a changing climate: (1) increase tree species richness, (2) increase structural diversity, (3) maintain and increase genetic variation within tree species, (4) increase resistance of individual trees to biotic and abiotic stress, (5) replace high-risk stands and (6) keep average growing stock slow. We use these principles to examine how three CNS systems (single-tree selection, group selection and shelterwood) serve adaptation strategies. Many attributes of CNS can increase the adaptive capacity of European temperate forests to a changing climate. CNS promotes structural diversity and tree resistance to stressors, and growing stocks can be kept at low levels. However, some deficiencies exist in relation to the adaptation principles of increasing tree species richness, maintaining and increasing genetic variation, and replacing high-risk stands. To address these shortcomings, CNS should make increased use of a range of regeneration methods, in order to promote light-demanding tree species, non-native species and non-local provenances.

17 Brockway, D. G. & Outcalt, K. W. (2017)

Though longleaf pine (*Pinus palustris* Mill.) forests have been primarily managed with even-aged methods, interest is increasing in uneven-aged systems, as a means of achieving a wider range of stewardship goals. Selection silviculture has been practiced on a limited scale in longleaf pine, but difficulty with using traditional approaches and absence of an evaluation across a range of site types has left managers in doubt concerning its suitability. This study was conducted to quantify the effects on stand dynamics of applying single-tree selection, group selection, irregular shelterwood and uniform shelterwood in longleaf pine forests on flatwoods and uplands of the south-eastern United States. Selection treatments reduced stand basal area to 11.5 m² ha⁻¹ and shelterwood treatments left a basal area of 5.8 m² ha⁻¹. In spite of initial decreases in tree density and standing volume, growth rates were normal in all stands (1–5% per year), as were subsequent increases in basal area and tree density. Despite the continuing abundance of saw-palmetto (*Serenoa repens* W. Bartram) cover and absence of prescribed fire during the eight post-treatment years, significant increases in pine regeneration were observed in all treated stands in the flatwoods. Because of a multi-year drought in the uplands, pine seedling numbers dramatically declined, no matter which reproduction approach was employed. Although seedling numbers eventually began to recover, they were again precipitously depressed by a wildfire in 2013. Even with such losses, sufficient pine seedlings remained in each treatment to foster successful stand regeneration. Single-tree selection produced less overall change in the forest ecosystem than group selection, which caused less alteration than shelterwood treatment. Single-tree selection appears to be an effective way for achieving stand regeneration, while maintaining a continuous canopy cover that aids in the control of woody competitors and supports an array of resource values. Selection silviculture seems to be a lower risk approach for guiding forests along a trajectory of gradual improvement, with adjustments provided by frequent surface fires and periodic tree harvest. Long-term observation will be required to verify that selection can sustain forest ecosystems on sites characterized by differing environments.

18 Calladine, J. et al. (2015)

Continuous cover systems are increasingly advocated for stand management but the implications for bio-diversity in European forests, and specifically in plantations of non-native trees, are poorly understood. Timed point counts were used to quantify differences in species richness and abundance of breeding birds supported by conifer plantations (with major Sitka

spruce components) under two contrasting management systems in upland Britain: continuous cover forestry (CCF) and clearfelling with replanting (CFR). Each CCF study area was paired with a comparable CFR study area. Sample points within CCF areas were divided into areas with extensive regenerating understorey and areas with none; sample points within CFR study areas were placed within young thicket and pre-thicket stands (trees < 10 years old) and older stands (15–30 years old). Poisson GLMMs were used to identify differences in bird species richness and abundance between the four treatments testing the predictions: (a) CCF can support an enhanced assemblage of forest birds relative to CFR (including mature CFR); and (b) CFR can support a broader range of open habitat and shrubland species relative to CCF (including those with a regenerating understorey). Ranking forest types in descending order of species richness gave: CCF with shrub understorey > CCF without shrubs > young pre-thicket CFR > mature CFR. Many 'mature forest birds' were more abundant, or recorded only, within CCF (e.g. blackcap, wood warbler, redstart and hawfinch). A small number of species associated with young-growth ('shrubland' and 'shrub-layer' species) were most abundant in pre-thicket CFR but a CCF understorey supported some species at densities approaching those found in pre-thicket CFR. Simulations of the effect of increasing the proportion of plantation under CCF indicated for example that a plantation managed exclusively as CCF could support as few as 53% of the willow warblers as one managed exclusively as CFR. A plantation managed exclusively as CCF could support as few as 70% of the lesser redpolls as one managed as CFR, but could support twice as many blackcaps. CCF could be of greater conservation value to many forest birds than CFR. However, CCF may not support such high densities of some species (e.g. dunnoek, willow warbler and lesser redpoll) as those found in young growth stage CFR. Forest management that includes some young growth areas alongside CCF could prove to be a strategy that maximises the capacity of a forested landscape to support a greater diversity of bird species.

19 Calladine, J. et al. (2017)

Continuous cover forestry (CCF) systems are increasingly advocated for stand management, with biodiversity among the ecosystem services perceived to benefit. However, long term (>100 years) influences of such silvicultural systems on biodiversity in managed forests are poorly understood. Timed point counts in Scots pine forests in Scotland were used to quantify associations between species richness, diversity and abundance of breeding birds and different forest structures provided by CCF. Managed forests with old growth features (some including particularly old pines and snags) were considered surrogates for long term CCF stands. A stand category with an understorey of young trees (understorey reinitiation) was the most species rich (other categories in descending order were old growth, commercially maturing stands with no regenerating understorey and exclusively pre-canopy-closure young growth stage) but differences were small and marginally non-significant. Heterogeneity in canopy layer structure at a scale typical of many song bird territories (ca 1 ha) and the occurrence of old growth features were associated with greater abundance in a number of individual bird species, but many associations were species-specific. Knowledge of species-specific responses to forest structure can inform management for the benefit of species of conservation concern and other priority species but requires better understanding of optimal structural mosaics including frequencies of old trees and snags for those species and groups. Bird distributions can change in response to extrinsic factors within the expected long-term plans for CCF managed forests; the contribution of structural mosaics to the resilience of forests in supporting a changing avifauna deserves further attention.

20 Cambi, M. et al. (2018)

Logging operations using heavy machinery effect changes in soil characteristics due to compaction; such conditions can negatively influence seedling development. In stands managed on the basis of close-to-nature silviculture or continuous cover forestry, successful establishment of natural regeneration after logging is important to ensure the proper functioning of a forest ecosystem, to promote soil recovery, and to prevent and mitigate land degradation processes (such as soil erosion, mudflow, waterlogging, and landslides) related to soil compaction and rutting. This work aimed to assess the early response of *Quercus robur* seedlings to soil compaction during the first 1.5 months after germination. The study was carried out in a controlled environment using 8 L containers filled with natural alluvial

soil. Three levels of soil compaction were applied in a laboratory using a compression-testing machine placed on the top surface of the soil in the containers. The morphological traits of the seedling shoot and root systems were analysed to compare 3 compaction levels. There were significant differences in seedling traits among the treatments, and they indicated that increasing levels of compaction reduced early seedling growth after emergence. Compaction had a larger impact on the root system, particularly the development at depth (root system depth, and main root length), compared with the shoot system. Our results suggest that compaction affects seedling root system growth following the first growth stages after germination; thus, compaction represents an additional critical factor for seedling establishment, particularly in environments where early growth is crucial for overcoming the dry season.

21 Cameron, A.D., Gardiner, B.A., Ramsay, J. & Drewett, T.A. (2015)

While numerous studies have considered the effects of initial planting spacing on wood properties, little is known about the properties of trees grown from dense natural regeneration and the effects of early release from competition. This study examined 40-year-old Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees originating from regeneration with an initial density 27,000 stem ha⁻¹. Treatments were a control of natural regeneration with no interventions and regeneration re-spaced to two metres (height~1.6 m). Density and strength measurements were made on the juvenile and mature wood. No differences were observed in density, modulus of elasticity (MOE) and modulus of rupture (MOR) between the juvenile and mature wood of the control trees. By contrast, the juvenile wood of re-spaced trees was less dense and had a lower MOE than the mature wood. The control trees revealed a uniformity of properties across the juvenile and mature wood zones, unlike the re-spaced treatment. Re-spaced trees appear to adapt to their new environment by producing more thin-walled conductive tissue and lowering overall cell wall density that continues from the juvenile to mature wood. Higher compression wood levels in the control trees are thought to be linked to stem slenderness.

22 Cameron, A. & Prentice, L. (2016)

While there is considerable interest in transforming even-aged stands into species-diverse, irregular structures, the rarity of stands close to the end of the transformation process has resulted in a lack of knowledge on optimum target structures that are considered sustainable. This study examined this problem in a mixed-species selection stand that has undergone transformation for over 60 years. Complete inventories of a one-hectare permanent sample plot were carried out in 2015 and previously in 2009, 2003 and 1997. The diameter distribution remained relatively static with the q factor remaining at 1.4 since the 2009 inventory. An improvement in the number of regenerating seedlings and saplings available for recruitment from previous inventories suggests that the current structure is relatively stable although shade-tolerating conifers are gradually dominating the stand. Not all the sustainability criteria were met; however, the stand could be described as having reached a balanced condition. It is recommended that the current stocking density and basal area (350 stems ha⁻¹ and 26 – 27 m²ha⁻¹, respectively) should be maintained and that future harvesting interventions should aim to reduce the number of large diameter stems (55 cm DBH), which represent 14 per cent of the stocking but 48 per cent of the stand basal area.

23 Chianucci, F. et al. (2016)

European beech (*Fagus sylvatica* L.) forests have a long history of coppicing, but the majority of formerly managed coppices are currently under conversion to high forest. The long time required to achieve conversion requires a long-term perspective to fully understand the implication of the applied conversion practices. In this study, we showed results from a long-term (1992–2014) case- study comparing two management options (natural evolution and periodic thinning) in a beech coppice in conversion to high forest. Leaf area index, litter production, radiation transmittance and growth efficiency taken as relevant stand descriptors, were estimated using both direct and indirect optical methods. Overall, results indicated that beech coppice showed positive and prompt responses to active conversion practices based on periodic medium-heavy thinning. A growth efficiency index showed that tree growth

increased as the cutting intensity increased. Results from the case study supported the effectiveness of active conversion management from an economic (timber harvesting) and ecological (higher growth efficiency) point of view.

24 Crotteau, J.S. et al. (2018)

Structurally diverse forests provide resilience to an array of disturbances and are a mainstay of multiple-resource management. Silviculture based on natural disturbance can increase structural heterogeneity while providing other ecological and economic benefits. One useful silvicultural tool for promoting structural heterogeneity is retention harvesting, whereby a portion of forest stands are left unlogged, transitioning even-aged stands to multi-aged. We report stand and tree dynamics 11 years after retention harvest in a central Montana Rocky Mountain lodgepole pine forest with evidence for a mixed-severity fire regime. Treatments were implemented on 16 experimental units with prescriptions for two 50% overstory basal area retention patterns (Aggregated and Dispersed) crossed with two levels of prescribed fire use (Burned and Unburned). The aim of this study was to identify (1) how retention harvest spatial pattern affects stand dynamics, (2) if stand dynamics after retention treatments are more simply attributable to tree size and competition, or if retention pattern affects dynamics beyond those measures, and (3) how stem and basal area heterogeneity varied over the 11-year measurement period. Retention pattern affected overstory density, growth, mortality, and regeneration density and stocking. After controlling for the fine-scale factors of tree size and competition, overstory mortality, regeneration stocking, and regeneration height growth did not vary by treatment-scale factors. Fine-scaled factors explained significant variation in overstory basal area growth, but at the scale of experimental units, growth was also greater in Dispersed treatments. Prescribed burning interacted with retention pattern to influence overstory tree growth, increased overstory mortality, and increased regeneration height growth. Overstory heterogeneity (e.g., in basal area) degraded more rapidly in treatments with the Dispersed spatial pattern than Aggregated. This study evaluates novel silvicultural treatments in a lodgepole pine forest and highlights the tradeoffs between retention patterns combined with broadcast burning on forest change. Our results are useful for planning silvicultural treatments in multiple-use forests designed to promote structural complexity and resilience to disturbances.

25 Davies, O. & Kerr, G. (2015)

Recently continuous cover forestry (CCF) has become an accepted approach to forest management in Britain, but uncertainty about its economic consequences may be a barrier to its wider use. A study was carried out to examine the costs and revenues of transforming a stand of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) to CCF. The main conclusion is that transformation to CCF need not be more costly than clear-felling and replanting if natural regeneration is successful and the aim is to produce a simple canopy structure. The long-term value of transformation to a more complex canopy structure, with three or more strata, is lower and the extra costs need to be justified in terms of management objectives. The main output from the study is an analysis spreadsheet that empowers practitioners and policy makers to investigate the effects of costs, revenues and discount rates on estimates of net present value over 20 years, 100 years and in perpetuity, to suit local conditions. This paper summarises the method and results of the study in a British context, sets these in a wider international context, and considers the merits, applications and possible further developments of the approach.

26 Deal, R. L. et al. (2014)

There is increasing interest worldwide in managing forests to maintain or improve biodiversity enhance ecosystem services and assure long-term sustainability of forest resources. An important goal of forest management is to increase stand diversity, provide wildlife habitat and improve forest species diversity. We synthesize results from natural spruce forests in southeast Alaska and suggest strategies for managing Sitka spruce plantations in other parts of the world to benefit biodiversity and enhance a variety of forest ecosystem services. We also discuss the roles of fungi in increasing both biological and structural diversity in Sitka spruce forests. New silvicultural systems that use partial cutting in older spruce forests could

alleviate some of the problems associated with conventional even-aged management and increase both stand structural diversity and biodiversity. We found that mixed red alder-conifer stands in Alaska provided more heterogeneous structures than the pure conifer stands that typically develop after clearcutting. Well-planned silvicultural systems that include broadleaved species such as alder or birch could provide trees for timber production, improve wildlife habitat and a variety of other ecosystem services that are often compromised in young pure conifer forests.

27 de-Miguel, S. et al. (2014)

The aim of this study was to predict th at the landscape level by means of a model-based scenario analysis. The study area was Catalonia region, north-eastern Iberian Peninsula. Mushroom yield models were developed for the most common pine dominated forest ecosystems. The models accounted for the effect of site and stand structure on mushroom occurrence and yield. The mushroom yield models and individual-tree growth models were used in continuous cover forestry simulation and optimization to assess the impact of alternative regional forest management intensity scenarios on landscape-level mushroom productivity. The baseline scenario was defined as the estimated current forest harvesting intensity in Catalonia (i.e., 25% of annual forest growth). The time frame was 30 yr. The current average productivity of valuable mushrooms is 14 kg ha⁻¹ yr⁻¹ (4600 tonnes yr⁻¹). Under the current forest management intensity, a loss of 220 tonnes yr⁻¹ (5%) in mushroom production at the regional level can be expected. In the absence of forest management, the loss in productivity can attain almost 500 tonnes yr⁻¹ (11%). With forest harvesting intensity similar to the average in Europe, an increase of 100 tonnes yr⁻¹ (2%) in mushroom production could be expected. If forest harvesting was equal to 100% of annual forest growth, an increase of 262 tonnes yr⁻¹ (6%) could be expected. Mushroom productivity increases with increasing forest management intensity. Low forest management intensities may result in a progressive reduction in mushroom yield. Intermediate management intensities would maintain the current mushroom productivity. Sustained yield harvesting policy would contribute to increasing mushroom productivity in continuous cover forestry.

28 Diaci, J. et al. (2017)

Forest managers are often required to restore forest stands following natural disturbances, a situation that may become more common and more challenging under global change. In parts of Central Europe, particularly in mountain regions dominated by mixed temperate forests, the use of relatively low intensity, uneven-aged silviculture is a common management approach. Because this type of management is based on mimicking less intense disturbances, the restoration of more severe disturbance patches within forested landscapes has received little attention. The goal of this paper is to synthesize research on the restoration of forests damaged by disturbances in temperate forests of Slovenia and neighbouring regions of Central Europe, where uneven-aged silviculture is practiced. Research indicates that active management aimed at favouring mixed uneven-aged forest reduces the risk of disturbance and improves the resilience of stands. Salvage logging may have positive or negative effects on regeneration, much of which is due to the method applied and the quality of work. The most prominent factors that negatively affect restoration are: lack of advanced regeneration and decomposed woody debris, high altitude, steep slopes, dense ground vegetation, and over browsing. Planting or sowing should be applied in post-disturbance forests where many negative factors interact and where a high demand for sustainability of forest ecosystem services is present.

30 Drössler, L. et al. (2017)

Forest management in Sweden can be characterized by even-aged silviculture heavily relying on three established harvest regimes: clearcutting, the seed-tree method, and the shelterwood system. Less intense, small-scale retention harvest systems such as single tree and group selection harvest are rarely used. In addition, natural regeneration dynamics without enrichment planting have barely been studied. Consequently, this study examined natural regeneration establishment in a multi-layered *Pinus sylvestris*-*Picea abies* forest stand in southwest Sweden after target diameter harvesting and soil scarification. The

creation of forest canopy gaps had a positive effect on total seedling density five years after harvest, mainly due to a significantly higher number of *Betula pendula* individuals. Seedling density of more desirable tree species suitable for continuous cover forestry such as *Fagus sylvatica*, *Quercus petraea* and *Picea abies* also increased substantially in gaps when compared to pre-harvest conditions or the unharvested plots. In contrast, soil scarification did not increase the number of seedlings of desired tree species due to a significant decrease in *Picea abies* abundance. Soil moisture and gap size significantly improved *Betula pendula* seedling establishment while a larger number of *Quercus petraea* seedlings were observed in *Vaccinium myrtillus* patches. We conclude that canopy gaps are beneficial under the encountered stand conditions to initiate forest regeneration, and that soil scarification without the timely occurrence of a mast year of desired tree species is not effective in the type of forest studied.

31 Drössler, L., Ekö, P. M. & Balster, R. (2015)

Harvest strategies that emulate natural disturbances are being promoted to restore multilayered forest heterogeneity, notably the harvest of largest trees. However, their use also increases management complexity, and more information on their practical feasibility and effects on forests is needed. Therefore, in this study, target diameter cutting treatments were applied to a heterogeneously structured stand in southern Sweden (exemplifying a conifer-dominated forest of the hemiboreal forest region in northern Europe) to assess their effects on gap dynamics, natural regeneration, and stand growth. The target diameter cutting resulted in an exponentially decreasing gap size distribution, with the largest canopy gaps measuring 0.1–0.2 ha. The gap closure rate was higher than reported rates for gaps in natural forests. After 5 years, sufficient numbers of seedlings had regenerated, but proportions of intermediate- and late-successional tree species were low. The observed stand growth exceeded rates simulated using the growth model Standwise in the Heureka forest planning software package. The findings from this case study are useful for refining the general concept of close-to-nature forestry, but they need to be complemented with the information available from other regeneration studies after partial harvest.

32 Drössler, L., Nilsson, U. & Lundqvist, L. (2014)

The study investigated the possibility to transform normal young Norway spruce (*Picea abies* (L.) Karst) forests to develop more heterogeneous stand structures, aiming for multi-layered forest in the long run. On three sites in central and south Sweden, 60 per cent of stand basal area was removed by thinning mainly medium-sized trees and leaving the smallest and the largest trees. Over the next 50 years, future stand development was simulated using a single-tree growth model. Simulations were run with and without ingrowth. An additional ingrowth scenario after soil preparation was tested. Basal area was kept between 10 and 20 m²ha⁻¹ during simulations. Projected stem wood production for the next 50 years was one-third lower compared with conventional thinning regimes. After 50 years, a multi-layered forest structure was indicated for the boreal sites in central Sweden, but not for the site in south Sweden.

33 Duduman, G. (2011)

A new model for computing the allowable cut for uneven-aged stands is described. The model is focused on the Gini index against basal area and the target structure of stand volume on diameter classes, assumed to be achieved by the end of transformation period from even-aged to the uneven-aged structure. The real structure of the stand is characterized by a given Gini index while the target structure is characterized by a benchmark Gini index. In order to determine the benchmark Gini index, the model allows the establishment of target structure of the stand based on a new idea: target structure of trees number in diameter classes for a particular stand corresponds to a certain target distribution of volumes on diameter classes. According to the difference between the two mentioned Gini indices, a certain period for directing the real structure to the target structure is further chosen while the computation of the allowable cut is based on the assumption of Gaussian distribution of volume against diameter classes. Eventually, the computation of allowable cut takes into

account the stand growth, the differences between the real and the target growing stock, the adopted transformation period and the management goals.

34 Eggers, J. et al. (2017)

Besides traditional timber production, other forest functions, such as biodiversity and recreation, have gained increasing importance during the last few decades. Demands on forests have become more diversified, thus making forest management and planning more complex. To meet these challenges, there is a growing interest in a more diversified silviculture, for which a number of different management options are available. However, it remains unclear how the various management options affect economic, ecological, and social aspects of sustainable forest management. Hence, in this study, we assess the consequences of various management options on different aspects of sustainable forest management through scenario analysis using a forestry decision support system. We evaluate 10 different forest management scenarios for two contrasting municipalities in Sweden, based on expert participation by way of a web-based multi-criteria decision analysis framework. We asked experts in economic, ecological, and social forest values, as well as those in reindeer husbandry, to weigh a number of indicators in their field of expertise against each other, and to create value functions for each indicator. We then determined scenario ranking for different sets of weights for economic, ecological and social forest values. Our results indicate that current management practices are favourable for economic aspects (wood production), while a number of scenarios would be better suited to fulfil the Swedish co-equal forest policy goal of production and consideration of environmental issues, such as scenarios with longer rotation periods, a larger share of set-asides and a higher share of continuous cover forestry. These measures would be beneficial not only for ecological values, but also for social values and for reindeer husbandry. Furthermore, we found that expert participation through the web-tool was a promising alternative to physical meetings that require more commitment in terms of time and resources.

35 Ex, S. A. & Smith, F. W. (2014)

Twenty-first century forests are managed for myriad benefits including aesthetics, habitat, and other ecosystem services. Multiple management objectives can often be accommodated by multi-aged stand structures. Consequently, multi-aged silviculture is increasingly considered in place of even-aged methods. When multi-aged methods are adopted in commercial forestry settings, it is important to consider potential impacts to wood production. Evaluating wood production efficiency (usually expressed as periodic annual increment per unit leaf area) of different sized trees in multi-aged stands helps illuminate the effects of stand structure on productivity. Growth dominance analysis is an alternative method that compares proportion of stand biomass or volume carried by trees with the proportion they produce. We analyzed production efficiency patterns in multiaged ponderosa pine stands and compared results to trends in growth dominance. Small trees in multiaged stands were ~20% less efficient than large trees, yet we found no overall difference between multiaged and even-aged structures. Surprisingly, dominance analysis implied that small trees were more productive than medium or large trees in multiaged stands. However, when dominance analysis was repeated using leaf area instead of stem volume as a metric of resource acquisition, this trend disappeared. Results indicated that multiaged prescriptions for wood production should consider production efficiency differences between size classes of trees and that growth dominance curves created using leaf area illustrate tree size-productivity trends in multiaged stands.

36 Ficko, A., Roessiger, J. & Bončina, A. (2018)

An increase in ungulate abundance in Europe in recent decades has raised concerns for the survival of browse-sensitive tree species in its early life history stages. A possible strategy for mitigating the browsing-induced mortality of natural regeneration is to optimize silviculture. We used matrix population models parameterized for three types of *Abies alba* - *Picea abies* - *Fagus sylvatica* forests (3,183 permanent sample plots from three study areas in Slovenia, 39,717 ha), and a non-linear optimization to: (i) schedule optimal timing and intensity of logging in the next 100 years to increase the recruitment of *Abies alba* without intervening in

the population of ungulates; and (ii) examine the influence of different natural recruitment rates on the potential for mitigating recruitment failure through silviculture optimization. The optimal management has required species-, growth- and diameter-specific logging, including intensive logging of large-diameter *Abies alba* in the first decades and strict conservation of recruits. The potential for mitigating recruitment failure through optimization increased progressively with natural recruitment rate and progressively at a decreasing rate with time. Optimizing silviculture was effective for maintaining *Abies alba* in stands exposed to low or moderate browsing pressures. Faced with chronic ungulate herbivory, forest managers should primarily focus on the reduction of herbivory and to a lesser extent on optimizing silviculture.

37 Ficko, A., Roessiger, J. & Bončina, A. (2016)

Chronic browsing and inappropriate stand management are often discussed as causes for recruitment failure of tree species in temperate mixed uneven-aged forests. Continuous cover forestry is thought to produce conditions that are conducive to the recruitment of native shade-tolerant and browse-sensitive tree species such as silver fir (*Abies alba* Mill.). This study used density dependent matrix population models parameterized for three main types of fir forests in Europe (53 048 measured trees from 3183 permanent sample plots) to project the effects of Business-As-Usual uneven-aged management (BAU) and three alternative management scenarios (Non-Intervention (NON), Profit Maximization (MAX) and stand management optimized for increasing recruitment (CONS)) on fir population dynamics over 100 years. BAU, MAX and, particularly, CONS improved the population parameters if natural recruitment was sufficient regardless of site, current and historical logging and transient and equilibrium growth rates under NON. In chronically browsed and recruitment-limited fir populations with transient and equilibrium growth rates,¹ under NON, the demographic ageing of fir can only be halted temporarily if silviculture is optimized for conservation, but none of the scenarios can prevent fir from decline. Our results suggest that a number of uneven-aged silvicultural systems, including more profit-oriented, can improve the demography of fir in central European mountain forests. However, they are not a pragmatic method to conserve fir when a population suffers from limited recruitment that causes an unmanaged population to decline.

38 Fu, L. et al. (2017)

Accurate estimates of forest site productivity are essential for environmental planning and forest management. In this study, we developed a new productivity index, hereafter termed basal area potential productivity index (BAPP), to estimate site productivity for irregular and complex forests characterized by multi-aged, multi-species, and multi-layer stands. We presented the biological relevance of BAPP with its computational details. We also compared BAPP against basal area realized productivity (BAPR) in order to verify the practicability and reliability of BAPP. Time-series data of the national forest inventory on 1912 permanent sample plots that were located in two main forest types and consisted of oak-dominated mixed forests and other broadleaf forests in northeast China were used to demonstrate the application of BAPP. The results showed that the value of BAPP for each sample plot was larger than or equal to the corresponding BAPR value for each forest type. For appropriately managed stands with relatively better site conditions, the values of both BAPR and BAPP were almost identical. The values of the difference between BAPP and BAPR could therefore be used to effectively assess forest site productivity. Meanwhile, BAPP also provides much reliable and valuable information that can aid decision-making in forest management.

39 Kerr, G. (2016)

The aim of this Guide is to provide you, the forest manager, with guidance on how to carry out underplanting. Underplanting is the planting of young trees under an existing canopy, either as part of a process of regenerating the existing stand or to introduce an understorey to enrich and diversify the forest structure. Planting trees into the sheltered environment of an existing forest can confer silvicultural advantages, particularly against unseasonal frosts and heavy rainfall; however, there are also risks, such as failure to prepare the stand and consider future operations. Underplanting is very different to restocking, which is familiar to

most forest managers in Britain, and the aim of this Guide is to give you clear information on how to achieve successful underplanting.

40 Graham-Sauvé, L. et al. (2013)

Partial cutting has been proposed as a means to better conserve biodiversity in managed forest landscapes. However, partial cutting encompasses many forms of silviculture; some with implicit goals of maintaining biodiversity such as multicohort harvesting or others which may specifically focus on regeneration of stands but may still provide some additional benefits for biodiversity such as shelterwood harvesting. Here we compared ground beetle assemblages of clear cuts, shelterwoods, multicohort harvested stands and uncut stands collected using pitfall traps both 2 and 3-years post-harvest. We hypothesized that partial cutting treatments would maintain assemblages that were more similar to uncut stands than to clear cuts. We further hypothesized that among partial cuts the multicohort harvested stands, with relatively high levels of retention (66%), would maintain beetle assemblages that were more similar to uncut stands than would shelterwoods, which had lower levels of retention (50%). We collected 6692 individuals, representing 42 species. Catch rates of beetles were similar among all harvested treatments (shelterwood, multicohort and clear cuts) and lower than uncut stands. Species richness and composition was similar between shelterwood and multicohort stands. Both partial cut treatments fell between clear cuts and uncut stands in terms of species richness and compositional similarity. Compositional differences between uncut stands and partial cut stands were defined primarily by reduced abundances of forest associated species such as *Agonum retractum* (LeConte), *Synuchus impunctatus* (Say) and four *Pterostichus* species within partial cuts. Within partial cuts, beetle assemblages differed between machine corridors with 0% retention and adjacent partial cut strips (50% retention) and uncut vegetation corridors (100%). We conclude that both shelterwoods and multicohort harvesting stands provide at least initially similar benefits for biodiversity compared to clear cutting although neither maintains assemblages consistent with those found in uncut stands. We expect that these similarities will end once trees are removed from shelterwoods. The reductions in abundances within partial cuts may extend the time necessary for individual populations to increase to pre-harvest levels in partial cuts. For land-managers, similar initial responses of beetle assemblages in multicohort and shelterwood harvests may permit some flexibility for conservation planning whereby final removal of seed trees within shelterwoods could be delayed depending on the status of recovering beetle populations.

41 Hanewinkel, M. et al. (2014)

Uneven-aged forests are assumed to have a high stability against storm damage but have rarely been analysed for vulnerability to storm damage due to a lack of a sufficient empirical database. Here we model storm damage in uneven-aged forest to analyse major factors that may determine the sensitivity of this type of forests to storms based on a broad database. Data are derived of public forests in the canton Neuchâtel in West Switzerland that are dominated by silver fir and Norway spruce and managed since the beginning of the 20th century following a single-tree selection system. A unique dataset of periodical (every 5–10 years) full inventories measuring the diameter of every single tree including salvage cuttings was available for the investigation. The time series reached back until 1920 and covered an area of 16 000 ha divided into 3000 divisions. The effect of a major winter storm ('Lothar') in December 1999 on these forests was investigated using a subset of 648 divisions. The influence of the vertical stand structure on the vulnerability of storm damage was studied using logistic regression models. To facilitate the analyses, an index of closeness to a J-shaped distribution (Like J) based on the number of trees in different diameter classes was developed. Besides structural indices, variables representing stand characteristics, soil-related and topography-related variables were included. The results of our study show that the overall damage level of the investigated forests was rather low. The variables that entered the model for the uneven-aged stands were different to those that are normally significant for even-aged stands. While variables like stand structure, the timing of the harvesting and topographic variables entered a multivariate statistical model as significant predictors, standard predictors for storm damage in even-aged stands such as stand density, thinning intensity or species composition were not significant. We

hypothesize that the uneven-aged structure of the investigated forests may be one reason for the low damage level we observed but emphasize the need for more detailed research to support this conclusion.

42 Hanewinkel, M., Frutig, F. & Lemm, R. (2014)

For this study, 18 permanent research plots in Switzerland with an area between 0.5 and 2.5 ha that have been installed between 1905 and 1931 were analysed using annuities. The plots cover a wide range of uneven-aged forest-types from pure Norway spruce to classical single-tree selection (plenter) forests dominated by Silver fir in different elevations (575–1810 m a.s.l.). The areas have been managed according to an uneven-aged silvicultural system and growth and yield characteristics have been assessed on a single-tree basis every 5–11 years. Net revenues of timber harvesting were computed as a time series from the installation of the plots until today and transformed into net present values and subsequently into annuities for each assessment interval. Three types of annuities: (1) for cutting cycles; (2) forward; (3) backward for the whole assessment period were calculated together with internal rates of return. The results display that annuities were usually positive with an interest of 2 per cent. High elevation (>1400 m) Norway spruce dominated forests as well as heavily overstocked (>900–1000 m³ ha⁻¹) plots showed the lowest or even negative annuities. The reduction of overstocks lead in the mid-term to an increase, but resulted in a short-term decrease of the annuities. For many of the research plots, especially those in higher elevations, there is a trend towards an increase of the annuities over time. The highest annuities were found in Silver fir dominated selection forests with a growing stock close to or slightly above an equilibrium structure. The backward calculation of the annuities improved for some plots the problem of the strong influence of the value of the initial growing stock. Implications for uneven-aged silviculture as well as for the analysis of the economic performance of uneven-aged and even-aged forests and the application of annuities are discussed in the paper.

43 Hanson, J. J., et al (2012)

Ecological forestry practices are designed to retain species and structural features important for maintaining ecosystem function, but which may be deficient in conventionally managed stands. We used the spatially-explicit, individual tree model CANOPY to assess tradeoffs in enhanced ecological attributes vs. reductions in timber yield for a wide variety of treatments in uneven-aged, late-successional northern hardwood forests. Treatments included various combinations of (1) larger retained maximum tree diameters in the post-harvest stand, (2) permanently reserved legacy trees, (3) variable opening sizes, (4) coarse woody debris retention, (5) species harvest restrictions, and (6) occasional moderate-intensity harvests with larger openings ('irregular multi-cohort harvests'). Compared to conventional single-tree selection, reduction in simulated harvest yields varied widely from a 9% decline with 7 reserve trees/ha to a 55% reduction in treatments that retained coarse woody debris along with a maximum residual live-tree diameter of 80 cm. Despite the dominance by shade-tolerant species, simulated declines were similar in magnitude to those predicted or observed for relatively shade-intolerant conifers of the Pacific Northwest. Treatments that protected 'sensitive' species from harvest or raised the maximum residual diameter to 80 cm appeared to have the best balance between fostering ecological values of old-growth forests and moderating the impact on timber yield. These treatments produced stands meeting minimum structural criteria of old-growth forests while causing harvest declines of 27–30% compared to conventional single-tree selection. Coarse woody debris volumes were similar to those produced by the reserve-tree treatments, but the species-protection and 80 cm treatments had higher densities of large trees, and there was less reduction in yield for each large tree retained in the residual stand. Most other treatments maintained mature forest structure or stands that vacillated between mature and borderline old-growth conditions.

44 Harmer, R. et al. (2017)

In the UK, the use of continuous cover forestry is increasing but the effects of such management on woodland ground flora has been little studied. In this investigation, vascular plants in the ground flora were observed before and after thinning to create plots with target

basal areas of 20, 15 and 10 m²ha⁻¹ within a semi-natural *Fraxinus excelsior* woodland: treatments to exclude deer and control bramble (*Rubus fruticosus*) were also applied. Although 45 new species appeared only 26 remained 5 years after thinning; their cover was often 1–2%. Before thinning 38 herbaceous species were present and although only one of these disappeared the frequency of most common species declined in plots without bramble control. In contrast, on plots with bramble control the frequency of some species increased significantly and 40–50% more species were present after 5 years. Species richness after thinning was positively related to the initial species richness and in general negatively related to bramble height and basal area of adjacent trees. Results suggest that silvicultural practices which maintain partial canopy cover should be avoided on some sites as the development of dense bramble cover can have adverse effects on the woodland ground flora present before harvesting.

45 Harmer, R., Morgan, G. & Beauchamp, K. (2011)

The removal of conifers planted during the twentieth century on sites that had been woodland for many centuries, with the intention of restoring native broadleaved species, is an important aim of forestry policy in Great Britain. Current guidance generally advocates gradual removal of plantation trees using continuous cover silviculture and restocking by natural regeneration, but methods are largely untested. This study investigated natural regeneration of trees and shrubs at sites where western hemlock had been established either pure or in mixture with native broadleaved species. Western hemlock had been cleared from 70% of the sites. There were c.10–300 stems ha⁻¹ providing canopy cover of 10–90%; the pre-dominant broadleaved canopy trees were ash, beech, birch and oak. The ground flora of all sites was species poor; bramble was the predominant vegetation type overall, but grasses, rushes and shrubs were relatively more abundant on open sites. A total of 15 native tree species were regenerating, birch was most common and at most sites there were few valuable broadleaved timber species. Although combined numbers of seedlings and saplings varied from 200 to 20,000 ha⁻¹, large areas of most sites had few regenerating trees and <10% of their area was becoming restocked with timber species. Relationships between seedling numbers and site characteristics were complex and varied with species, but there was a consistent positive relationship between the presence of nearby parent trees and the frequency and abundance of seedlings. The results indicate that the current reliance on natural regeneration may be unwise especially for those broadleaved species such as oak and beech which are valued for their timber.

46 Heaphy, M. J. et al. (2014)

Background: The effect of soil erosion on New Zealand production forestry is not well known and there has been no research prior to our study into the relationship between soil nutrient status and planted forests growing in eroded soils in steep lands. Methods: The impact of soil erosion by mass movement on forest productivity was investigated in a paired plot trial in a planted forest in a mainly hilly to steep-land catchment (Pakuratahi) near Napier, eastern North Island, New Zealand. Tree growth and form were measured, and soil properties analysed to compare productivity and productivity drivers in adjacent non-eroded and eroded plots. Results: Regression analysis showed that the decreased soil total nitrogen, total carbon, total phosphorus, and soil organic matter content in eroded plots had a negative impact on tree volume, resulting in a 10% decrease in measured tree volume. Based on an assessment of log quality, trees in the eroded plots were forecast to produce 16% less volume from high-quality pruned logs (with associated reduction in revenue of around \$4000 per hectare), than trees in non-eroded plots. The total recoverable volume (TRV), estimated (for a 25-year rotation) from the measured *Pinus radiata* D. Don trees growing on the eroded sites, was valued at \$68,500, about 9% less than the estimated TRV from trees measured on non-eroded plots (\$76,000). Tree form and mean tree height in eroded and non-eroded plots were not significantly different. Conclusions: Soil erosion impacts production in planted forests. Afforestation of erodible land provides a valuable ecosystem service through land and soil stabilisation, but this service is currently not reflected in the market prices for timber in New Zealand. Maintaining the productive capacity of erodible soils through practices such as fertilisation or continuous-cover forestry can add further costs to production forestry. To

ensure that sustainable forest practices are carried out to protect the productivity of soils, financial incentives may be justified.

47 Helliwell, R. & Wilson, E. (2012)

This paper presents a historical review of Continuous Cover Forestry (CCF) in Britain, and outlines both the opportunities and challenges associated with wider application in sustainable forest management of alternative silvicultural approaches (such as CCF), relative to conventional even-aged systems. The paper also highlights the benefits of CCF in relation to enhancing woodland resilience, and in response to threats from climate change, pests and diseases. It also addresses the delivery of multiple ecosystem services, including a wide range of ecological, environmental, economic and social values of woodlands in Britain.

48 Helliwell, R. (2014)

Very often, if not always, the main point to consider when undertaking the management of a population of trees should be "Which, if any, trees need to be removed?" This question should take precedence over the question "Which, if any, trees need to be pruned?" There might of course be a need for some pruning, but the long-term management of amenity trees needs to involve a basic framework for their development and replacement. This should be in such a manner that the tree population as a whole can be maintained without any sudden or significant reduction of amenity, and this is likely to require the removal of some trees from time to time. Removal of trees should be seen as a normal requirement, and not something that can be avoided, ignored or postponed indefinitely. If there are, for example, 200 trees of mixed age and condition on a site, one would expect that about 10 trees will be removed about every 5 years, on a regular basis; sometimes more, sometimes less, depending on their species, age and condition. There might be periods when no trees need to be removed but these are likely to be the exception rather than the rule. Operations such as pruning are also likely to be needed, but these operations are unlikely, in themselves, to be sufficient, unless they include coppicing (which is a form of periodic felling). In most cases, management should enable the tree population to change gradually, thereby avoiding sudden loss of amenity, ensuring that there are suitable younger trees to carry on growing when others are removed, and reducing future problems of safety and major expenditure. This will be likely to result in a regular programme of work, with less expenditure on emergency action or on trees which it would be more sensible to remove than to prune. It should also reduce the number of unsafe trees and provide a basis from which safety requirements can be met. It might also provide a more regular supply of fuelwood or other by-products, possibly enabling local markets for such products to be supported. Public opinion might not, at least initially, favour such an approach. However, opinion will probably change, over time, when it is seen that this approach does not in fact result in any overall reduction in amenity or any progressive loss of tree cover, as many people currently seem to fear.

49 Helliwell, R. (2012)

In cloudy regions such as Great Britain, diffuse light from the sky is the only source of light for a large part of the time. Additionally, within woodland, trees are also likely to obscure direct sunlight for most of the time, even when there is no cloud cover. I had, therefore, assumed that direct sunlight would be of lesser significance than diffuse light for the growth of tree seedlings and other vegetation within woodland. The literature on this subject appears to be somewhat confusing and contradictory; and any guidelines, which are provided by one author, are likely to be in conflict with the conclusions of at least some other authors. The aims of this research were therefore to carry out a very small experiment in an attempt to clarify these conflicting views. The results of this experiment were not what I would have predicted, and further work (by myself or others) appears to be needed in order to clarify the factors which are of greatest relevance to the woodland manager.

50 Helliwell, R. (2013)

This booklet covers similar ground to that covered by two earlier booklets; Continuous Cover Forestry (Helliwell 2002) and Fundamental Woodland Management (Helliwell 2006), which is currently out of print. My intention is to provide a brief introduction, explaining the basis of Continuous Cover forestry. The primary audience is intended to be owners and managers of woodlands, but it is also hoped that it might be helpful to others who have an interest in how forests and woodlands are, or could be, managed. I have not attempted to cover more general aspects of forest practice, such as how to measure a tree, control deer, market timber, assess the safety of roadside trees, or the current availability of grant aid, etc., for which the reader must look to more general texts (e.g. Lanier 1986, Hart 1991, Wohlleben 2010, Blakesley and Buckley 2010) and local guidance.

51 Hessenmöller, D. et al. (2018)

Maintaining a permanent forest canopy cover and eventually harvesting wood in a final harvest according to predefined dimensions is often considered as prototype for future management of deciduous forests. An uneven-aged structure is considered by the public to resemble “natural” conditions, and by forest engineers it is considered as being more resilient to disturbances. In the Hainich-Dün region of Thuringia, Germany, beech-dominated selection forests covering about 10,000 ha have been managed for almost 1000 years, initially by irregular use, but as regular selection system since about 200 years. Managing these stands remains difficult, due to the lack of yield tables and a quantification of harvest of uneven-aged stands considering differences in site conditions and handling of over-sized trees. It is the objective of the present study to develop tables of target stand volumes, increments, and harvest for different diameter ranges of uneven- aged stands according to site conditions. The present study is based on repeated grid-based inventories of about 2150 plots, which were partly re-inventoried 3 times over the past 20 years. The recommended target wood volumes vary between 296 and 388 m³ ha⁻¹. Stand growth rates of different yield classes were estimated to range between 6.7 and 7.7 m³ ha⁻¹ yr⁻¹ which is 30% lower than for age class forest. Nevertheless, the economic returns are higher. Thus, selective cutting with single tree selection remains a viable silvicultural system, but it may change over time into small-scale shelter-woods for improving growth of regeneration.

52 Hevia, A. et al. (2015)

This study presents a new approach permanent sample plots installed in even-aged birch (*Betula alba*) dominated stands were used to link models with different levels of resolution. Data from 50 develop both, a whole-stand growth model and an individual-tree model. In a first step, six disaggregation approaches to link number of trees per hectare with tree survival were combined with four disaggregation approaches to link stand basal area with tree basal area growth predictions. To analyse the effect of stand variable predictions on disaggregation estimates, two different methods to obtain these predictions were evaluated: (a) 1-fold cross-validation of the stand growth model and (b) a method involving composite estimators. Therefore, altogether 48 different approaches in linking models were analysed in this first step. In a second step, two common methods based on the use of a threshold to translate the survival tree probabilities into a discrete event, i.e. dead or alive, were combined with the four disaggregation approaches to link stand basal area with tree basal area growth predictions and the two methods to obtain stand variable predictions. Therefore, altogether 16 different approaches in linking models were analysed in this second step. Finally, the best combinations obtained in each step were compared. Regarding the disaggregation of predicted stand density, the approach based on considering the intercept of the logit function for tree survival as a specific parameter of each sample plot and optimizing its value produced the best results. Regarding the disaggregation of stand basal area among trees, the constrained least squares method was selected, since it showed the best results among four alternative approaches. The use of composite estimators instead of the 1-fold cross validation predictions improved the accuracy of both, tree survival and tree basal area estimates, although the differences were not significant. Finally, disaggregation approaches performed better than the methods based on the use of a threshold. The results show that the combination between composite estimators and disaggregation provided compatible and reliable predictions of stand density, tree survival, stand basal area and tree basal area. The main limitation of this new approach is the dependency of accurate stand

growth predictions, therefore, it should be tested in future studies with more complicated stand structures, such as mixed and un-even aged forests, or to include the effect of silvicultural treatments.

53 Hjältén, J. et al. (2017)

Large scale use of even-aged silviculture (clear-cutting) commencing in the mid-20th century has had negative impacts on forest biodiversity considered to help meet the ecological and social criteria required for sustainable forest management. Uneven-aged silviculture (e.g. selective felling) involves selective removal of some older trees in a stand. As a consequence, uneven-aged silviculture is currently being which may to some extent mimics natural small-scale stand dynamics and thus potentially benefit species associated with old forests. Here we test whether selective felling benefits beetle biodiversity by producing beetle assemblages that better resemble those of old growth stands than those found in uncut production stands. We conducted a field study in northern Sweden, comparing beetle assemblages collected with window traps in three spruce dominated stand types: (1) Stands recently (on average 7 years prior to the study) subjected to selective felling (Selective felling), (2) mature uneven-aged stands without recent history of management, resembling selective felling stands prior to management (Uncut), and (3) old-growth stands with high conservation values (Old growth). As predicted, we found that assemblage composition was similar in selective felling and old growth stands, and that assemblages of cambivores and obligate saproxylics (marginally significant) differed between these two stand types and uncut stands. The differences were largely explained by a higher abundance of saproxylic species presumably associated with old growth conditions and large volumes of deadwood. Thus, although overall assemblage composition did not differ between stand types, part of the beetle community seemingly benefited from selective felling. We therefore recommend that selective felling is considered as an alternative to clear-felling to maintain biodiversity values.

54 Honkaniemi, J. et al. (2014)

Heterobasidion annosum (Fr.) Bref. s.l., a group of fungi causing root rot, is a serious threat to Norway spruce (*Picea abies* (L.) Karst.) stands in northern Europe. A new stochastic spatial model (Hmodel) was developed to simulate *H. annosum* s.l. infection and spread within a stand. Hmodel was combined with the stand-level decision support system MOTTI, resulting in a platform for estimating *H. annosum* s.l. development and its effect on tree growth and timber quality. Three *H. annosum* s.l. scenarios, representing different levels of risk for *H. annosum* s.l. infections simulated for a typical Norway spruce stand in southern Finland, demonstrated that the mycelial growth rate in the roots of living trees was the most critical parameter influencing the simulation results. In addition, the simulation results indicated that the number of infected trees in the previous stand plays a major role in *H. annosum* s.l. dynamics within the subsequent tree generation. Hmodel was designed to be a flexible platform for researchers to simulate the effects of *H. annosum* s.l. on stand dynamics and, vice versa, the effects of different silvicultural methods on *H. annosum* s.l. dynamics.

55 Huth, F. et al. (2017)

The direct seeding method of artificial regeneration has a long tradition in silvicultural management. The main application of the direct seeding of silver fir (*Abies alba* Mill.) today occurs in the context of the conversion of Norway spruce stands in central Europe. Although direct seeding is often considered to closely resemble natural regeneration in many respects, tree planting is currently more commonly employed in forestry. Presented in this paper is an extensive historical review showing the variety of facets associated with and experiences of direct seeding gleaned through scientific experiments or based on forestry practice. This review also illustrates the fluctuating practical relevance of the direct seeding of silver fir depending on the prevailing objectives of forest owners, harvesting methods, forest structures and the possibilities for technical implementation. An overview of the available ecological knowledge of the development stages and processes within the natural

regeneration cycle of silver fir is provided, highlighting the most relevant environmental factors and the resources determining the success of natural regeneration. Having identified these factors, the individual technical steps involved in direct seeding can be analysed. The means by which the individual steps in the direct seeding approach can be used to manipulate environmental factors and microsite conditions such as the density of overstorey shelter, soil and seedbed preparation, and to reduce competition pressure to optimise the direct seeding of silver fir are outlined. Finally, on the basis of the analyses presented, these complex relationships are integrated in a step by step decision pathway to provide an individual forest stand decision-making process. This ecologically based approach can improve the success of direct seeding and may allow for the adaptation of the direct seeding process to suit individual forest stand conditions. Consequently, the growing efforts to convert and enrich homogenous Norway spruce stands by means of the direct seeding of silver fir can be promoted in a close-to-nature way, while employing controlled silvicultural measures.

56 Jacobsen, J. B., Vedel, S. E. & Thorsen, B. J. (2013)

Programmes for forest habitat protection and some certification schemes restrict forest owners' choice of regeneration methods, even in continuous-cover systems such as the use of the shelterwood system in beech (*Fagus sylvatica* L.) forests in Denmark. The aim of this study is to reduce environmental pressure on e.g. groundwater or to protect species dependent on deadwood or undisturbed soils, which is beneficial/important from a welfare economic perspective. Such restrictions come at a cost to both the forest owner and society. Using a case study approach, we investigate the possible financial losses from placing such restrictions on current shelterwood beech management practices. Apart of the restrictions implies lower input, intensity and costs in regeneration activities, but this is outweighed by potential future losses arising from incomplete regeneration and prolonged re- generation phases. The cost in terms of present value reductions of a mature stand may be up to 10 per cent (with an interest rate of 3 per cent) but in many cases is much less. Another set of restrictions implies leaving single trees for natural aging and decay, and we estimate the costs of such measures too.

57 Jacobsen, J., Jensen, B. & Thorsen, F. (2018)

The Faustmann forest rotation model is a celebrated contribution in economics. The model provides a forest value expression and allows a solution to the optimal rotation problem valid for perpetual rotations of even-aged forest stands. However, continuous forest cover forest management systems imply uneven-aged dynamics, and while a number of numerical studies have analysed specific continuous cover forest ecosystems in search of optimal management regimes, no one has tried to capture key dynamics of continuous cover forestry in simple mathematical models. In this paper we develop a simple, but rigorous mathematical model of the continuous cover forest, which strictly focuses on the area use dynamics that such an uneven-aged forest must have in equilibrium. This implies explicitly accounting for area reallocation and for weighting the productivity of each age class by the area occupied. We present results for unrestricted as well as area-restricted versions of the models. We find that land values are unambiguously higher in the continuous cover forest models compared with the even-aged models. Under area restrictions, the optimal rotation age in a continuous cover forest model is unambiguously lower than the corresponding area restricted Faustmann solution, while the result for the area unrestricted model is ambiguous.

58 Jönsson, A. M., Lagergren, F. & Smith, B. (2013)

To adapt to climate change, forest managers request information on management options for obtaining environmental, societal and economic goals. In this study, we assess the potential of adaptive forest management to influence the productivity and storm sensitivity of nemoral and boreal forest. The forest growth across Sweden over the 21st century was simulated by the ecosystem model LPJ-GUESS, comparing four management options: 1) default forest management, 2) shorter rotation period 3) increased fraction of broadleaved trees and 4) continuous cover forestry. The simulations indicated that a management strategy implemented by a majority of forest owners can have a large-scale effect on the standing volume and risk taking. The modelled risk of storm damage, expressed as the

combined effect of tree properties, ground frost and wind load, was higher in the southern than in the northern part of the country due to latitudinal variations in all three components. We conclude that whereas the probability of a significant volume loss increase with the age of a forest, the calculated economic loss can be as high in young and mid-age forest stands. To reduce the risk of storm damage and fulfil a variety of management goals, a portfolio of adaptation strategies is needed. It should include active measures such as tree-species mixtures to spread the risks and shorter rotation periods of highly exposed stands, as well as reactive measures such as salvage and sanitary cutting to reduce the risk of subsequent spruce bark beetle outbreaks.

59 Kerr, G & Mackintosh, H. (2012)

The Glentress Trial Area is an extensive research area in southern Scotland of 117 ha where a long-term trial of the transformation of even-aged plantations to continuous cover has been in progress since 1952. During the assessment of permanent sample plots in 1990 information on the species and spatial position of saplings (trees taller than 1.3 m with a diameter at breast height of <7 cm) was recorded. This provided a unique opportunity to investigate the long-term survival of saplings during the transformation process when the Trial Area was reassessed in 2009. The main finding was that 37% of saplings survived the 19-year period and the majority developed into trees (≥ 7 cm diameter at breast height). There was considerable variation between species, the lowest survival of saplings was European larch (*Larix decidua* Mill.) (13%) and the highest European beech (*Fagus sylvatica* L.) (55%); however, differences between species were not significant. There were, however, significant differences between the six management areas with three with high sapling survival (55% to 61%) but others much lower (27% to 32%). If this result is confirmed by other studies, covering a broader range of sites, management guidance.

60 Kerr, G. et al. (2017)

The aim of this study was to examine the species composition and structure of woodlands that have been managed using the Bradford–Hutt system for 54 years on the Tavistock Estate, Devon in England. The Bradford–Hutt system is a unique method of transforming even-aged stands to continuous cover management because it is not inspired by traditional silvicultural systems such as shelterwood or selection. Instead the system takes the main elements of clearfelling, i.e. planting, thinning and felling, and organizes them on a small-scale, grid pattern in such a way that there will be continuous canopy cover and good access for forest operations. The system has been successful in creating mixed species stands with an uneven-aged structure that meet present policy requirements for resilience but, to our knowledge, it was not applied elsewhere. Options for future management include continued use of the Bradford–Hutt system; however, now that the structure has been created and natural regeneration is apparent, this may not be the best method and other options are examined. The system was developed by the sixth Earl of Bradford and his forester Phil Hutt, both of whom deserve credit for their pioneering efforts and challenging the ‘forestry establishment’ to examine alternatives to clear-felling some 30–40 years before continuous cover became part of mainstream forest management in Britain.

61 Kerr, G., Stokes, V., Peace, A. & Wylder, B. (2011)

Recent moves towards the increased use of ‘continuous cover’ and ‘low-impact’ methods of managing conifer forests in Britain have led to greater interest in natural regeneration. This paper describes a project that designed and tested a model to predict the likelihood of natural regeneration in an environment where long-term datasets were not available. A spreadsheet-based model known as REGGIE (REGeneration GuldanceE) was designed based on first principles and silvicultural experience. It was tested on 129 sites of four conifer species on a wide range of sites throughout Britain; at each site an expert judged the likelihood of regeneration in the next 5 years in one of five classes: 0-20%, 21-40%, 41-60%, 61-80% and 81-100%. The REGGIE model agreed with the expert prediction on 63 of the 129 sites (48.8%). The validation data were then analyzed using an ordinal logistic regression. The minimal adequate model included fewer terms compared with REGGIE and, not surprisingly, was more accurate with respect to the expert prediction on 113 of the 129 sites (87.6%). An

advantage of the ordinal logistic model is that we have devised a simple score-based method of application which is easy to apply in the field. Informal validation of this model has suggested that it has potential to be used by forest managers as part of a strategy to raise understanding of how to use natural regeneration when transforming conifer stands to continuous cover in Britain.

62 Klapwijk, M. J. et al. (2016)

Current silvicultural practices are under revision as result of changing demands and pressing environmental issues. We compared the monoculture clear-cut regime commonly used during the recent decades in Europe, especially in Fennoscandia, and in North America, with three alternative forest management methods, short rotation forestry, mixed forest stands and continuous cover forestry. We evaluate how these alternative management methods are likely to affect the natural control of forest insect (regeneration pests, defoliators and bark beetles). Particular emphasis was placed on the effects of forest management on natural enemy pressure. We argue that changing forest management to any of the methods discussed will, in most cases, decrease the relative effects of bottom-up forces (resource quality and quantity) and increase the relative effects of top-down forces (natural enemy pressure) on forest pests. As population growth of the pest species presently causing most damage in European managed forests (i.e. pine weevil and spruce bark beetle) is mainly limited by bottom-up forces (quantity of suitable breeding material), changes in forest management could increase the relative importance of top-down forces by modifying stand characteristics to actively support the natural enemies. However, it remains to be investigated to what extent such alterations will result in decreased damage to trees even though some evidence points in that direction.

63 Klopčič, M. & Boncina, A. (2012)

Recruitment is an important process in forest stand dynamics, especially in uneven-aged stands. Continuous recruitment is a prerequisite for diverse, uneven-aged silvicultural systems, but patterns may vary significantly. The main goals of the study were to examine the recruitment of the main tree species in selection and irregular shelterwood stands in silver fir–European beech–Norway spruce forests and to determine the main predictors of the recruitment occurrence. Data from 5,486 permanent inventory plots were used to study recruitment of saplings into the tree layer (diameter at breast height ≥ 10 cm). & Results Recruitment rate differed significantly between selection (7.6 trees ha⁻¹ year⁻¹) and irregular shelterwood (26.1 trees ha⁻¹ year⁻¹) stands. Shade-tolerant fir and beech recruited with higher probability in selection stands, while light-dependent sycamore recruited with higher probability in irregular stands. In addition, forest types, soil pH, stand basal area, mean diameter, and the basal area of the same tree species with respect to recruitment were found to be important predictors of recruitment occurrence. The application of different uneven-aged silvicultural systems and their forms makes it possible to considerably influence the future tree species composition of uneven-aged forests.

64 Klopčič, M., Simoncic, T. & Boncina, A. (2014)

Research on the early stages of stand dynamics in uneven-aged forests often favours regeneration over recruitment of trees into forest stands. We contrasted both regeneration (i.e. seedlings and saplings existing in a stand) and recruitment (i.e. the number of trees annually crossing the threshold of 10 cm dbh) in two main stand types of uneven-aged forests (plenter and group selection). Data from 1710 permanent plots across the Dinaric Mountains in Slovenia were used to study recruitment; on 165 plots, regeneration was additionally analysed. The zero-inflated negative binomial modelling procedure was applied to identify factors influencing regeneration and recruitment. Total regeneration (30 212 ha⁻¹ year⁻¹) and that of light-demanding species (14 879 ha⁻¹ year⁻¹) were abundant. The latter regenerated more successfully in group selection stands compared with plenter stands. A large reduction in regeneration density was determined during its growth, which was more dramatic for light-demanding species (e.g. *Acer pseudoplatanus*) than for shade-tolerant species (e.g. *Fagus sylvatica*, *Abies alba*). The number of recruited trees (5.83 ha⁻¹ year⁻¹) seemed to be sufficient to maintain the uneven structure but was less promising for light-demanding species (0.13

ha21y21). However, light-demanding species have the potential to establish and recruit into uneven-aged stands with a limited target proportion in the growing stock. Both indicators—regeneration and recruitment—are indispensable for understanding patterns of stand dynamics in uneven-aged forests.

65 Knoke, T., Paul, C. & Härtl, F. (2017)

The long planning perspective is one of the unique features of forestry. How to value money flows expected in the far distant future is therefore a crucial question. Applying time declining discount rates (DDR) may offer an appropriate alternative to conventional discounting, but few studies have applied DDRs in forest economics. We expect that theoretical assumptions behind welfare analyses based on DDR will be important. Using a dataset from the UK (Davies and Kerr (2015) [Forests 6: 2424–2449]) we investigate the effects of 1) more than marginal contributions from forestry to consumption, 2) the role of the assumed scenarios for return on capital, and 3) ignoring optimization (i.e. adopting predefined management scenarios) on the ranking of different silvicultural strategies. These include various clear-felling options (with replanting, natural regeneration or under-planting) and the transition to continuous cover forestry. Our analysis reveals that changes in these aspects affect the ranking of forest management options more strongly than a pure change in the coefficients of a benefit cost analysis. Decreasing marginality, cautious assumptions about the worst-case return on capital and optimization of silvicultural operations all increase the relative attractiveness of continuous cover forestry. We conclude that applying DDR makes valuation in forestry more demanding and should be applied with appropriate care. In addition, the precise assumptions behind the particular schedule of DDRs should be explicit. Finally, theoretical considerations support the importance of combining optimization of silvicultural management strategies with their economic evaluation.

66 Korosuo, A. et al. (2014)

In northern Sweden, the forests are used simultaneously for both timber production and reindeer husbandry. During the winter months, lichen is the most important fodder for reindeer. Forest management operations are generally considered having a negative impact on reindeer husbandry as harvesting and dense stands remove or obscure the ground lichen cover. In this study, we simulate three different scenarios for forest management, differing in the intensity and types of harvest operations. The resulting 100-year scenarios are analysed with respect to their estimated suitability for providing reindeer pasture areas. Suitability is determined by vegetation type, stand density and stand height. The results indicate that the current trend of a decrease in lichen area will continue if existing forestry practice prevails. Implementing continuous cover forestry as a management alternative and carrying out precommercial thinning could halt the decrease in reindeer pasture area and even lead to a future increase in pasture area, with losses of approximately 5% in the net present value of forestry.

67 Kuehne, C. et al. (2018)

Detailed measures of growth pattern and structural heterogeneity applied in this study helped to quantify the immediate effects of various thinning regimes on forest structure and the resulting alterations in tree size as well as observed longer term stand dynamics. Forest management stand structure, and tree growth are highly inter-correlated. Prior analyses, however, have resulted in mixed outcomes with limited success in revealing ecological mechanisms. The study aimed at evaluating the relationship between forest structure and stand dynamics by applying several sophisticated measures of growth pattern and structural heterogeneity. Data from a controlled and fully stem-mapped commercial thinning experiment with seven contrasting treatments including a non-thinned control at six locations across the Acadian Forest of Maine, USA, was used. Stand-level attributes examined included tree size and growth heterogeneity, spatial tree distribution, and growth dominance. Thinning generally reduced stand structural heterogeneity compared to the non-thinned control. In addition, the spatial arrangement of trees changed from fully random (non-thinned control) to a more clustered (removal of dominant and co-dominant individuals) or regular distribution (removal of intermediate and suppressed individuals). Overall, stand growth

exhibited increasing (non-thinned control, removal of intermediate and suppressed individuals) or decreasing growth dominance of large trees (removal of co-dominant competitors). Forwarder trails increased basal area growth of individual trees up to a distance from the trail of approximately 5 m. Findings of this study validate an earlier insight according to which interactions between management practices, forest structure, and tree growth form a permanent feedback loop.

68 Kuuluvainen, T., Tahvonen, O. & Aakala, T. (2012)

Since WWII, forest management in Fennoscandia has primarily been based on even-aged stand management, clear cut harvesting and thinning from below. As an alternative, uneven-aged management, based on selection cutting of individual trees or small groups of trees, has been proposed. In this review we discuss the theoretical aspects of ecology and economics of the two management approaches. We also review peer-reviewed studies from boreal Fennoscandia, which have aimed at comparing the outcomes of uneven-aged and the conventional even-aged forest management. According to a common view the main obstacle of practicing uneven-aged forestry is its low economic performance. However, the reviewed studies did not offer any straightforward support for this view and several studies have found uneven-aged management to be fully competitive with existing even-aged management. Studies on the ecological aspects indicated that selection cuttings maintain mature or late-successional forest characteristics and species assemblages better than even-aged management, at least at the stand scale and in the short term. We conclude that although the number of relevant studies has increased in recent years, the ecological and economic performance of alternative management methods still remains poorly examined, especially for those stands with multiple tree species and also at wider spatial and temporal scales. For future research we advocate a strategy that fully takes into consideration the interdisciplinary nature of forest management and is better connected to social goals and latest theoretical and methodological developments in ecology and economics.

69 Laiho, O., Lähde, E. and Pukkala, T. (2011)

The article summarizes results obtained from several field experiments, measured in uneven-aged forests during a long period; from the 1930s until the present. Experiments have been established in both Norway spruce- and Scots pine-dominated stands. The purpose is to evaluate the feasibility of uneven-aged forest management under Finnish conditions and compare uneven-aged management to the current even-aged forestry. The analysed datasets demonstrate relatively rich regeneration under many types of tree canopies. The number of stabilized (height 0.1–1.3 m) spruce seedlings does not always correlate with the stand density. The amount of small labile (height < 0.1 m) spruce seedlings may even increase with increasing stand volume. Contrary to spruce, the regeneration of birch and pine decreases with increasing stand volume. The yield comparisons show that uneven-aged stands have often grown faster than even-aged stands with the same post-cutting stand density. High thinnings have resulted in better volume increments than low thinnings. Recent studies show that uneven-aged management is more profitable than even-aged rotation forestry (RF), especially with high discount rates. Uneven-aged management seems to be superior to current even-aged RF also with respect to environmental and multifunctional aspects, such as carbon sequestration, bilberry yield, structural diversity and scenic values.

70 Laiho, O., Pukkala, T. & Lähde, E. (2014)

Stands having advance regeneration of spruce are logical places to start continuous cover forestry (CCF) in fertile and mesic boreal forests. However, the development of advance regeneration is poorly known. This study used regression analysis to model the height increment of spruce understorey as a function of seedling height, site characteristics and canopy structure. Results: An admixture of pine and birch in the main canopy improves the height increment of understorey. When the stand basal area is 20 m²ha⁻¹ height increment is twice as fast under pine and birch canopies, as compared to spruce. Height increment of understorey spruce increases with increasing seedling height. Between-stand and within-stand residual variation in the height increment of understorey spruces is high. The increment of 1/6 fastest-growing seedlings is at least 50% greater than the average. The results of this

study help forest managers to regulate the density and species composition of the stand, so as to obtain a sufficient height development of the understorey. In pure and almost pure spruce stands, the stand basal area should be low for a good height increment of the understorey.

71 Laurent, L. et al. (2017)

Plant competition and deer browsing are two main factors which limit tree recruitment. We examined natural tree-recruitment processes under continuous-tree-cover management. Changes in plant communities and tree regeneration were monitored over an eight-year period at two different sites in a temperate hardwood forest in the North-East of France. We used paired control plot (unfenced areas, free access to deer) and exclosures (fenced areas, excluding deer) at both sites. Shade-tolerant browsing-tolerant opportunistic species (beech, *Fagus sylvatica* at site 1 and bramble, *Rubus* spp. at site 2) were present in low numbers at the beginning of the study. We found that these species used a sit-and-wait strategy, waiting for opportunities to proliferate (thinning and deer exclusion). In the exclosure at site 1, beech proliferate slowly. In the exclosure at site 2, bramble proliferated enough during the first two growing seasons to prevent tree recruitment. Thus, fencing encouraged beech sapling or bramble growth, and this growth in turn was detrimental to the richness and diversity of the plant community. The two study cases presented show that both plant competition and deer browsing can be problematic for tree recruitment. Our results further suggest that excluding deer is not sufficient to enhance the growth of browse-sensitive and moderately shade-tolerant tree species such as oaks (*Quercus petraea* and *Q. robur*).

72 Li, Y. et al. (2014)

The selection of harvested trees is key to the success of near-natural forest management, yet few people have focused on the structural characteristics of harvested woods. Here, we examined the structural characteristics of harvested trees in Korean pine-broadleaf forest and pine-oak mixed forest in China using bivariate distributions of spatial structure parameters and the distribution of diameter classes. The stands were strictly managed according to the principles of structure-based forest management. We found that trees cut from both types of forest had wide structural diversity: they were widely distributed across vertical levels of the forest stand, including dominant, medium, and suppressed trees. Most trees from the Korean pine-broadleaf forest were of small-medium size and were highly mixed and randomly distributed in relation to their neighbours. In contrast, trees cut from pine-oak mixed forest tended to be clumped in relation to their neighbours. The majority were dominant trees surrounded by other species or distributed randomly and were generally evenly distributed across stem diameters. In both forest types, most individuals were highly mixed and distributed in a random pattern, and trees in a clumped or regular distribution were more likely to be retained. In addition, the distribution of diameter at breast height size classes retained a reversed-J-shaped curve before and after management. These structural features closely matched the prior conditions of both forests and the purpose of management. They may also be conducive to quick selection of trees cut from the same forest type in the future, and can aid the recognition and interpretation of forest structure. indications to promote the regeneration of mixtures of species of different shade tolerances. In particular, creating gaps of about 500 m² provided adequate light for small regeneration clumps. Cutting from below, species-specific cutting and uniform cutting were also appropriate for tree regeneration but uniform cutting required higher harvest intensity. Cutting from above slightly increased understory light and promoted more shade tolerant species.

73 Ligot, G. et al. (2014)

Close-to-nature management of forests has been increasingly advocated. However, forest managers often face difficulties in maintaining mixtures of species with different shade tolerance. In uneven aged stand management, understory light can be manipulated by modifying stand structure and composition, in addition to stand density. Using a forest radiative transfer model, we analysed how different cutting strategies could modify light availability under the post-harvest canopy. To calibrate the model, we measured and mapped trees in 27 plots with structures ranging from secondary-successional oak forests to late-

successional beech forests. We measured understory light and crown openness and verified that our forest radiative transfer model well captured the variability of understory light among the studied stands ($R^2 = 87\%$). We then compared cutting strategies varying in type and intensity and provided indications to promote the regeneration of mixtures of species of different shade tolerances. In particular, creating gaps of about 500 m² provided adequate light for small regeneration clumps. Cutting from below, species-specific cutting and uniform cutting were also appropriate for tree regeneration but uniform cutting required higher harvest intensity. Cutting from above slightly increased understory light and promoted more shade tolerant species.

74 Ligot, G. et al. (2013)

The mid-successional sessile oak (*Quercus petraea* (Matt.) Liebl.) and the late-successional European beech (*Fagus sylvatica* L.) are two major species of temperate forests. According to the literature, in mixed stands, large canopy openings should promote the growth of the light-demanding oak over the shade tolerant beech. Nevertheless, foresters who manage mixed oak and beech forests with continuous-cover silviculture in Western and Central Europe, face difficulties to promote the regeneration of oak. In the Belgian Ardennes, we monitored the mixed advanced regeneration of 7–13-year-old oak and beech trees scattered across 23 sites to test the hypotheses regarding the relative advantage of the two species across the light gradient, the outcome of interspecific competition exerted by neighbouring saplings, the effect of direct and diffuse radiation and the site effect. We adjusted a set of mixed non-linear models of the height growth of saplings for the two species and selected the best model for the two species. In contrast to expectations, we found that beech saplings had the highest height growth rate at all light levels. Beech saplings reached an optimum growth at transmittance of 10%, whereas oak saplings needed more than 20%. The two species responded positively to soil richness, but only oak saplings responded to direct radiation and micro-climatic variations. These results indicate that oak saplings are systematically outcompeted by beech saplings across the light gradient. Thus, the control of canopy opening is not sufficient to promote the natural regeneration of oak beneath a stand also containing beech in the Belgian Ardennes.

75 Looney, C. E. et al. (2016)

Most research on tree-tree competition and size-growth relationship (SGR – a stand-level metric that infers the relative efficiency with which different sized trees utilize available resources) has focused on upland systems. It is unclear if inferences from these studies extend to wetland forests. Moreover, no study to date has thoroughly investigated the relationship between individual tree-tree competition and SGR. To fill these research gaps, we conducted a dendrochronological study examining the relationship of tree-tree competition, SGR, and climate in late-successional *Fraxinus nigra* (black ash) wetland forests in northern Minnesota, USA. We took advantage of a detailed, stem-mapped dataset of 1670 trees in five late-successional, multi-aged stands to explore the following research questions: (1) how do competitive interactions, particularly size symmetry, influence individual-tree growth; (2) do late-successional *F. nigra* stands display inverse asymmetric SGR; and (3) do short-term variations in drought influence SGR in *F. nigra* wetland forests? Using neighbourhood competition indices, which characterize the growth of individual trees based on the size, number, and distance of competitors, we examined the nature and strength of individual tree-tree interactions. Additionally, we used SGR to determine how tree size and individual tree contributions to stand productivity relate to changes in stand growth and competitive interactions during stand development. At the individual tree level, we found evidence of size-asymmetric competition, with larger trees disproportionately suppressing the growth of smaller trees. However, tree size was a stronger predictor of growth than competition at all sites. At the stand level, our multi-aged *F. nigra* sites showed consistent patterns of inverse size-asymmetric SGR (i.e., smaller individual trees growing at disproportionately higher rates relative to larger trees), which is generally consistent with previous observations of mature upland forests and supports the hypothesis that large trees decline in relative growth as stands age. While seemingly counter-intuitive, the simultaneous presence of size-asymmetric individual tree-level competition and stand-level inverse asymmetric SGR suggests declines in large tree production efficiency. Drought effects on

SGR, as expressed by PDSI, while sometimes evident, appeared weak on both relatively mesic and extremely wet sites. Our findings, which are consistent with previous studies of both *F. nigra* wetlands and upland forests, demonstrate that the combined results of individual-tree competition models and stand-level SGR can provide deeper insights into growth and competition in *F. nigra* and other forest types.

76 Lorimer, C.G. & Haplin, C. R. (2014)

Late-successional forests often have complex disturbance histories that can result in stands with widely varying structure, ranging from young pole stands to uneven-aged old growth. Arranging stands in chronosequences, however, is problematic because 'stand age' is not a meaningful concept for multi-aged stands and 'time since last stand-replacing disturbance' often cannot be determined from tree-ring evidence. In this paper, we describe a systematic approach for classifying developmental stages in late-successional forests using structural metrics known to be correlated with key ecological properties such as total biomass, carbon storage, stand production rates, and wildlife habitat. While conceptually based on the amount of aggregate crown area occupied by different size classes of trees, the computations in this study, for ease of use, are based entirely on absolute and relative basal area of four size classes (saplings, poles, mature, and large trees). Eight forest structural stages are recognized, including four stages of old growth (early-, mid-, late-transition, and steady state). The method was used to classify developmental stages of 70 primary northern hardwood stands (*Acer*–*Betula*–*Tsuga*) in large landscape reserves in upper Michigan, USA. The degree to which the developmental stages mimic underlying temporal trends in stand dynamics was investigated with the aid of 30-year permanent plot records in primary forests and multi-century simulations using the CANOPY forest dynamics model. Results indicated good correspondence between the postulated developmental sequence in the 70 field stands compared with CANOPY simulations of structural changes over time and changes observed on the permanent plots. Results support the Bormann–Likens hypothesis that the number of large trees reaches a maximum toward the end of the lifespan of an even-aged cohort and subsequently declines in the steady state. While most of the field plots were uneven-aged, both simulations and field data suggest that developmental pathways of even-aged and multi-aged stands after disturbance are very similar and are difficult to distinguish based on the form of the size distributions. In the study area landscapes, 78% of the stands were classified as old growth, with 39% in early or mid-transition and 39% in late transition or steady state. The method should be useful, with appropriate site-specific modifications, in evaluating the degree to which stands meet structural goals under ecological forestry methods, in monitoring responses to environmental change, and in examining biotic changes along a gradient of structural development following disturbance.

77 Lundmark, T. et al. (2016)

Continuous-cover forestry (CCF) has been recognized for the production of multiple ecosystem services and is seen as an alternative to clear-cut forestry (CF). Despite the increasing interest, it is still not well described how CCF would affect the carbon balance and the resulting climate benefit from the forest in relation to CF. This study compares carbon balances of CF and CCF, applied as two alternative land-use strategies for a heterogeneous Norway spruce (*Picea abies*) stand. We use a set of models to analyse the long-term effects of different forest management and wood use strategies in Sweden on carbon dioxide emissions and carbon stock changes. The results show that biomass growth and yield is more important than the choice of silvicultural system per se. When comparing CF and CCF assuming similar growth, extraction and product use, only minor differences in long-term climate benefit were found between the two principally different silvicultural systems.

78 Lundqvist, L. (2017)

The review gives a short general history of the selection system, suggests a way to systematize silviculture and summarizes research on the selection system in Fennoscandia. The review is restricted to Norway spruce, *Picea abies* (L.) Karst, being the only tree species having documented examples of being managed with selection system in boreal Fennoscandia. It covers four main subjects: (i) the dynamics governing the stand structure

and the possibilities to maintain a full-storied structure over time; (ii) how ingrowth is affected by stand density and structure, and by internal dynamics within the seedling-sapling layer, and to what extent it is possible to get sufficient ingrowth to perpetuate the selection system; (iii) the key characteristics governing volume growth at stand level; and (iv) the maximum long-term growth compared to the rotation-forestry system. The residual standing volume is crucial to the long-term growth level. A moderate harvest strength at relatively short intervals, focusing on the largest trees and leaving behind a large standing volume, results in a high sustainable volume growth, low requirement of ingrowth, large average stem volumes and low levels of damage to the remaining stand. Long-term volume growth can then be approximately equal to the site productivity expressed by site characteristics, which is lower than the level expected in even-aged plantations managed with rotation-forestry. The review ends with suggestions for future research.

79 Magagnotti, N. and Spinelli, R. (2011)

The authors compared the financial and energy performance of horse and tractor skidding, under the conditions of continuous cover forestry (CCF) operations in steep terrain. Horse skidding incurs lower unit costs than tractor skidding, when the extraction distance is short or when pre-existing skidding trails are not available. The cost-efficiency of horse skidding is significantly increased by detaching two horses per driver, since the additional cost of the second horse is lower than the additional productivity it generates. Furthermore, it is more difficult to find drivers than horses, and using two horses per driver is a good way to extend the capacity of the few remaining horse-logging operations. Horse logging requires from 8 to 20 times less fossil energy inputs than tractor extraction, and a significant share of its fossil energy use (10–50%) is caused by relocation on motor vehicles. When necessary, trail building adds 30–60% to the unit consumption of fossil energy in the tractor system. In general, the forestry system considered in this study requires from 12 to 60 times less fossil energy than conventional agricultural systems, and it contributes very little to the dependence on non-renewable energy sources.

80 Márialigeti, S. et al. (2016)

Herbaceous understory vegetation is an important part of temperate forested ecosystems, the diversity and composition of which are strongly dependent on the conditions of the forest stand and the landscape. The aim of this study was to find the most important environmental drivers influencing understory herb layer species composition (explored with multi-variate analysis), and richness and cover (analysed by linear modelling) in managed mixed forests in West Hungary. Our detailed inventory showed that the most important factors increasing the diversity and cover of the understory are light, tree species richness, and landscape diversity. Composition is also mainly influenced by light conditions and tree species richness, with minor effects of tree species composition, soil texture, and moss cover. As the strongest influencing factors are closely linked to stand structure and tree species composition, they can either directly or indirectly be altered by forest management. In the studied region, heterogeneous light conditions and canopy structure, the maintenance of tree species richness and forest continuity are key elements for the conservation of forest herbs. Forestry that maintains continuous forest cover and the tree selection management system can better provide these conditions than the presently widely used shelterwood management system.

81 Mason, W. (2015)

Planted forests of Sitka spruce, a non-native species from north-west America, are the major forest type in Great Britain and Ireland. Standard management involves even-aged stands, rotations of 40–50 years and a patch clear-felling system with artificial regeneration. However, forest policies support managing these forests for multifunctional objectives with increased diversity of species composition and stand structure. Continuous cover forestry (CCF) is an alternative silvicultural approach used to provide such diversity, but the amount of CCF forest is under 10% of the forest area, and less in Sitka spruce forests; This paper reviews research carried out in the last two decades to support the implementation of CCF in Sitka spruce planted forests; Stand structures and microclimate favouring natural regeneration are understood. Harvesting systems have been adapted for use in CCF stands,

a single-tree growth model has been calibrated, comparative costs and revenues have been determined, and operational trials established. The interaction between thinning and wind stability in irregular stands is problematic, together with the lack of suitable species for growing in mixture with Sitka spruce; Introduction of an alternative silvicultural approach may take decades and must overcome technical challenges and cultural resistance.

83 Messerer, K., Pretzsch, H. & Knoke, T. (2017)

Non-stochastic portfolio optimization of forest stands provides a good alternative to stochastic mean- variance optimization when available statistical data is incomplete. The suggested approach has a theoretical background in the areas of robust optimization, continuous multicriteria decision-making, and fuzzy theory. Resulting robust portfolios only show slight economic losses compared to the efficient frontier of a stochastic optimization. & Context Economic optimization addressing diversification in mixed uneven-aged forest stands is a useful tool for forest planners. The study aims to compare two approaches for optimizing rotation age cohort portfolios under risk. Rotation age cohorts emerge from age-based regeneration-harvesting operations simulated for two tree species: *Picea abies* and *Fagus sylvatica*. The first optimization approach is a stochastic mean-variance approach. The second is a non-stochastic optimization approach, which has rarely been applied to optimize tree species composition and the distribution of harvested timber over many periods. It aims at relatively good solutions, even if the deviation from the initially assumed return is very high. The objective function for both approaches is sensitive to the selection of various harvesting periods for different parts of the stand. For the stochastic approach, the objective function maximizes the annuitized net present value (economic return) for specific levels of risk by allocating area proportions to harvesting periods and tree species. In the non-stochastic approach, the allocation of area proportions instead minimizes the maximum deviation from the greatest possible economic return among many uncertainty scenarios (non-stochastic approach). Portfolios from both approaches were diverse in rotation age cohorts. The non-stochastic portfolios were more diverse when compared with portfolios from the efficient frontier, which showed the same standard deviation. However, *P. abies* clearly dominated the non-stochastic portfolios, while stochastic portfolios also integrated beech to a greater extent, but only in very low risk portfolios. The economic losses of the non-stochastic portfolios compared to the efficient frontier of the mean-variance approach lay between 1 and 3% only for different levels of accepted risk. The non-stochastic portfolio optimization over a large uncertainty space is so far uncommon in forest science, yet provides a viable alternative to stochastic optimization, particularly when available data is scarce. However, further research should consider ecological effects, such as increased resistance against hazards of conifers in mixed stands.

84 Metslaid, M. et al. (2018)

The goal of this study was to assess the long-term effects of partial harvesting and supplementary soil scarification on the frequency of root and butt rot in managed uneven-sized Norway spruce stands. Frequency of rot and the population structure of the rot fungi were assessed on 1353 stumps after clear-cutting 21 years after a selection harvesting experiment. The initial experiment was comprised of three harvest strength (low, intermediate and high) of single-tree selection, removing approximately 25, 45 and 65% of the stand basal area. Uncut control plots were established at the same time. Supplementary soil scarification was applied in subplots within the single-tree selection plots, using a medium-sized excavator. After clear-cutting the stumps were analysed with respect to rot caused by *Heterobasidion parviporum*, *Armillaria* spp., *Stereum sanguinolentum* as well as other rot fungi. Rot caused by *Armillaria* spp. was most common (8.6% of the stumps), while infection by *H. parviporum* (2.9%) or *S. sanguinolentum* (3.0%) was less frequent. The group "other rot" (5.4%) comprised 21 identified taxa, each occurring in 1–15 stumps. Significantly lower rot frequencies were found for the uncut control (16.3%) and intermediate harvest strength (15.7%), compared with low harvest strength (23.6%). A rot frequency of 21.0% was found in the high harvest strength. In two of three harvest strengths, the rot frequency was higher than for the uncut control. As the observed rot frequencies did not increase consistently with increasing harvest strength, the results do not completely support the initial expectations of increased rot after single-tree selection compared with the uncut control. However, since the

probability of rot in individual stumps on plots treated with single-tree selection was significantly affected by the distance to the nearest strip road (*H. parviporum*) as well as dependent on the size of and distance to the nearest stump of trees cut during the experimental harvest (*H. parviporum*, *S. sanguinolentum* and total rot), it is evident that the single-tree selection harvesting was partially responsible for some of the observed rot. One of the selection criteria in the initial harvest was a sanitary removal of trees of poor vitality. Varying degrees of sanitation felling may therefore have offset the effects of new infections in wounds or spread of rot fungi through adjacent stumps. Supplementary soil scarification in small gaps of the residual stand had no significant effect on the frequency of rot, suggesting that such treatment may be used to facilitate regeneration in uneven-sized spruce stands on similar sites.

85 Mölder, A., Streit, M. & Schmidt, W. (2014)

Current nature conservation policy is going to alter the tree-layer composition of many Central European deciduous forests. As a consequence of ceasing silvicultural management, the competitive ecosystem engineer European beech (*Fagus sylvatica* L.) will spread and the proportion of secondary tree species will considerably decrease. Thus, changes can also be expected in herb-layer diversity, productivity and composition. To predict these changes, we analysed relationships between tree- and herb-layer diversity and composition along tree-diversity gradients in the Central German woodland areas of the Hainich National Park (unmanaged) and the Göttinger Wald (managed by close-to-nature forestry). The flora of both study areas was dominated by typical forest species. In the Hainich, the herb-layer vegetation in beech-dominated stands was less diverse compared to stands richer in canopy species. Herb-layer productivity was also lower in beech-dominated stands. In the Göttinger Wald, herb-layer diversity and productivity were not related to tree-layer diversity and beech proportion, instead to the light transmissibility of the canopy layer. The different results can be explained by logging effects in the Göttinger Wald, which promoted the light factor as significant for herb-layer diversity and productivity. In the consistently darker stands of the Hainich, soil variables, particularly influenced by the ecosystem engineer beech, were decisive. Areas of high canopy diversity in the Hainich result from former management practices and can, in the future, be expected to decrease with the spread of beech. We conclude that forest management cessation will result in decreasing herb-layer diversity and productivity in many Central European deciduous woodlands, especially in landscapes where historical management practices led to unnaturally low proportions of beech. The short-term consequence of management cessation is a loss of herb-layer diversity due to reduced light availability; in the long-term, herb-layer diversity is expected to decrease due to the expansion of beech. If the key aim of nature conservation policy is to preserve and develop the typical diversity of near-natural beech forests, then a complete cessation of forest management can be advised. However, if the typical forest herb diversity of the semi-natural, century-old cultural landscape is to be maintained, close-to-nature forestry management is necessary.

86 Nagel, T. A. et al. (2017)

Integrative forest management attempts to simultaneously fulfil both wood production and biodiversity conservation in a given forest region, and presumably supplants the need for unmanaged forest reserves. This is the dominant management paradigm in the temperate zone of Europe, yet few studies have examined the validity of this approach. We used Slovenia as a test bed to examine how the long-term practice of integrative forest management has influenced two structural components of mature forest conditions, namely coarse woody debris (CWD) and large living trees, as well as the distribution of the White-backed Woodpecker, a species dependent on such conditions. Data were compiled from national inventory plots, coupled with separate surveys in 51 forest reserves. The mean volume of CWD and density of large beech trees across managed forests in Slovenia was 15m³ ha⁻¹ and 6 ha⁻¹, respectively; these mean values were significantly higher (165m³ ha⁻¹ and 55 ha⁻¹) in old-growth reserves. CWD was primarily comprised of small diameter pieces in managed forest, whereas large diameter pieces in multiple stages of decay represented most of the volume in reserves. These results, coupled with the limited distribution of the woodpecker across the country, suggest that integrative management

practiced over a large scale may be insufficient for maintaining biodiversity dependent on mature forest conditions at current levels of wood extraction.

87 Nordström E.-M., Holmström H. & Öhman K. (2013)

Forests are increasingly managed both to provide a sustainable yield of timber and for supplying a range of ecosystem services in line with the concept of sustainable forest management. Several incommensurable interests must then be considered, and it is necessary to strike a balance between different objectives. In evaluation of trade-offs to be made, both objective factors and subjective values need to be taken into account. In recent years, continuous cover forestry (CCF) has been put forward as an alternative to even-aged forestry. The aim of this study was to use scenario analysis in combination with multi criteria decision analysis (MCDA) to evaluate whether CCF is a suitable strategy based on the decision makers' objectives and preferences for sustainable forest management in a specific landscape. This approach was applied to a planning case on the forest estate of the Linköping municipality in southwestern Sweden. The scenario analyses provided insights into relevant quantitative factors, while the MCDA evaluation helped in clarifying the objectives of the forest management and in assessing the relative importance of various objectives. The scenario analyses showed that in this case CCF is a good management strategy in ecological and social terms but yields worse economic outcomes than conventional even-aged forestry. In the Linköping case, there was a relatively strong emphasis on ecological and social aspects and thus, in summary, CCF seemed to be the most suitable option.

88 O'Hara, K. L. (2016)

Silviculture is a means to meet objectives ranging from timber production to wildlife habitat to naturalness. A common global trend in forestry is development of new silvicultural approaches as alternatives to plantation forestry that bear names that include the words 'nature', 'ecological' or some other positive expression regarding their intent or effects. Some approaches are attempting to emulate natural processes and others to minimize disturbance effects in an attempt to be more natural. In any case, the effects of climate changes, non-native plants, insects, pathogens and animals, and other anthropogenic effects are creating novel forest ecosystems where the silviculture of the past may not be appropriate. It should be recognized that forestry has always attempted to manage stands to meet objectives in ways that would not be similarly met without management. Rather than acquiescing to pressures to follow a nature-based model based on the past, we need to recognize that our forest ecosystems are changing, and the rate of change may accelerate in the future. Natural processes and stand structures are important information about natural systems, but not necessarily for the management of these changing systems. Management of these novel ecosystems to meet societal needs will have to be novel. Rather than striving to be close to a nature that is under constant change, silviculture should strive to be better than nature. 'Close-to-nature' is flawed in both its intent to emulate nature and as a means to meet shifting ecological conditions and societal needs.

89 O'Hara, K. L. & Ramage, B. S. (2013)

Forest management faces an uncertain future with changing climates and disturbance regimes. Multi-aged forest management systems represent a promising approach for increasing resistance and resilience, thereby limiting major disruptions to timber production and other ecosystem services. Multi-aged stands inherently have greater resistance and resilience to disturbances because of the presence of several age classes and more potential pathways for post-disturbance management and recovery. The preponderance of research also indicates few differences in productivity between multi-aged and even-aged management strategies. These factors combined suggest that increased adoption of multi-aged management systems will lead to a reduction in long-term risks. We advocate a disturbance integration management strategy that encourages managers to emulate disturbance effects with management, anticipate disturbances in planning, integrate the management of residual stand structures into salvage operations and build variable treatment intervals or cutting cycles into management regimes.

90 **O'Hara, K. & Nagel, L.M. (2013)**

The stand concept is in question because of a trend toward more complex structures and broad-scale management of many forests. The stand was traditionally a uniform operational unit designed to make management efficient. Stand-level objectives on some ownerships have recently shifted toward increasing within-stand variability through the use of various treatments including multiaged systems, variable retention regeneration methods, or variable-density thinning. The result may be greater heterogeneity within rather than between stands, thus leading to this discussion of the relevance of the stand concept in contemporary forestry. We recognize stands as being the logical operational unit for forestry, but with the flexibility to change in boundary over time due to stand dynamics, through management intent, or to include a variety of different stand structures. As a result, stands may be managed to enhance within-stand variability. A new terminology is not needed nor do stands need to be endlessly split into smaller and smaller units as management creates more and more stand variability. The stand remains the logical operational unit of ecosystem-based forestry on a variety of land ownerships, within the context of multiple scale management.

91 **Pang, X. et al. (2017)**

Forests provide a multitude of ecosystem services. In Sweden, the goal to replace fossil fuels could induce substantial changes in the current management and use of forests. Therefore, methods and tools are needed to assess synergies and trade-offs between ecosystem services for policy and planning alternatives. The aim of this study was to develop methods for integrated sustainability assessment of forest management strategies for long-term provisioning of various ecosystem services. For this purpose, the Landscape simulation and Ecological Assessment (LEcA) tool was developed to analyse synergies and trade-offs among five ecosystem services: bioenergy feedstock and industrial wood production, forest carbon storage, recreation areas and habitat networks. Forest growth and management were simulated for two scenarios; the EAF-tot scenario dominated by even-aged forestry (EAF), and the CCF-int scenario with a combination of continuous-cover forestry (CCF) and intensified EAF. The results showed trade-offs between industrial wood and bioenergy production on one side and habitat, recreation and carbon storage on the other side. The LEcA tool showed great potential for evaluation of impacts of alternative policies for land zoning and forest management on forest ecosystem services. It can be used to assess the consequences of forest management strategies related to renewable energy and conservation policies.

92 **Pasinelli, G. et al. (2016)**

Understanding the factors underlying habitat selection is important in ecological and evolutionary contexts, and crucial for developing targeted conservation action in threatened species. However, the key factors associated to habitat selection often remain poorly known. We evaluated hypotheses related to abiotic and biotic factors thought to affect territory selection of the wood warbler *Phylloscopus sibilatrix*, a passerine living in an unpredictable environment owing to irregular rodent outbreaks and showing long-term declines particularly in Western Europe. Comparing breeding territories to unoccupied areas located close-by revealed that territory occupancy in north-western Switzerland was positively related to slope steepness (topographic hypothesis supported) as well as to numbers of tussocks and trees, respectively, while it showed a unimodal relationship to cover of herb layer (forest structure hypothesis supported). Furthermore, a strong negative correlation between breeding territory occupancy and rodent numbers was found, suggesting that wood warblers avoid areas with high rodent densities (rodent-avoidance hypothesis supported). Comparing breeding territories to abandoned territories showed that breeding territories were located on steeper slopes (topography hypothesis supported), at larger distance from the forest edge (anthropogenic disturbance hypothesis supported) and harboured more trees (forest structure hypothesis supported) than abandoned territories. Aside from structural and topographic features of the habitat, wood warblers are affected by rodent numbers when settling, making habitat selection unpredictable from year to year. Forestry practices promoting relatively high tree densities, few bushes and an intermediate low-growing ground

vegetation cover would enhance habitat quality for this declining passerine. In contrast, forestry practices aiming at increasing light in forests (selective thinning, group-felling) or keeping forest stands permanently covered with shrubs, bushes and trees of various sizes (continuous cover forestry) do not benefit the wood warbler.

93 Peura, M. et al. (2018)

Earlier research has suggested that the diversification of silvicultural strategies is a cost-efficient tool to ensure multifunctionality in production forests. This study compared the effects of continuous cover forestry and conventional rotation forestry on ecosystem services and biodiversity in boreal forests in Finland. We simulated over 25,000 commercial forest stands for 100 years under continuous cover and rotation forest management. Forests without management were used as a reference. We compared the effects of silvicultural practices over space and time on ecosystem services, biodiversity indicators and multifunctionality. Our results revealed that continuous cover forestry was better than rotation forest management in terms of timber net present value, carbon sequestration, bilberry production, scenic beauty and the number of large trees. It provided higher habitat availability for indicator species dependent on deciduous trees and mature forest structure. Rotation forest management was better than continuous cover forestry in terms of harvested tree biomass, cowberries, mushrooms, and species dependent on high tree volume. In general, multifunctionality was higher in continuous cover forests than in rotation forests. Therefore, continuous cover forests may have a greater potential to produce simultaneously multiple benefits from forests. However, unmanaged forests often provided the highest levels of services and biodiversity making their role indispensable in delivering forest related ecosystem services and, especially, in the maintenance of biodiversity. Continuous cover forestry does not itself guarantee the maintenance of all ecosystem services and biodiversity in commercial forests but it can be an important part of a successful progression towards more sustainable forestry.

94 Piispanen, R. et al. (2014)

This study focused on wood density and annual ring width in Norway spruce (*Picea abies* (L.) Karst.) grown in uneven-aged stands (UAS). In total, 96 trees were harvested from five UAS that had been managed by single-tree selection for decades. A data set of 27 trees from even-aged stands (EAS) was used for comparison. In the UAS trees, high density and narrow annual rings were found in the juvenile wood near the pith. Thereafter, wood density rapidly decreased until the 20th annual ring, followed by an increase toward the bark. In the outermost rings, wood density again slightly decreased. The trends in wood density in the UAS trees correspond with those reported for naturally regenerated, even-aged Norway spruce stands, with the exception of the decrease in the outermost rings. A mixed linear model with ring width, cambial age, and canopy position as fixed parameters accounted for 53% of the variation in wood density of the UAS trees. In contrast to UAS trees, EAS trees showed increased wood density in the outer rings as a result of decreasing growth rate. The abrupt change in wood density of UAS trees may affect the properties of timber sawn close to the pith.

95 Pommerening, A. et al. (2018)

The process of selecting individual trees by humans for forest management purposes is the result of a plethora of factors and processes that are hard to disentangle. And yet in the past many textbooks and other publications have maintained that this selection leads to somewhat unanimous results. In this study, we analysed the data of 36 so-called marteloscope experiments from all over Britain, which are managed by the Ae Training Centre (Scotland, UK). Our objective was (1) to establish how much agreement there actually was when asking test persons (raters) to apply two different thinning methods, low and crown thinning. In addition, we (2) were interested in understanding some of the processes leading to certain levels of agreement and in relationships between the agreement measures and characteristics of forest structure. Our analysis was based on multivariate statistics, particularly using Fleiss' kappa. This was the first time that an analysis of rater behaviour was performed at such a large scale and it revealed that the general agreement in tree

selection in Britain was only slight to fair, i.e. much lower than in medical experiments. The variability of selecting individual trees was considerable. We also found that agreement in tree selection was much stronger in low-thinning as opposed to crown-thinning experiments. As the latter is an important method of Continuous Cover Forestry and British forestry is increasingly adopting this forest management type, our results suggested that there is a need to provide more training. Interestingly the different levels of agreement as identified by Fleiss' kappa could not be explained by measures of forest structure, however, the mean conformity number, a surrogate of Fleiss' kappa, showed correlations and indicated that conformity increased with increasing complexity of tree stem diameter structure.

96 Pretzsch, H. & Rais, A. (2016)

As they fulfil many ecological and social functions and services better than even-aged monocultures, heterogeneous pure and mixed-species stands are on the advance in Central Europe. Even so, knowledge of how different stands compare in terms of the quantity and quality of the produced wood remains limited, as forest research has been focused on pure stands in the past. Therefore, the still limited comparative studies on timber quality in mixed versus pure stands were reviewed. Further, approximately 100 studies on the morphology of mixed versus pure stands have been reviewed. As is known, the close connection between morphology and timber quality from many studies in pure stands as well as the morphological and structural properties of trees in mixed stands is used as proxies for their timber quality. The number of studies reporting a decrease or increase in timber strength and stiffness in complex stands compared with homogeneous stands was balanced. Knottiness is mostly higher in complex stands. Wood density behaves indifferently. Distortion, as indicated by eccentricity of crown, bending of stems, or irregularity of the tree-ring width, is generally higher in complex forests. This rather ambiguous pattern becomes clearer by typifying the findings depending on the species-specific morphological plasticity of the trees and the spatial conditions they are exposed to. When growing in strong lateral restriction in even-aged pure or mixed-species stands (type 1), trees follow a "keep abreast" strategy which results in high-quality timber especially in case of species with low plasticity. Trees in uneven-aged forests with vertically restricted growing space (type 2) often use a "sit-and-wait" strategy that may result in tapering stem shapes, wide and long crowns with low branch diameters, and high wood density. Distortion may be low in case of species with low morphological plasticity but increase with increasing shade tolerance and plasticity. Growth in widely spaced and heavily thinned pure and mixed stands (type 3) may let trees follow the "stabilisation" strategy. Because of their strong dominance, these trees develop tapering stem shapes, knots of big size and wide appearance along the stem axis, as well as lower wood density, especially in the case of conifers. In arrangements of types 1–3, the "transition" strategy may also emerge, which leads from the "sit-and-wait" stadium to the "keep abreast" strategy. It starts when trees strongly increase their height growth at the expense of the stem diameter growth. It results in slender stems, low knottiness, high wood density, and low distortion, with the result that the tree gets access to the upper canopy at the expense of lateral expansion of stem and crown. In fact, it is not primarily the species mixing that modifies the morphology, structure, and wood quality of the trees but the species-specific morphological plasticity and the structural heterogeneity of the stand. The latter is often higher in mixed than in pure stands and in uneven-aged than in even-aged stands. The more variable the stand structure, the wider the range of wood attributes. The discussion is focused on the relevance of the results for stand management and interdisciplinary research at the intersection of forest growth and yield science and wood science.

97 Puettmann, K. J. et al. (2015)

The development of forestry as a scientific and management discipline over the last two centuries has mainly emphasized intensive management operations focused on increased commodity production, mostly wood. This "conventional" forest management approach has typically favoured production of even-aged, single-species stands. While alternative management regimes have generally received less attention, this has been changing over the last three decades, especially in countries with developed economies. Reasons for this change include a combination of new information and concerns about the ecological consequences of intensive forestry practices and a willingness on the part of many forest

owners and society to embrace a wider set of management objectives. Alternative silvicultural approaches are characterized by a set of fundamental principles, including avoidance of clearcutting, an emphasis on structural diversity and small-scale variability, deployment of mixed species with natural regeneration, and avoidance of intensive site-preparation methods. Our compilation of the authors' experiences and perspectives from various parts of the world aims to initiate a larger discussion concerning the constraints to and the potential of adopting alternative silvicultural practices. Results: The results suggest that a wider adoption of alternative silvicultural practices is currently hindered by a suite of ecological, economic, logistical, informational, cultural, and historical constraints. Individual contexts display their own unique combinations and relative significance of these constraints, and accordingly, targeted efforts, such as regulations and incentives, may help to overcome specific challenges. In a broader context, we propose that less emphases on strict applications of principles and on stand structures might provide additional flexibility and facilitate the adoption of alternative silvicultural regimes in a broader set of circumstances. At the same time, the acceptance of alternative silvicultural systems as the "preferred or default mode of management" will necessitate and benefit from the continued development of the scientific basis and valuation of a variety of ecosystem goods and services. This publication is aimed to further the discussion in this context.

98 Pukkala, T. et al. (2016)

Wind damage causes significant economic losses in boreal forests and elsewhere. Climate change may increase the occurrence of strong storms and decrease tree anchorage, making wind risk management an important aspect of future forest management. This study modeled the probability of wind throw as a function of thinning type, time since previous cutting, characteristics of the subject tree and stand, and shelter provided by adjacent upwind stands. The data were collected from two long-term silvicultural experiments, which experienced strong storm events during the past few years. The analyses showed that the most risky cutting was shelterwood cut, followed by even-aged silviculture characterized by repeated low thinnings. Cuttings where the probability of wind throw was lowest were selective high thinnings of uneven-sized stands, and dimension cutting. Very dense un-thinned stands had very low probability of wind damage. Increasing tree size, increasing height/diameter ratio, decreasing stand basal area, and decreasing basal area of adjacent upwind stands increased the probability of wind throw. Stands were most vulnerable to wind damage immediately after thinning. Uneven-sized stand structure was associated with low probability of wind throw. It was concluded that continuous cover management decreases wind damage, as compared to even-aged management.

99 Pukkala, T. et al. (2014)

The study used an existing forest planning system to analyse the influence of fuel feedstock harvesting and type of forest management on the carbon balance of forestry. The carbon balance module simulated changes in the carbon storage in living biomass, dead organic matter and products. Carbon releases from timber harvesting, transporting and manufacturing were included in the carbon balance, as well as the substitution, recycling and reuse effects of different types of wood products (avoided releases from fossil fuels due to the use of wood). Prediction models were developed for the initial pools of wood products and dead organic matter. The results show that collecting branches, stumps and coarse roots for bioenergy improves the carbon balance very little during the first 30 years of biofuel harvesting. This is because decreased carbon balance of forest soil partially cancels the positive substitution effects of fuel feedstock harvesting. Using high thinnings and continuous cover management, instead of low thinnings, clear felling and artificial regeneration have an immediate positive effect on the carbon balance. This is because the sizes of the wood product and living biomass pools increase, and manufacturing releases decrease.

100 Pukkala, T. (2015)

Decisions on forest management are made under risk and uncertainty because the stand development cannot be predicted exactly, and future timber prices are unknown. Deterministic calculations may lead to biased advice on optimal forest management. The

study optimized continuous cover management of boreal forest in a situation where tree growth, regeneration, and timber prices include uncertainty. Both anticipatory and adaptive optimization approaches were used. The adaptive approach optimized the reservation price function instead of fixed cutting years. The future prices of different timber assortments were described by cross-correlated auto-regressive models. The high variation around ingrowth model was simulated using a model that describes the cross- and autocorrelations of the regeneration results of different species and years. Tree growth was predicted with individual tree models, the predictions of which were adjusted on the basis of a climate-induced growth trend, which was stochastic. Residuals of the deterministic diameter growth model were also simulated. They consisted of random tree factors and cross- and autocorrelated temporal terms. Of the analysed factors, timber price caused most uncertainty in the calculation of the net present value of a certain management schedule. Ingrowth and climate trend were less significant sources of risk and uncertainty than tree growth. Stochastic anticipatory optimization led to more diverse post-cutting stand structures than obtained in deterministic optimization. Cutting interval was shorter when risk and uncertainty were included in the analyses. Adaptive optimization and management led to 6%–14% higher net present values than obtained in management that was based on anticipatory optimization. Increasing risk aversion of the forest landowner led to earlier cuttings in a mature stand. The effect of risk attitude on optimization results was small.

101 **Pukkala, T. et al. (2011)**

The choice between even- and uneven-aged forest management is a topical issue as the negative impacts of clear-felling are being increasingly criticized and the profitability of even-aged management has been questioned. This study compared these management systems in spruce and pine stands in terms of timber, carbon, and bilberry benefits, all of which can be predicted with reasonable accuracy and quantified in terms of money. Management was optimized by maximizing the total net present value (NPV) of the three benefits in a steaged management was also included in the comparisons. Uneven-aged management was the best in terms of the total NPV and with respect to bilberry benefits (NPV of bilberry harvesting). It was also better than even-aged management in terms of timber benefits when the discount rate was more than 1%. The ranking was less clear in terms of carbon sequestration and discounted carbon benefits. The currently recommended type of even-aged management was also included in the comparisons. Uneven-aged management was the best in terms of the total NPV and with respect to bilberry benefits (NPV of bilberry harvesting). It was also better than even-aged management in terms of timber benefits when the discount rate was more than 1%. The ranking was less clear in terms of carbon sequestration and discounted carbon benefits.

102 **Pukkala, T. (2016)**

Forest landowners are interested in management alternatives which do not involve clear felling and planting. Also, many citizens that do not own forest are against clear-felling do to its harmful effects on amenity values and ecosystem services. Most studies on continuous cover forest management (CCF) deal with regular, steady state uneven-aged forests (Plenterwald), or with the conversion of stands into steady-state structure. However, people who want CCF management seldom want Plenterwald in particular; continuous tree cover would in most cases be sufficient. This type of management corresponds to the German Dauerwald concept. This study compared the profitability of Plenterwald, Dauerwald and clear-cutting schedules in Finnish spruce forests. As expected, Dauerwald was more profitable than cutting schedules that converted the stand into steady-state Plenterwald structure. The difference in net present value decreased with increasing number of conversion cuttings. Clear-cutting and planting was more profitable than optimal CCF only in a mature initial stand when the planted spruces were assumed to grow 20% faster in dbh and height, compared to naturally regenerated spruces. In young, medium-aged and uneven-aged initial stands, CCF was more profitable even when 20% tree breeding benefit was assumed in the plantation that was established in the clear-felling site.

103 **Pukkala, T., Lähde, E. & Laiho, O. (2014)**

The current trend of forest management in many countries is reduced use of clear-felling and planting, and increased use of continuous cover management. In Finland, the new forest act of 2014 made all types of cuttings equally allowable on the condition that if the post-cutting residual stand basal area is too low, the stand must be regenerated within certain time frame. Forest landowner can freely choose between even- and uneven-aged management. This study developed a method for optimizing the timing and type of cuttings without the need to categorize the management system as either even-aged or uneven-aged. A management system that does not set any requirements on the sequence of post-cutting diameter distributions is called any-aged management. Planting or sowing was used when stand basal area fell below the required minimum basal area and the amount of advance regeneration was less than required in the regulations. When the cuttings of 200 stands managed earlier with even-aged silviculture were optimized with the developed system, final felling followed by artificial regeneration was selected for almost 50% of stands. Reduction of the minimum basal area limit greatly decreased the use of artificial regeneration but improved profitability, suggesting that the truly optimal management would be to use natural regeneration in financially mature stands. The optimal type of thinning was high thinning in 97–99 % of cases. It was calculated that the minimum basal area requirement reduced the mean net present value of the stands by 12–16% when discount rate was 3–5 %.

104 **Pukkala, T., Lähde, E. & Laiho, O. (2014)**

Studies on optimal stand management often make simplifications or restrict the choice of treatments. Examples of simplifications are neglecting natural regeneration that appears on a plantation site, omitting advance regeneration in simulations, or restricting thinning treatments to low thinning (thinning from below). This study analysed the impacts of simplifications on the optimization results for Fennoscandian boreal forests. Management of pine and spruce plantations was optimized by gradually reducing the number of simplifying assumptions. Forced low thinning, cleaning the plantation from the natural regeneration of mixed species and ignoring advance regeneration all had a major impact on optimization results. High thinning (thinning from above) resulted in higher NPV and longer rotation length than thinning from below. It was profitable to leave a mixed stand in the tending treatment of young plantation. When advance regeneration was taken into account, it was profitable to increase the number of thinnings and postpone final felling. In the optimal management, both pine and spruce plantation was gradually converted into uneven-aged mixture of spruce and birch. The results suggest that, with the current management costs and timber price level, it may be profitable to switch to continuous cover management on medium growing sites of Fennoscandian boreal forests.

105 **Pukkala, T., Lähde, E. and Laiho, O. (2011)**

Almost all commercial forests of Finland are simultaneously used for timber production, outdoor recreation and biodiversity maintenance. For the past 60 years, the official line of silviculture has been even-aged management. However, uneven-aged management and other forms of continuous cover forestry are gradually gaining popularity and also official acceptance. This study analysed variable density thinning (VDT) in the context of uneven-aged management of Norway spruce (*Picea abies* L.Karsten) stands. The aim was to find economically profitable management systems, which would result in forests that are good for recreation and biodiversity maintenance. The stand compartment was divided into cutting segments and only one segment was harvested at a time. When economic profitability was maximized as the sole management objective, 15-year cutting cycle with uniform thinning (UT) was the optimal management system. All trees larger than 19 cm in diameter at breast height (all saw log-sized trees) were removed in the cutting. When a continuous presence of large trees was required, VDT was clearly more profitable than UT. In VDT, all large trees were removed from the thinned places but there were large trees in the segments that will be cut in the next logging operation. The optimal cutting cycle (interval between successive cuttings in the same place) of VDT was 20–30 years when large trees were required in the post-cutting forest. Several combinations of the length of cutting cycle and number of cutting segments were nearly equally profitable. Profitable options were, for instance, to divide the

stand into four cutting segments each cut at 20-year interval or three segments each cut at 30-year interval.

106 Pukkala, T., Lähde, E. and Laiho, O. (2015)

In economically optimal management, trees that are removed in a thinning treatment should be selected on the basis of their value, relative value increment and the effect of removal on the growth of remaining trees. Large valuable trees with decreased value increment should be removed, especially when they overtop smaller trees. This study optimized the tree selection rule in the thinning treatments of continuous cover management when the aim is to maximize the profitability of forest management. The weights of three criteria (stem value, relative value increment and effect of removal on the competition of remaining trees) were optimized together with thinning intervals. The results confirmed the hypothesis that optimal thinning involves removing predominantly large trees. Increasing stumpage value, decreasing relative value increment, and increasing competitive influence increased the likelihood that removal is optimal decision. However, if the spatial distribution of trees is irregular, it is optimal to leave large trees in sparse places and remove somewhat smaller trees from dense places. However, the benefit of optimal thinning, as compared to diameter limit cutting is not usually large in pure one-species stands. On the contrary, removing the smallest trees from the stand may lead to significant (30–40 %) reductions in the net present value of harvest incomes.

107 Pukkala, T., Timo, M. & Gadaw, K. (2012)

Although the majority of the world's forest ecosystems are dominated by uneven-sized multi-species stands, forest management practice and theory has focused on the development of plantation monocultures to maximize the supply of timber at low cost. Societal expectations are changing, however, and uneven-aged multi-species ecosystems, selectively managed as Continuous Cover Forestry (CCF), are often believed to be superior to monocultures in addressing a wide range of expectations. This book presents methods which are relevant to CCF management and planning: analysing forest structures, silvicultural and planning, economic evaluation, based on examples in Europe, Asia, Africa and North and South America.

108 Purser, P., Ó'Tuama, P., Vítková, L. & Dhubháin, Á.N. (2015)

Economic comparisons between Continuous Cover Forestry and rotation-based forestry are complex and often inconclusive as there are fundamental difficulties in comparing even-aged and uneven-aged management systems from an economic point of view. These difficulties are multifactorial, but they can be broadly grouped into methodological factors and management related factors. This paper explores some of the most influential issues affecting outcomes in economic valuations and in particular how they affect CCF compared with rotation-based management. The discussion of these issues will help to inform the debate on CCF and its applicability to forest owners more familiar with rotation-based forestry.

109 Rämö, J. & Tahvonen, O. (2015)

The subject of this study is the economics of harvesting boreal uneven-aged mixed-species forests consisting of Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), birch (*Betula pendula* Roth and *B. pubescens* Ehrh.), and other broadleaves. The analysis is based on an economic description of uneven-aged forestry, applying a size-structured model. The optimization problem is solved in its general dynamic form using gradient-based interior point methods. When volume yield is maximized, the optimal steady state is a nearly pure Norway spruce stand at all site types, producing slightly higher yields than single-species stands. After including sawlog and pulpwood prices, the net present value of stumpage revenues is maximized using 1%, 3%, and 5% interest rates and a 15-year harvesting interval. At less productive sites, the stands are nearly pure Norway spruce stands, regardless of the interest rate. At more productive sites, increasing the interest rate increases the species diversity, with optimal steady states consisting of both Norway spruce and birch.

In some cases, rather small changes in relative prices change the optimal steady state into a birch-dominated stand. Optimal solutions converge to the same steady-state solutions, independent of the initial stand state. If other broadleaves without commercial value are not harvested, they will eventually dominate the stand.

110 Rämö, J. & Tahvonen, O. (2017)

We analyse continuous cover or uneven-aged forest management with optimized harvest timing. The analysis is based on an economic description of uneven-aged forestry using a size-structured transition matrix model. In discrete time with fixed harvesting costs, optimizing harvest timing requires solving of a vector of integer variables in addition to the usual number of harvested trees. This mixed integer problem is solved using bilevel optimization, where the times of harvest are solved by a hill-climbing algorithm, and harvest intensities by a gradient-based interior point algorithm. Optimizing the integer harvest timing variables is crucial especially when the initial stand is an outcome of a plantation type of even-aged management and the forest owner prefers to continue forestry without clearcuts. Optimal harvest timing is shown to depend strongly on a fixed cost level, initial stand state, and interest rate. A steady state harvesting interval is typically 10–25 years, however, during transition it may be as long as 55 years. Increasing the interest rate decreases the average steady state capital value of the stand but may cause the steady state harvest frequency to decrease or increase due to flexibility in targeting harvests to different tree size classes. It appears that the legal limitations both in Sweden and Finland are constraining the optimal solutions.

111 Rasche, L. et al. (2011)

The empirical study of forest ecosystem dynamics is difficult because of the longevity of trees. Many types of models were developed to assist with this problem, all of them with advantages and disadvantages. The strengths of gap models are that they are able to simulate forest dynamics under changing climatic conditions and are therefore suitable for exploring future forest dynamics. Most temperate and boreal forests are managed, making it important to incorporate harvesting functions depicting a wide range of silvicultural practices into the models and to test them under different climatic conditions. This is a necessary prerequisite to the application of these models under climatic change scenarios. Most gap models, however, do not feature such submodels, which disqualifies them as decision support tools. We implemented a management submodel in the gap model ForClim that is able to simulate a wide range of cutting and thinning techniques, including continuous cover forestry ('plentering'). We tested the new submodel against long-term data (72-111 years) from eight growth and yield research plots across climatic conditions ranging from warm-dry to cold-wet. Stem numbers were simulated accurately in nearly all cases, basal area showed a good fit on *Quercus*-dominated plots, but an over/underestimation on *Fagus sylvatica*-dominated and *Picea*-dominated plots. The diameter distributions simulated for the time of the most recent inventory did not differ significantly from empirical data except for two cases. Harvested basal area and stem numbers mostly agreed well with empirical data but showed the same deviation from reality as simulated basal area. Simulations run with an accurate management plan taken from foresters' reports for the plots yielded nearly the same results as those run with a generic management setting. Synthesis and applications. We have demonstrated that (i) the management submodel adequately depicts silvicultural treatments, including continuous cover forestry; (ii) a generic harvesting setting can be substituted for a very detailed one, thus eliminating a major source of uncertainty in assessments of future forest dynamics; and (iii) as the new version of ForClim is able to deal with widely differing current climates, it can be employed with reasonable confidence to simulate future management strategies under climatic change. Overall, this modelling work is a major step towards the use of succession models as decision support tools in forest management.

112 Raymond, P. & Bédard, S. (2017)

Even-aged systems including clearcutting and its variants have been used for decades in North America for managing conifer-dominated stands with the goal to achieve sustainable wood production. Although clearcutting has been successfully applied in conifer-dominated

stands of the boreal forest, it has proved maladapted in the temperate mixedwood forest where hardwood and shrub competition is more intense. Over time, regulated even-aged management has simplified the structure and composition of the temperate mixedwood forest which used to be dominated by late-successional stands with high conifer proportions. This study assesses alternative silvicultural systems inspired by natural dynamics for balsam fir (*Abies balsamea* [L.] Mill.) – yellow birch (*Betula alleghaniensis* Britton) stands growing in Québec, Eastern Canada. In absence of stand-replacing disturbances, spruce budworm outbreaks (*Choristoneura fumiferana* [Clem.]) and windthrow trigger regeneration phases through gap dynamics that result in multi-cohort, irregular stand structures. Here, we assess irregular shelterwood systems aiming at regenerating red spruce (*Picea rubens* Sarg.), balsam fir and yellow birch. In 2009, we established an experiment made of four randomized blocks comparing a gradient of treatments of increased cutting intensity: (i) uncut control (0% removal, 30m²/ha); (ii) continuous cover irregular shelterwood (19m²/ha of residual basal area [RBA] at the first cut, 25–30 years intervals without final cut), (iii) extended irregular shelterwood (RBA 17m²/ha, final cut at year 30), (iv) uniform regular shelterwood (RBA 15m²/ha, final cut at year 10) and (v) clearcut (harvest of merchantable trees >9 cm DBH). We monitored light transmission, seedbed quality and lower vegetation (<3 m) during the first 5 years postcut. Shelterwood treatments diversified both understory light and seedbed conditions, thereby increasing the array of available regeneration niches. Shade-tolerant red spruce and balsam fir established more successfully in the less intense irregular shelterwood treatment (continuous cover) and with a higher spruce: fir proportion. All cutting treatments increased seedling density >30 cm of mid-tolerant yellow birch. Interspecific competition dominated by pin cherry (*Prunus pensylvanica* L.f.) and red maple (*Acer rubrum* L.) was the main factor limiting conifer establishment and was more abundant in the clearcut. Maintaining a partial cover in shelterwood treatments successfully limited competition expansion while regenerating target species. Even if relatively short term, results show that irregular shelterwood systems could be a sound alternative to clearcutting for regenerating and maintaining the structure of late-successional balsam fir-yellow birch stands.

113 Redon, M. et al. (2014)

Uneven-aged management systems based on selection silviculture have become popular in European mountain forests and progressively replace other silvicultural practices. In time, this trend could lead to a homogenisation of the forest mosaic with consequences on structural indices recognised as beneficial to forest biodiversity. This study was conducted to investigate the potential effects of a generalisation of the selection silvicultural system on structural diversity in the forest landscape with consequences for forest biodiversity conservation. We compared four structural indices (tree species richness, diameter heterogeneity, deadwood volume and basal area of mature trees) in five different stand types typical of the northern French Alps, using forest plot data in the Vercors mountain range. Through virtual landscape simulations, we then calculated predicted mean proportions of stand types under two different conservation strategies: (i) maximising mean index values at the landscape level and (ii) maximising the number of plots in the landscape with index values above given thresholds. Multi-staged forests did not maximise all indices, the best solution being to combine the five stand types in uneven proportions to improve biodiversity conservation. The expansion of selection silviculture in European heterogeneous forest landscapes could enhance biodiversity conservation if other stand types with complementary structural characteristics are maintained.

114 Roessiger, J. et al. (2016)

This study presents economically optimal management of uneven-aged mixed mountain forests that takes into account tree growth variability. We divided 9846 silver fir (*Abies alba*), beech (*Fagus sylvatica*), and spruce (*Picea abies*) trees measured on 898 forest inventory plots in the Sneznik and Leskova dolina management units (4905 ha, Dinaric mountains, Slovenia) into three growth classes (slow-, medium-, and fast-growing trees) to simulate optimal forest management over a period of 100 years with respect to changing tree growth, stand density, diameter distribution, and tree species composition. We developed a density-dependent and stage and growth-structured matrix transition model which simultaneous to the long-term stand dynamics projection—scheduled optimal harvesting to maximize the net

present value using a nonlinear approach. The ecology of tree species was considered by using tree species-specific and stand-density and diameter-dependent logistic functions for ingrowth, transition, and mortality. The model projected a shift in tree species composition from fir-dominated to beech-dominated forests within 100 years. A change from harvesting slow- and fast-growing trees as if they all had medium revenue and maintained the uneven-aged stand structure. Optimal harvest diameters varied among growth classes, time periods, and tree species according to the economic maturity of individual trees and ranged from 12 (pre-commercial thinning) to 72 cm (target diameter). The simulation highlights the potential of improved bio-economic models for increasing yield from uneven-aged forests and scheduling optimal management regimes with multiple objectives.

115 Roessiger, J., Griess, V. C. & Knoke, T. (2011)

Based on a literature review and on a new bioeconomic modelling approach, we investigated whether or not clear-cutting and mono-species forests are the optimal silvicultural strategies under the presence of risk. The model reflects a risk-avoiding attitude and builds upon portfolio theory. The selected tree species and the timing of regeneration harvests constitute a total of 22 management alternatives. Optimal area fractions of the alternatives were combined at the stand level to find the maximum value at risk (VaR, annualized net present value exceeded with probability of 0.99). Relevant uncertainties were integrated via Monte Carlo Simulation and bootstrapping. The results showed a maximum VaR for a highly diversified treatment combining 42 per cent Norway spruce and 58 per cent European beech and included area fractions with regeneration harvests from age 50 to 120 years. This treatment avoids clear-cutting and a mono-species forest composition. It uses tree species diversification and extends the regeneration period over 70 years to diversify hazard and price risks. The resulting scenario may be called 'near-natural' and emerges as the optimal choice, particularly for cautious, and thus risk-avoiding forest owners who do not have the opportunity to diversify risks by means of large-scale forest properties.

116 Rosa, R., Soares, P. & Tomé, M. (2018)

Continuous cover practices are likely to better respond to the increasing demand for social, aesthetic and environmental values provided by forest ecosystems than even-aged forest plantations. Also, uneven-aged forestry may be especially attractive for non-industrial private forest owners, as it provides more regular revenues and, by taking advantage of natural regeneration, reduce installation costs. Knowledge on alternative regimes to even-aged forestry is therefore in high demand. We first add to the literature by proposing a new maritime pine forest growth model that can be readily used in optimization studies. Second, we are the first to analyse optimal uneven aged forest management for this species. Highlighting the contribution of this study, a comparison of our results with currently suggested silvicultural management scenarios is provided. We show that the economic profitability of this species significantly increases under optimal forest management and may thus present a viable alternative to rotation forests. In particular, we show that optimal forest management may entail harvesting cycles.

117 Sačkov, I. et al. (2017)

This study is concerned with the assessment of application possibilities for remote sensing data within a forest inventory in close-to-nature forests. A combination of discrete airborne laser scanning data and multispectral aerial images separately evaluated main tree and forest stand characteristics (i.e., the number of trees, mean height and diameter, tree species, tree height, tree diameter, and tree volume). We used eCognition software (Trimble GeoSpatial, Munich, Germany) for tree species classification and reFLex software (National Forest Centre, Zvolen, Slovakia) for individual tree detection as well as for forest inventory attribute estimations. The accuracy assessment was conducted at the ProSilva demo site Smolnícka Osada (Eastern Slovakia, Central Europe), which has been under selective management for more than 60 years. The remote sensing data were taken using a scanner (Leica ALS70-CM) and camera (Leica RCD30) from an average height of 1034 m, and the ground reference data contained the measured positions and dimensions of 1151 trees in 45 plots distributed across the region. This approach identified 73% of overstory and 28% of

understory trees. Tree species classification within overstory trees resulted in an overall accuracy slightly greater than 65%. We also found that the mean difference between the remote-based results and ground data was -0.3% for tree height, 1.1% for tree diameter, and 1.9% for stem volume. At the stand level, the mean difference reached values of 0.4%, 17.9%, and -21.4% for mean height, mean diameter, diameter, and growing stock, respectively.

118 **Saksa, T. & Valkonen, S. (2011)**

The aim of this study was to describe the dynamics of seedling establishment and development in spruce-dominated uneven-aged boreal forests. The study was based on empirical data from 15 stands with permanent plots, which had been intensively monitored for 10 years in southern Finland. All trees (height > 1.3 m) were measured every fifth year. Regeneration was measured on 64 permanent sample plots (4 m²) in each stand. The establishment of first-year seedlings was analysed on a yearly basis. The survival and development of older Norway spruce (*Picea abies* (L.) H. Karst.) seedlings were analysed based on observations made every five years. The establishment of spruce seedlings was closely correlated with the abundance of seed crops. Seedling cohorts originating from abundant seed crops were clearly detectable in the development of seedling height distributions over time. It took about 15 years for spruce seedlings to reach a height level of 15–30 cm. Local basal area had hardly any effect on the emergence or survival of small spruce seedlings, while the number of higher spruce seedlings decreased with increasing local basal area.

119 **Sevillano, I. et al. (2018)**

Commitment to sustainable forest management (alternatives to clear-felling) has led to a renewed interest in continuous cover forestry systems, which promote the control of light to produce stand benefits. Physiological performance of shade-tolerant European beech (*Fagus sylvatica* L.) in response to light availability was investigated in natural regeneration below the canopy in contrast to planted seedlings under artificial-shade conditions. Although beech seedlings had higher photosynthetic capacity with increasing light availability, they were able to maintain positive CO₂ assimilation rates under low light levels in both field and controlled conditions. Leaves of seedlings under low light had the ability to use light more efficiently (higher PSII efficiency) than those in high light, which offer some physiological explanation for the ability of beech seedlings to grow under very low light conditions. Whilst caution is advised to interpret results from controlled to field studies, the overall general correspondence in the trend of the physiological response to light levels within beech grown below the canopy and under artificial-shade conditions suggests that it might be possible to extrapolate results from studies performed under artificial shade (nets) to field conditions. Hence, the use of nets may be an alternative way of assessing the potential physiological responses of seedlings to light availability.

120 **Shanin, V. et al. (2016)**

Uneven-aged forest management is suggested to be a sustainable management alternative in boreal forests, but knowledge on applicable harvest intensities is very limited as majority of the studies has focused on even-aged management practices. The ecosystem model EFIMOD was used to assess the effect of selection cuttings on ecosystem production, carbon sequestration and volume increment in spruce stands. The model was calibrated and validated against experimental data from 20 permanent forest plots in southern Finland where stand responses to uneven-aged management had been monitored for 25 years. The simulated scenarios started with planting trees on bare land, simulation of first decades according to even-aged management, and a subsequent transformation into uneven-aged stand structure and management. Simulated selection cutting scenarios contained variations of both harvest interval (10–30 years) and postharvest stand density (basal area 8–16 m² ha⁻¹). We hypothesized that longer harvest intervals and higher post-harvest basal areas will positively affect the net ecosystem production, nitrogen use efficiency, and forest carbon sequestration. The results presented here are for a period of 90 years. Simulations showed that net ecosystem production (NEP) increased from 0.25 to 0.5 kg m⁻² of carbon with longer

harvest intervals and higher postharvest density and was generally less than that at undisturbed development. Nitrogen use efficiency (NUE) varied from 100 kg NPP per kg consumed N for heavy cuttings to 300 kg NPP per kg consumed N for light removal of trees. Changes in soil carbon stocks were negative for most scenarios (5–20% decline in terms of total soil C), and the decline was most pronounced with lowest postharvest density and short harvest intervals. The volume of harvested timber was between 320 and 400 m³ha⁻¹ for a 60-year period. Longer harvest intervals resulted in increased timber production. Stem volume growth (5–7 m³ ha⁻¹yr⁻¹) was equally affected by both harvesting parameters. The cumulative volume of deadwood of 80–120 m³ ha⁻¹ was substantially higher with the longest harvest interval (30 years) than with the shorter alternatives where it comprised 40–60 m³ ha⁻¹. The simulations provide novel results on different harvesting options for uneven-aged forest management of boreal Norway spruce stands. These results fill a gap in knowledge on ecosystem responses to alternative management regimes and support the development of sustainable management practices.

121 Stokes, V. & Kerr, G. (2013)

Stands of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) originating from natural regeneration can be extremely dense with high mortality, poor growth form and low volume production. Although costly, respacing (pre-commercial thinning) can reduce resource competition for the remaining trees, altering the final crop produced. Three experiments were established to examine the effect of respacing 1–2 m tall trees to different target densities. The impact on stand growth and yield was measured 11–17 years after respacing, and the longer-term impact was modelled to year 50. Unrespaced control treatments self-thinned at a similar and constant rate at two sites. At the third, extremely high initial density resulted in a higher rate of self-thinning and lower density after 11 years. Wider respacing treatments resulted in larger mean tree diameter, but there was no significant effect of respacing on stand volume 11–17 years after respacing; greater diameter growth did not compensate for low tree number. Results indicate a volume penalty associated with delaying respacing until trees were 4 m tall, but this treatment was unreplicated. Modelled stand volume in year 50 was higher for the 2.6 m × 2.6 m respacing treatment than for the 1.8 m × 1.8 m, 2.1 m × 2.1 m or 3.3 m × 3.3 m treatments. However, open-grown conditions may reduce timber quality compared to closer spacing treatments. The results are presented using a stand density management diagram for Sitka spruce growing in Canada and support recent suggestions that British stands have a shallower size–density relationship than Canadian stands.

122 Süsse, R., Allegrini, C., Bruciamacchie, M. & Burrus, R. (2011)

Presents the approach to irregular silviculture developed over the last 15 years by leading French private forest managers. Describes the AFI network of irregular silviculture research stands set-up by a leading forest scientist across France, Belgium, England, Luxemburg and Ireland. Records 20 years of monitoring irregular silviculture through measurements of dendrological, economic and environmental parameters. Presents results from 6 research stands of biological and economic growth and development. Includes 11 Information Sheets detailing all aspects of management and transformation of even-aged stands.

123 Tahvonen, O. & Ramo, J. (2016)

Optimization models on continuous cover forestry are complicated and typically incompatible with rotation models. This dichotomy is theoretically unsatisfactory and makes the choice between clearcuts and continuous cover forestry vague. We present a theoretically sound and empirically detailed generalized setup with an optimal clear-cut regime (or even-aged management) and optimal continuous cover regime (or uneven-aged management) as special cases. It includes a size-structured growth model, variable and fixed harvesting costs, and allows for the completely flexible optimization of harvest timing in both regimes. Flexible harvest timing becomes essential when optimizing the transition from clear-cut regimes toward continuous cover forestry. The model is applied to Norway spruce (*Picea abies* (L.) Karst.) and solved as a dynamic mixed-integer problem. Low or moderate site productivity, an interest rate above 2%, and a high artificial regeneration cost support the optimality of continuous cover forestry. In its most general form, the optimal clear-cut regime does not

exist when the continuous cover regime is globally optimal, and when it exists, the rotation period lengthens with interest rate. The optimal choice between forest management regimes may depend on the initial stand state and whether the naturally regenerated seedlings are utilized in solutions with clearcuts. Maximizing sustainable yield favours clearcuts.

124 Tahvonen, O. (2011)

Optimal harvesting of Norway spruce (*Picea abies* (L.) Karst.) forests is studied applying an individual-tree model for uneven-aged management. Optimization is carried out by gradient-based, large-scale interior point methods. Assuming volume maximization and natural regeneration, it is optimal to apply uneven-aged management. Under artificial regeneration, the result is the reverse. Economically optimal solutions with a 20-year harvesting interval produce an annual sawn timber output of $4.4 - 2.4 \text{ m}^3 \cdot \text{ha}^{-1}$ depending on thermal zone and interest rate. Before harvest basal area varies between 18 and $12 \text{ m}^2 \cdot \text{ha}^{-1}$ and the diameter of harvested trees between 15 and 33 cm. In contrast with the classic inverted J-structure, optimal steady-state size structure resembles a serrate form. Profitability of even- and uneven-aged management is compared assuming that the initial stand state represents an optimal uneven-aged steady state. A switch to even-aged management is optimal given the most favourable growth conditions and interest rate below 1%–2%. In other cases, it is economically optimal to continue uneven-aged management although volume output remains lower than under even-aged management.

125 Tahvonen, O. (2015)

An economic model for naturally regenerating, heterogeneous forests is specified to yield both clearcuts and continuous cover forestry endogenously. The model includes nonconvexities and any number of state variables but is, in its simplest form, a one-state variable problem. Clear-cuts with various rotation lengths and continuous harvesting appear as locally optimal solutions. Necessary and sufficient conditions for the local and global optimality of these two forest management types are obtained. Discounting is found to increase rotation length and to favour continuous harvesting. Initial state may determine the optimality of continuous forest cover versus clear-cuts. The relative value of large trees is an important factor in the optimality of different solutions. Analytical results are demonstrated by an empirical application.

126 Tahvonen, O. (2016)

A continuous time-economic model for optimal thinning and rotation is modified to include natural regeneration. The respecified model is capable of describing both optimal forest rotation and continuous cover forestry (uneven-aged management). Continuous cover forestry is shown to be optimal if the preset value of continuous sustainable harvesting income over an infinite horizon is higher than the clearcut revenue and the highest possible value of bare land. Negative bare land value implies optimality of continuous cover forestry but only if clearcut stumpage prices are not higher than thinning stumpage prices. Given low interest rate optimized thinning is shown to increase rotation length.

127 Tang, X. et al. (2017)

Disturbances and climatic changes significantly affect forest ecosystem productivity, water use efficiency (WUE) and carbon (C) flux dynamics. A deep understanding of terrestrial feedbacks to such effects and recovery mechanisms in forests across contrasting climatic regimes is essential to predict future regional/global C and water budgets, which are also closely related to the potential forest management decisions. However, the resilience of multi-aged and even-aged forests to disturbances has been debated for N 60 years because of technical measurement constraints. Here we evaluated 62 site-years of eddy covariance measurements of net ecosystem production (NEP), evapotranspiration (ET), the estimates of gross primary productivity (GPP), ecosystem respiration (Re) and ecosystem-level WUE, as well as the relationships with environmental controls in three chronosequences of multi- and even-aged coniferous forests covering the Mediterranean, temperate and boreal regions. Age-specific dynamics in multi-year mean annual NEP and WUE revealed that forest age is

a key variable that determines the sign and magnitude of recovering forest C source-sink strength from disturbances. However, the trends of annual NEP and WUE across succession stages between two stand structures differed substantially. The successional patterns of NEP exhibited an inverted-U trend with age at the two even-aged chronosequences, whereas NEP of the multi-aged chronosequence increased steadily through time. Meanwhile, site-level WUE of even-aged forests decreased gradually from young to mature, whereas an apparent increase occurred for the same forest age in multi-aged stands. Compared with even-aged forests, multi-aged forests sequestered more CO₂ with forest age and maintained a relatively higher WUE in the later succession periods. With regard to the available flux measurements in this study, these behaviours are independent of tree species, stand ages and climate conditions. We also found that distinctly different environmental factors-controlled forest C and water fluxes under three climatic regimes. Typical weather events such as temperature anomalies or drying-wetting cycles severely affected forest functions. Particularly, a summer drought in the boreal forest resulted in an increased NEP owing to a considerable decrease in Re, but at the cost of greater water loss from deeper groundwater resources. These findings will provide important implications for forest management strategies to mitigate global climate change.

128 Temperli, C. et al. (2017)

Timber use in central Europe is expected to increase in the future, in line with forest policy goals to strengthen local wood supply for CO₂-neutral energy production, construction and other uses. Growing stocks in low-elevation forests in Switzerland are currently high as exemplified by the Swiss canton of Aargau, for which an average volume of $346 \pm 16 \text{ m}^3 \text{ ha}^{-1}$ was measured in the 3rd Swiss National forest inventory (NFI) in 2004–2006. While this may justify a reduction of growing stocks through increased timber harvesting, we asked whether such a strategy may conflict with the sustainability of timber production and conservation goals. We evaluated a range of operationally relevant forest management scenarios that varied with respect to rotation length, growing stock targets and the promotion of conifers in the regeneration. The scenarios aimed at increased production of softwood, energy wood, the retention of potential habitat trees (PHTs) and the conversion to a continuous cover management system. They were used to drive the inventory-based forest simulator MASSIMO for 100 years starting in 2007 using the NFI sampling plots in Aargau. We analysed model outputs with respect to projected future growing stock, growth, timber and energy yield and harvesting costs. We found growing stock to drop to $192 \text{ m}^3 \text{ ha}^{-1}$ in 2106 if business-as-usual (BAU as observed between the 2nd and 3rd NFI) timber volumes were set as harvesting targets for the whole simulation period. The promotion of conifers and a reduction of rotation lengths in a softwood scenario yielded 25% more timber over the whole simulation period than BAU. An energy wood scenario that reduced growing stock to $200 \text{ m}^3 \text{ ha}^{-1}$ by 2056 and promoted the natural broadleaved regeneration yielded 9% more timber than BAU before 2056 and 30% less thereafter due to decreasing increments. The softwood scenario resulted in higher energy yield than the energy wood scenario despite the lower energy content of softwood. Retaining PHT resulted in a reduction of timber harvest ($0.055 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ per habitat tree) and higher harvesting costs. Continuous cover management yielded moderate timber amounts throughout the simulation period, yet sustainably. Considering climate change, we discuss the risks associated with favoring drought- and disturbance-susceptible conifers at low elevations and emphasize that continuous cover management must allow for the regeneration of drought-adapted tree species. In conclusion, our simulations show potential for short-term increases in timber mobilization but also that such increases need to be carefully balanced with future forest productivity and other forest ecosystem services.

129 Thurnher, C., Klopf, M. & Hasenauer, H. (2011)

Harvesting models are needed within simulation studies to assess 'business as usual' scenarios in future stand development. Such models require data from repeated observations addressing the removals as they are based on specific silvicultural management regimes. The purpose of this paper was to develop and apply a harvesting model for uneven-aged single-tree forest management based on data from the forest company 'Forstbetrieb Ligist, Souveräner Malteser Ritterorden' in Austria. This company has

been known for its transition from even-aged to uneven-aged forest management since the 1930s. Our harvesting model comprises two logistic functions to simulate a single-tree selection process: (1) predicting the probability of harvesting and (2) removal. The set of equations are tested and implemented in the tree growth model MOSES (MOdelling Stand rESponse). MOSES is used as a diagnostic tool to assess different forest management regimes. In this study, we are specifically interested in (1) evaluating the model by comparing predicted and observed removals and (2) predicting future stand development considering the current management practices—the business as usual as it can be derived from the harvesting model. The results suggest that in combination with MOSES, our model correctly mimics the growth development over time since no systematic trends between predicted and observed diameter growth at breast height classes are apparent. Furthermore, it is evident that by applying the current plenter harvesting strategy, a constant stand basal area of $\sim 35 \text{ m}^2\text{ha}^{-1}$ will be achieved.

130 Timo, M. & Pukkala, T. (2016)

Forest ecosystems are increasingly seen as multi-functional production systems, which should provide, besides timber and economic benefits, also other ecosystem services related to biological diversity, recreational uses and environmental functions of forests. This study analysed the performance of even-aged rotation forest management (RFM), continuous cover forestry (CCF) and any-aged forestry (AAF) in the production of ecosystem services. AAF allows both even-aged and uneven-aged management schedules. The ecosystem services included in the analyses were net present value, volume of harvested timber, cowberry and bilberry yields, scenic value of the forest, carbon balance and suitability of the forest to Siberian jay. Methods: Data envelopment analysis was used to derive numerical efficiency ratios for the three management systems. Efficiency ratio is the sum of weighted outputs (ecosystem services) divided by the sum of weighted inputs. The linear programming model proposed by Charnes, Cooper and Rhodes was used to derive the weights for calculating efficiency scores for the silvicultural systems. Results and conclusions: CCF provided more ecosystem services than RFM, and CCF was more efficient than RFM and AAF in the production of ecosystem services. Multi-objective management provided more ecosystem services (except harvested timber) than single-objective management that maximized economic profitability. The use of low discount rate (resulting in low cutting level and high growing stock volume) led to better supply of most ecosystems services than the use of high discount rate. RFM where NPV was maximized with high discount rate led to particularly poor provision of most ecosystem services. In CCF the provision of ecosystem services was less sensitive to changes in discount rate and management objective than in RFM.

131 Tíscar, P. A. & Linares, J. C. (2011)

Since climate change projections contain many uncertainties and are normally unable to predict the direction and magnitude of change at the small scale needed by forest managers, some understanding about the functioning of the target forest should be obtained before a robust management strategy can be applied. Structure and regeneration patterns are related to key ecosystem processes which, on the other hand, can be modified by silvicultural treatments. In this research, the structure and recruitment dynamics of two stands with different histories of management were investigated in the southern limit of the range of *Pinus nigra* subsp. *salzmannii* (Southeast Spain). We described forest structure and facilitation effects by forest canopies and nurse shrubs, and quantified the processes affecting each stage of regeneration (dispersed seed, first year seedling and second year seedling) in different microhabitats. Forest structure was more complex in the stand scarcely influenced by human activities. *Juniperus communis* shrubs seemed to facilitate the establishment of tree saplings. Most seedlings died of desiccation during their first summer. At best, 190 out of 10,000 emerged seedlings survived the first summer. In light of these results, the possibilities of applying close-to-nature forestry in the study forests and other aspects of silviculture under a frame of adaptive forest management are discussed.

132 **Vanclay, J. K. (2015)**

The contemporary forestry preoccupation with non-declining even-flow during yield simulations detracts from more important questions about the constraints that should bind the end of a simulation. Whilst long simulations help to convey a sense of sustainability, they are inferior to stronger indicators such as the optimal state and binding conditions at the end of a simulation. Rigorous definitions of sustainability that constrain the terminal state should allow flexibility in the planning horizon and relaxation of non-declining even-flow, allowing both greater economic efficiency and better environmental outcomes. Suitable definitions cannot be divorced from forest type and management objectives, but should embrace concepts that ensure the anticipated value of the next harvest, the continuity of growing stock, and in the case of uneven-aged management, the adequacy of regeneration.

133 **Vítková, L. et al. (2013)**

There is increasing interest in continuous cover forestry (CCF) in Ireland, however little is known about the extent to which CCF is currently practiced. To this end, a survey of forest owners/managers was conducted in 2012 to determine the extent to which, and on what site types, CCF is being practiced in Irish forests. The survey revealed that there are 271 forests managed under CCF in Ireland, 235 public (Coillte and the National Parks and Wildlife Service) and 36 private, with a total area of 10,603 ha (8,292 ha and 2,311 ha, public and private respectively). The survey further indicated that the average size of a CCF forest property is 50 ha and that most of the forest area being managed under CCF comprises mixed-species stands. The survey further revealed that 66% of the properties have been managed under CCF for less than 15 years. A 10% random sample of the properties for which questionnaires were completed were visited. This showed that there was little evidence yet of management specifically directed at transforming stands to CCF – suggesting that CCF management was more likely to be an “aspiration” rather than a “reality” to date. Nevertheless, it was shown that over two-thirds of the surveyed forest properties appeared suitable for CCF management. Although some initiatives have been taken to increase the awareness of CCF in Ireland, and to expose foresters to aspects of CCF management, more needs to be done if those aspirations are to be realised.

134 **Vítková, L., Ni Dhubhain, A. & Pommerening, A. (2016)**

New methods for sustainable forest management are being introduced in Ireland and other countries worldwide. These require different approaches to thinnings. This study explored how different levels of expertise in managing forest ecosystems affect the way individuals approach the task of selecting trees before and after training. Both experts and novices responded differently when provided with the same task. Before training, when presented with the task to carry out a thinning without specific instructions, experts applied the method of thinning they were most familiar with. When trained in one of these alternative thinning methods, novices successfully applied this method, whereas the experts did not. The level of agreement as to the choice of trees for removal was generally surprisingly low and among experts it was highest before training and declined most after training. Prior knowledge in managing forest environments affected how participants approached the task; the longer an expert applies a task in a particular way, the harder it is to change this strategy. This is crucial information, suggesting that if new approaches to selective forest management are to be successfully implemented, more effort should be made to convince experts and/or training should focus on individuals who have yet to become familiar with using a specific approach. The results of this study also suggest that the success rate of applying new methods should be monitored. This will ensure the application of forest management most suited to a given environment.

135 **Wagner, J. E., Kiernan, D. & Bevilacqua, E. (2013)**

We propose an approach to develop economic-based yields for even- and uneven-aged stands that could be compared with yields generated by using silvicultural treatments. Economic-based yields are derived from economic parameters that describe markets and the landowner's ownership goals and objectives. This study highlights five conclusions. First,

economic- based yields define a lower bound on silvicultural-based yields required to just satisfy these economic parameters and provide a metric of confidence that a silvicultural prescription would increase (or decrease) the landowner's wealth. Second, a main driver of the economic-based yields is the opportunity costs of the reserve growing stock or regeneration costs and the land. Third, the economic-based yields followed a similar pattern regardless of whether the stand was defined as even- or uneven-aged. Fourth, the economic-based yields illustrate the physical impacts that recreational leases, taxes, or the sale of nontimber forest ecosystem goods and services have on this lower bound. Finally, if the economic-based yields are greater than the silvicultural-based yields and if physical output estimates could be derived for the suite of nontimber forest ecosystem goods and services resulting from the forest structure, then implied economic values for this suite of goods and services could be derived using the models presented.

136 **Wilson, S. M. (2013)**

An independent review was undertaken of progress with adoption of alternative silvicultural systems to clearfell/ replant (ATC) in Britain. These are often termed "continuous-cover forestry" (CCF) or Lower Impact Silvicultural Systems (LISS). This project used conventional enquiry methods of literature review, expert and owner/ manager discussions and a programme of rapid-appraisal field visits by the author. Outputs of the work include a spatial register of ATC adoption examples, of which a sub-sample have been worked up as short, illustrated case-studies covering a range of ATC adoption contexts and objectives. Some locations have potential to serve as future demonstration sites with owner consent. This report highlights emerging issues in the field of ATC adoption and makes recommendations in support of its wider uptake, many of which would require a co-ordinated effort over time.

137 **York, R. A. et al. (2012)**

Multi-aged stands in a mixed conifer forest of California were treated to mitigate harvest-related increases in surface fuels and to prepare sites for natural regeneration of *Pinus* species. The study was designed to (1) assess effectiveness of small gap fuel treatments (piling and burning in 0.04 ha gaps) on surface fuel and modelled fire behaviour; (2) test the effect of substrate quality on germination of *Pinus* species; (3) measure the influence of gap creation on light availability and stand-level light heterogeneity. While the fuel treatment only covered 10 per cent of stand area, it was effective in avoiding increases in stand-level surface fuel following harvests. Fire behaviour was predicted to be moderate following the treatments. The harvest coupled with the gap surface fuel treatments did not change predicted fire behaviour compared with the pretreatment stands. There was a significant but variable increase in germination of *Pinus ponderosa* seed when sowed on ash substrates compared with bare soil. No substrate effect was detected for *Pinus lambertiana*. The 0.04-ha gaps created distinct pockets of light and greatly increased stand-level light heterogeneity. This gap-based approach to regenerating multi-aged stands coupled with small-scale fuel treatments is promising for reducing fire hazard and regenerating shade-intolerant species.

The optimum size of gaps made in a forest stand in group shelterwood or selection cuttings is an important issue for foresters working with continuous cover forestry methods. In Latvia, shelterwood and selection cuttings are usually practised in forests where clear-cutting is forbidden or there are a high proportion of mature stands, as well as in private holdings. To assess the influence of gap size on the growth and survival of seedlings, rectangular gaps (size 100 to 1600 m²) were created in two 100-year-old Scots pine (pine) dominated stands in *Hylocomiosa* forest type. Pine and Norway spruce (spruce) were planted in the gaps and arranged in a square pattern, so that the distance from the gap edge would be known for each tree planted. For performance analysis of the planted trees, the survival and height increment over a period of three years was used. Significance of the test site, initial tree height, gap size and the distance from the closest gap edge on survival and growth of seedlings was tested using univariate analysis of variance. Survival rate of the pine 3 years after planting notably differed between test sites (66% and 24%) but did not differ regarding the gap size and the distance from the closest gap edge. Survival rate of the spruce 3 years after planting was at least 86% regardless of gap size, and at least 80% regardless of the position within the gap. Gap size had a significant ($p < 0.05$) influence on the growth in height for both species, but the distance to the closest gap edge only had a significant ($p < 0.05$) influence on the growth of spruce. Based on these results, it can be concluded that the gap size must be larger than 10×10 m to ensure sufficient growth during the first years after planting pine and spruce.

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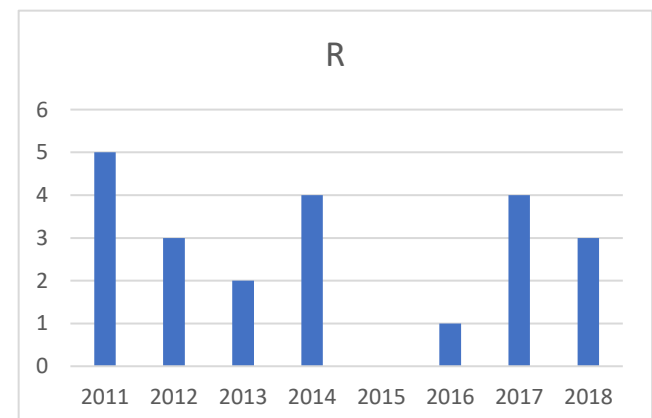
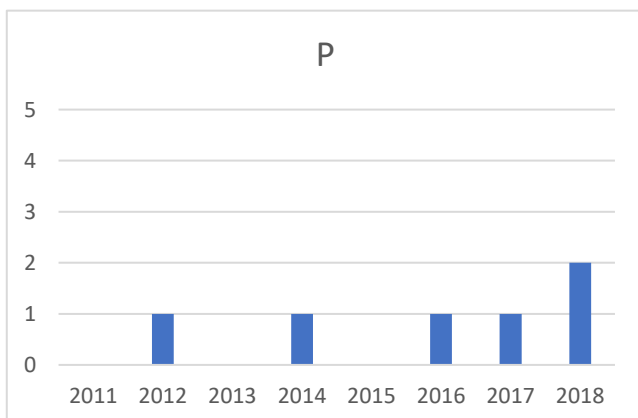
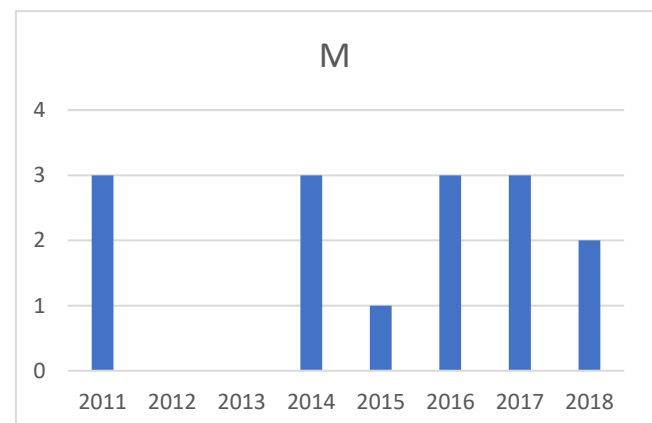
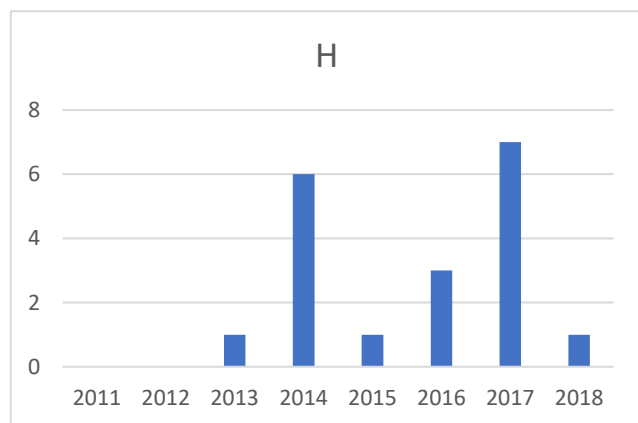
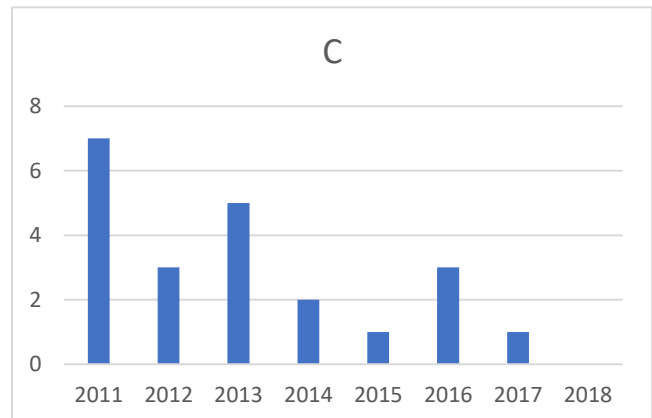
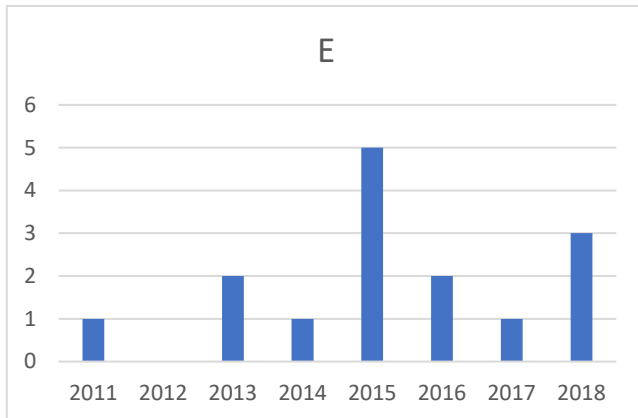
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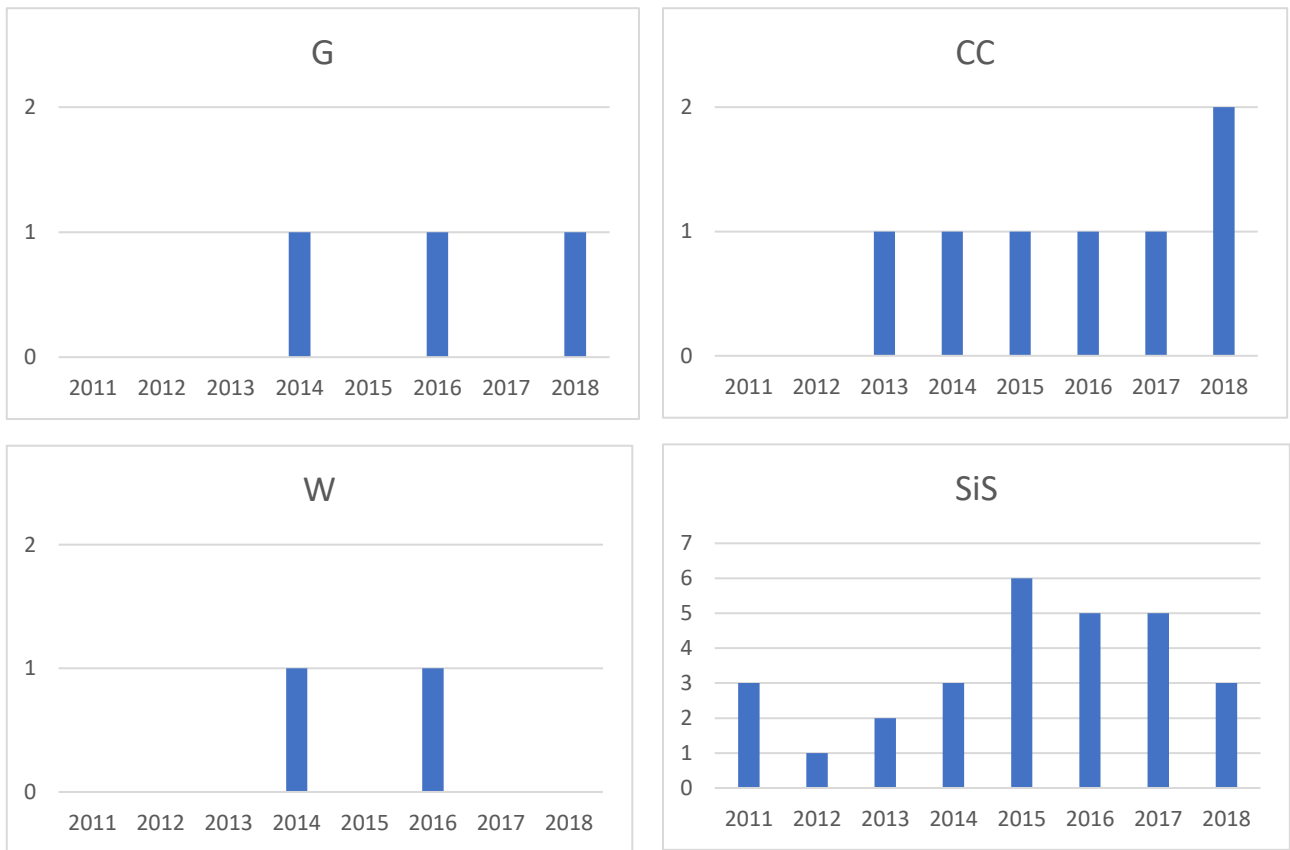


Figure 3: Graphs illustrating number of papers published each year in each subject category

For more information on CCF, the '**Continuous Cover Forestry Group**' are actively involved in the development and education of the subject.

Find out more at:

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