Using birch as shelter with Sitka spruce – description and outcome of the Kronoberg approach

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Abstract

The feasibility of Sitka spruce and birch mixtures on nutritionally impoverished sites was investigated based on experimental data and single tree growth model simulations. The Kronoberg silvicultural approach was considered as a management option, which is traditionally applied to naturally regenerating birch and Norway spruce sites with two major economic objectives: bioenergy production from the initial thinning of birch, and production of good quality spruce sawlog at clearfell. The silvicultural system was tested using field data from planted mixed species trials to initialise model simulations under three proposed scenarios a) a no thin pure Sitka spruce stand (SS-NT), b) a 50:50 birch/Sitka spruce mixture under a no thin silvicultural scenario (M-NT) and c) the Kronoberg management approach (KM) adapted for planted birch/spruce mixtures. Analysis of simulated harvest and growth data suggest that gradual removal of birch from the mixed stands is required to maximise timber volume production of Sitka spruce. Economic analysis shows that the SS-NT and M-NT scenarios, where stands are clearfelled at 40 years or earlier, for bioenergy or timber sale, may not be commercially viable, based on net present value (NPV) using discount rates above 2%. The KM approach yielded positive NPV returns at discount rates of 3 to 6%. The potential use of this alternative silvicultural system for nutritionally poor sites Dublin 4.

requires further field testing to validate model simulations and economic assumptions used in the study.

Keywords: *Kronoberg, silviculture, Sitka spruce, birch, mixtures, peatland*

Introduction

The first description of birch and spruce mixtures in the Irish Forestry journal was documented by Clear (1944). He noted: "*In Sweden, the birch is regarded with great reverence owing to its important role as a 'pioneer' species on deforested land. I will always remember the fervour of a Swedish forester as he told of the wondrous 'mothering' qualities of the birch. He pointed out an area where fire had destroyed*

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a large section of spruce forest many years previously. Artificial regeneration was immediately resorted to, but repeated plantings of spruce failed and the attempt was abandoned in despair. By degrees the bare, abandoned ground was colonised by birch and when, a canopy formed, natural spruce seedlings began to spring up in quantity. When we visited the area there was a complete understorey of vigorous spruce, some well up in the now lightening birch canopy." In recent years the potential of birch as a nursing crop or shelter system for both Norway and Sitka spruce has gained much attention, both in Ireland and Scandinavia (Tham 1988; Johansson 2003; Fahlvik et al. 2011; Black et al. 2017c).

The suitability of major conifer species for industrial cutaway and blanket bog peatlands in Ireland is limited to a narrow range of site types (Renou-Wilson et al. 2008; Black et al. 2017a, Horgan et al. 2004). There are also increasing environmental regulation requirements which may limit aerial fertilisation of these nutrient poor sites, thereby further reducing species suitability in these areas. Recent studies suggest that establishment of Sitka spruce *(Picea sitchensis* (Bong.) Carr.) with birch, as a mixed stand or by under planting spruce in an established birch canopy, can improve the productivity of the conifer crop (Black et al. 2017a; 2017c). These mixtures may be particularly suitable for nutrient poor sites with good or moderate drainage (Black et al. 2017a, b). Management of mixed Norway spruce (*Picea abies* (L.) Karst.) and birch stands is a well-established management model used in southern Sweden (Kronoberg approach).

The Kronoberg approach is not strictly a silvicultural system, but an approach applied to naturally regenerating birch (*Betula* spp.) and Norway spruce sites, or sites planted with Norway spruce (Tham 1988, Johansson 2003, Fahlvik et al. 2011). The removal of birch and treatment of stands vary considerably depending on owners' objectives and management knowledge. Johansson (2003) describes the approach to avoid frost damage to Norway spruce followed by removal of birch for bioenergy production (Table 1 and Figure 1). Johansson (2003) considers two major economic objectives: bioenergy production from initial thinning of birch, and production of good quality spruce sawlog at clearfell. He reported a higher total mean annual increment (MAI) in mixed stands of birch and Norway spruce (11.5 m^3 ha^{-1} $year^{-1}$) than in pure spruce stands (7.2 m^3 ha^{-1} yr^{-1}). Tham (1988) describes an approach where birch is rather used as a shelter with a greater emphasis on maximising total production (MAI) of both birch and spruce. Fahlvik et al. (2011) describe a variation on the approach were birch is retained for the full rotation, whilst still maintaining a high MAI for Norway spruce (15 m^3 ha^{-1} yr^{-1}). Although the Kronoberg approach is a long-established approach (see Table 1), the density of the nurse crop and the time of thinning have been found to be critical for Norway spruce growing on Finnish peat soils (Hilli et al. 2003). Results from field experiments suggest an apparent positive mixture ("over-yielding") effect of birch

Table 1: *A description of the five main stages in the "Kronoberg" approach of thinning naturally regenerating spruce/birch mixtures for bioenergy and timber production*.

Stage 1:	When the birch is 3-4 m high, reduce (thin to waste or for bioenergy harvest) birch stocking to 3,000-4,000 stems ha^{-1}. No treatment of Norway spruce.
Stage 2:	When the dominant height of birch is 6-9 m tall, reduce (bioenergy harvest) the birch stocking to 1,000-1,500 stems ha^{-1}.
Stage 3:	At 20-25 years or when dominant height of birch is 8-12 m tall, harvest the birch for bioenergy the stocking of spruce to 2,000 stems (they should be 3-4 m tall at this point).
	Alternatively, leave 600-800 stems of birch for 10-15 years but ensure there is no competition with spruce. Ensure birch crown cover is always lower than spruce in the canopy.
Stage 4:	Clearfell the birch for bioenergy. Continue to grow the spruce crop until final harvest. Possibly consider subsequent thinning of spruce and cleaning of regenerating birch.
Stage 5:	Clearfell spruce or consider some sort of continuous cover forest management involving birch and spruce. Sometimes get natural regeneration of spruce under birch.

on spruce (Johansson 2003, Hilli et al. 2003, Black et al. 2017c) and this is thought to result from utilisation of different ecological niches (Pretzch 2009), where, in this case, one or both species grows better than when grown alone (i.e. a true mix). However, there is evidence that the nurse effect on spruce is not maintained unless there is silvicultural intervention (Hilli et al. 2003, Black et al. 2017c).

Black et al. (2017c) reported a 50% increase in stand productivity of spruce in a 16-year-old 50:50 downy birch (*Betula pubescens* Ehrh.) / Sitka spruce mixture, planted in alternative rows at a spacing of 2.0 m, when compared to a pure spruce crop grown on cutaway peatlands in the Irish midlands. In Sweden, mixtures may include downy or silver birch (*Betula pendula* Roth) with Norway spruce. This nursing effect can be considered as facilitation, where the growth of spruce is favoured when grown with birch apparently due to protection against frost or enhanced crop nutrition (Johansson 2003). However, is it not clear if "over-yielding" of Sitka spruce in these mixed stands can be sustained in the long-term. Some Kronoberg approaches attempt to maximise productivity of the spruce crop by selectively removing birch (e.g. Johansson 2003). However, this approach has not been tested in Ireland. In addition, the Kronoberg approach should be economically feasible, given the high establishment costs and current bioenergy and timber prices.

The objectives of this study were to develop indicative yield tables for planted birch/ Sitka spruce mixtures (50:50 mix), based on data from a 16-year-old experimental site located on cutaway peatlands in the midlands (see Black et al. 2017c) and by using a single-tree growth model (CARBWARE, see Black 2016) to simulate stand transitions

Mixed birch/Norway spruce woodland (Stage 2)

Norway spruce woodland after birch removal (Stage 3)

Regenerating Norway spruce under birch canopy after spruce removal (Stage 5)

Figure 1: *Examples of different stages over the Kronoberg rotation (taken from Fahlvik and Ulvcrona (2012).*

under different management scenarios. These simulated management approaches were developed in an attempt to estimate potential economic returns from bioenergy and timber production on sites that are not suitable for pure Sitka spruce crops, such as the cutaway or blanket bogs. The Kronoberg system would also offer additional ecosystem service value compared to mono-culture conifer crops, particularly in relation to biodiversity and amenity value.

Methodology

The experimental dataset

The experiment was established in 2000 in the Blackwater production area of Bord na Mona's industrial cutaway peatland near the Shannonbridge ESB peat-fired power plant (geographic coordinates at centre of experiment in ITM WGS 84 projection are 53.2938° N and -7.9794° E). The experiment was set out in three blocks, with six randomised plot treatments in each block (see Black et al. (2017c) for a detailed description of experiment site and measurements undertaken). Previous analysis conducted by Black et al. (2017c) suggested that only one treatment had potential as a new silvicultural system. This involved the planting of alternate rows of Sitka spruce (origin: SQ UK Scot V12) and downy birch (origin: BC UK106 ZP20) at a density of 2,500 trees ha^{-1} at a row spacing of 2 × 2 m. Sitka spruce was planted as bare-root stock 2+1 (i.e. a 3-year old transplanted seedling). Birch was planted as bare root stock 1U1 (i.e. a 2-year old undercut seedling). Data form the replicated plots with 50% mixed species and pure Sitka spruce treatments at 16 yearswas used for all model simulation and data analysis.

All plot data were collected as described by Black et al. (2017c) using the Field Map system (IFER, Czech Republic). Height (H) values for unmeasured trees in the plot were then derived from measured DBH values using a DBH-H model for Sitka spruce and birch using Eq. 1 (Pienaar and Turnbull 1973):

$$H = 1.3 + a(1 - Exp(b - DBH))^{\left(\frac{1}{c}\right)} \quad [1]$$

where H is tree height (m), DBH is diameter (cm) and coefficients a, b and c were solved using non-linear least squares curve fitting procedures using R. All coefficients and model fits were significant at $p<0.05$. Additional statistical analysis of model residuals using the Shapiro-Wilk test was carried out to ensure the DBH-H model residuals were normally distributed. Top height for each treatment was estimated from the measured height of the maximum DBH tree within the sample plot.

Over-yielding analysis was carried out on the mixed stands based on a delta statistic (Mason and Connolly 2020). The difference between current annual increment (CAI) of Sitka spruce in the mixed crop and that of a pure Sitka spruce crop grown on the same site was used. A positive delta statistic over a rotation indicated "over-yielding", while negative values indicated under-yielding" of Sitka spruce in the mixture.

The modelling framework

The CARBWARE single tree model (Black 2016) was used to simulate diameter and height increment for individual trees and mortality on an annual basis. The distance and age independent model have been shown to provide accurate simulations of trees grown in mixed species and uneven aged stands (Black 2016) because the model contains growth modifiers that are based on competition indices. However, no species-specific interaction modifiers and regeneration sub-models are included in the modelling framework (see Black (2016) for an overview).

The model requires metrics on DBH and height and a species identifier for each tree in the plot. The replicated plot measurements were run separately using different management scenarios to provide statistics for stand outputs based on a measured stand initiation state at 16 years of age. Single tree volume was derived using height and DBH for spruce as described by Black (2016). Single tree model coefficients for birch were taken from the Irish National Forest Inventory (NFI 2017).

The CARBWARE stand modifier function allows the selection of individual trees for harvest to meet specific mensuration thresholds, such as target basal area, proportion mixtures or standing volume. The stand modifier function was used to simulate a pure spruce stand and mixed stands under two different management scenarios. All simulations were run up to a rotation age, which is equivalent to the age at maximum mean annual increment (MMAI) of Sitka spruce in stand subject to the Kronoberg silvicultural approach (see descriptions below). Although stand age at MMAI will vary depending on treatment, a single rotation age was selected to enable cross comparison between treatments.

Silvicultural scenarios and conditions

The following silvicultural approaches were tested (see yield tables in the appendix section):

- *Pure Sitka spruce* (SS-NT), under a no thinning management option which is standard for the estimated yield class (Table 1A, in the appendix). The estimated yield class is YC 12 based on top height measurements carried out at 16 years of age.
- *Mixed stand no thin scenario* (M-NT), 50:50 birch/spruce mixture where there was no silvicultural intervention, except clearfelling (Table 2A in the appendix).
- *The Kronoberg* (KM) *system* (Table 3A in the appendix) the birch/spruce mixed stand metrics were simulated, starting at stage 2 (see Box 1). However,

initial stand characteristics at intervention were different for the experimental data set because of artificial planting and lower initial stocking rates, when compared to the conventional Kronoberg approach (Box 1):

- When birch was 4-8 m high at year 16, every 3rd row of birch was harvested (for bioenergy) and negative selection in other rows (i.e. selection of large diameter birch trees to reduce competition) was simulated to leave 500-700 stems ha^{-1} of birch and 1,200-1,400 stems ha^{-1} of Sitka spruce.
- When birch was 10-13 m high (age 27), all of the remaining birch was harvested as bioenergy, and spruce stocking was reduced to ca 1,000 stems ha^{-1} by removing smaller diameter spruce trees.
- An intermediate thinning (predominantly pulp and pallet) of the half of the Sitka spruce crop at age 34 was carried out to minimise over stocking and a reduction in productive potential. This treatment is consistent with the stage 4 treatment (see Box 1).
- Clearfell age for the managed scenarios was defined as the age at which mean tree volume was close to 1 m^3 per tree and the age where MMAI occurs. Commercial rotations for Sitka spruce typically occur when mean tree volume is 0.7 to 1 m^3 (Phillips 2009). A commercial rotation, defined as the age at maximum mean annual increment (MMAI) less 20% for Sitka spruce, yields a higher economic return than a classical silvicultural rotation (i.e. age at MMAI, see Phillips (2009)).

Economic analysis

Economic analysis was based on estimation of net present value (NPV) of cash flows at rotation age, which was standardised to 40 years, the clearfell age under the Kronoberg approach. Since NPV is very sensitive to discount rates, a range of rates from 2 to 6% was applied.

The management objective of one of the Kronoberg approaches is to produce bioenergy from thinnings and sawlog from the final crop (Johansson 2003). In order to do an economic analysis, it was assumed that all harvested birch timber and most pulpwood from the harvest of spruce is sold as bioenergy at a price of €6.50 GJ^{-1}, or €45 t^{-1} at 55% moisture content. Basic wood densities of 0.61 and 0.40 m^{3}t^{-1} were assumed for birch and spruce timber, respectively. A biomass expansion factor of 1.5 t t^{-1} was applied to convert stem biomass to total aboveground biomass (range 2.1 to 1.3, see Tobin et al. 2007). Extraction and chipping where assumed to cost €3.80 GJ^{-1}, and transport (50 km) was estimated to cost €1.50 GJ^{-1} (Kofman 2010). It is plausible that extraction costs may be higher for smaller trees, but this would be offset by a higher biomass expansion factor for smaller trees (Tobin et al. 2007). Harvest losses for whole tree biomass were assumed to be 10%.

Our preliminary analysis suggested that the pulpwood price for spruce was only more attractive than the bioenergy prices at a minimum standing volume price of €23 m^{-3}, which is equivalent to tree sizes greater than 0.174 m^3 per tree, based on the long-term standing timber prices and bioenergy assumptions outlined above. Therefore, spruce harvested from thinnings, in the KM approach was assigned to pulpwood only if the mean tree size was greater than 0.174 m^3 per tree. The standing price for tree sizes between 0.175 and 0.240 m^3 per tree was assumed to be €23 m^{-3} and harvest losses were assumed to be 13%.

Standing timber revenues for the final clearfell of spruce from the Kronoberg management scenarios was assumed to be €54 m^{-3} for the mean stem size of 0.9-1.0 m^3, based on long term standing timber prices (Coillte, 2008-2016). Harvesting losses for these large volume trees was assumed to be 7%. Timber revenues at clearfell for the unthinned Sitka spruce (SS-NT) and mixed stands (M-NT) were based on a long-term standing timber prices for corresponding stem size categories (see notes to Tables 1B and 2B in the appendix). Harvest losses were assumed to be 13%.

Afforestation/reforestation and maintenance costs were assumed to be equivalent to the current Forest Service grant scheme value for GPC 3 (€3,650 ha^{-1}). No additional costs were allocated to overheads or additional roads etc.

Results

Stand metrics

The delta statistic of CIA for the birch/spruce mixed stands (M-NT and KM) was slightly positive at 16 years (0.5, Figure 2), confirming the over-yielding effect of the mixture on Sitka spruce was still evident. However, the total standing volume at 16 years was c. 2-fold higher in the mixed stands when compared to pure Sitka spruce

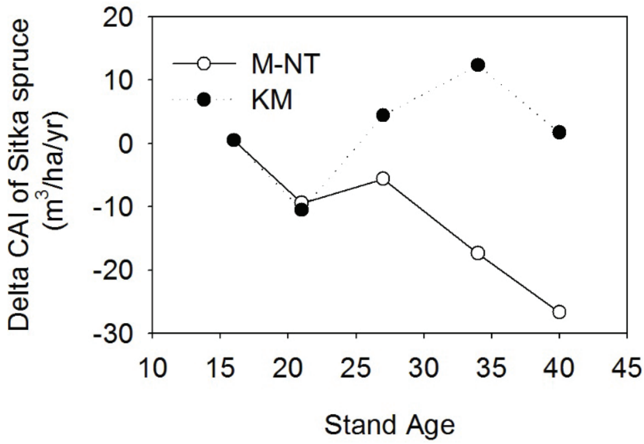

Figure 2: *Delta current annual increment (CAI) of Sitka spruce in the mixed stands relative to a pure stand (SS-NT). Abbreviations: mixed birch/spruce with no thinning (M-NT), mixed birch/spruce stands under the Kronoberg management approach (KM).*

(Tables 1A, 2A and 3A), suggesting that the over-yielding response could have been higher before the first stand metrics were collected.

Productivity of the mixed stand under no thinning (M-NT) declined over time, relative to the pure spruce stand as seen by the negative delta statistics from year 21 (-9.5) to 40 years (-26.6, Figure 2). Simulations also suggest that natural mortality of Sitka spruce in the no thin mixed stand was higher than that of birch in the no thin mixed stand (see Tables 1B). In addition, the natural mortality of spruce in the no-thin, mixed stand, was 1.3 to 3.6 times higher than that observed for the pure Sitka spruce stand (Table 1A and 1B). The effects of a higher mortality rate and lower productivity if the M-NT stand, relative to the pure Sitka spruce stand, resulted in a lower cumulative Sitka spruce timber volume over the rotation (Figure 3). However, the final crop spruce trees for the M-NT stand had a higher mean tree volume, when

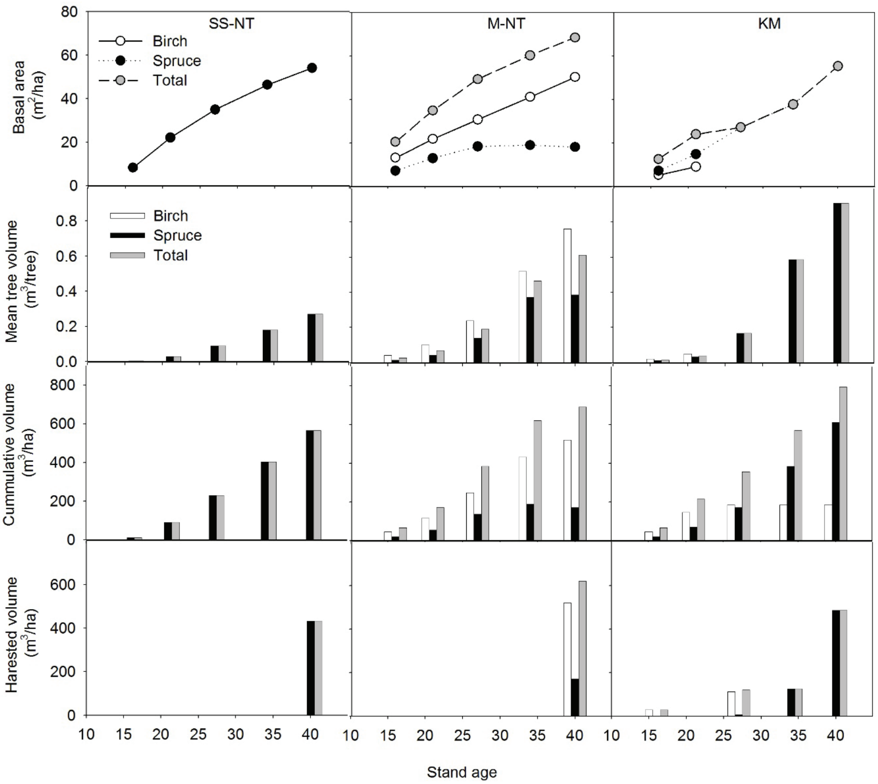

Figure 3: *Comparison of main crop stand attributes and harvest volumes across the different stands. Abbreviations: pure Sitka spruce no thinning (SS-NT), mixed birch/spruce with no thinning (M-NT) and mixed birch/spruce stands under the Kronoberg management approach (KM).*

compared to the pure spruce stand (Figure 3).

Thinning of birch to release spruce under the Kronoberg approach (KM) resulted in a higher mean tree volume for spruce trees and higher cumulative timber production of spruce trees, when compared to the pure and mixed species no thin stands (Figure 3, Tables 1A, 2A and 3A). The timber harvest of spruce trees was higher at clearfell under the Kronoberg approach than in the other two treatments (Figure 3). This was in addition to the bioenergy and pulpwood harvested from thinnings under the KM approach (Figure 3 and Table 3A). The most striking difference between the KM and the no-thin options was the large mean tree volume at rotation age (Figure 3), which influenced both timber price and economic returns (Figure 4).

Economics

Supply of birch for bioenergy appeared to be a better market option for thinnings than the pulpwood timber market, because: a) initial thinnings in the KM scenario produce material that is too small to quantify as pulpwood (Table 2B and 2C); b) the discounted cash flow from bioenergy revenues for 2nd and 3rd thinnings was still higher than that from pulpwood, based on long-term timber prices; and c) there is no market for birch timber.

The SS-NT and M-NT scenarios are only an economically viable commercial forestry option at a discount rate of 2% or less (Figure 3, Table 2A and 2B), which is generally considered to be below the threshold used for forestry investments. The NPV

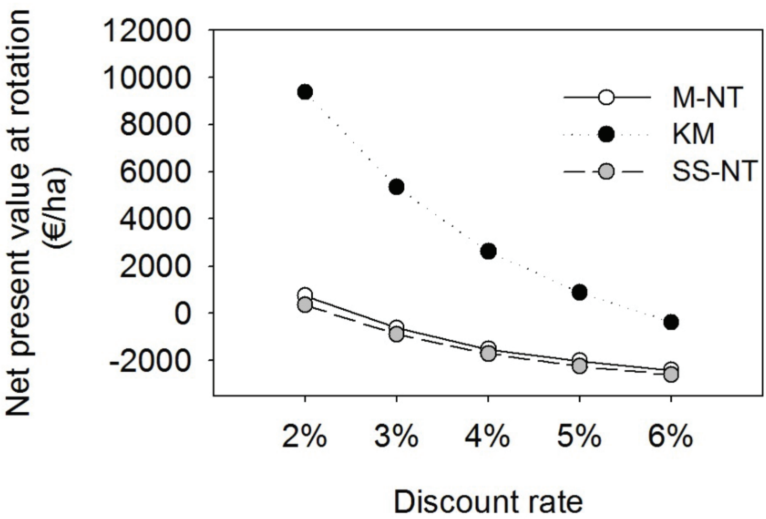

Figure 4: *Net present value at discount rates of 2 to 6% for the pure Sitka spruce no thinning (SS-NT) stands, mixed birch/spruce with no thinning (M-NT) and mixed birch/spruce stands under the Kronoberg management approach (KM).*

values remain negative for these scenarios if the rotation is shorted to 34 or extended up to 60 years (data not shown). The rotation age of the pure Sitka spruce stand had to be increased to 65 years to obtain a mean tree volume of 0.7 m^3 per tree (data not shown), which is generally considered the minimum threshold tree volume at clearfell age.

The Kronoberg approach appears to be economically viable at discount rates of 2 to 5%. (Figure 4 and Table 3B). Additional analysis based on a 5-year delayed initial intervention to remove competing birch does not show an improvement in discounted cashflows over the entire rotation (data not shown).

Discussion

The results from our study suggests that Sitka spruce over-yields by 1.6 to 12 m^3 ha^{-1} yr^{-1} (expressed as CAI) when grown as a mixture with birch and managed using the Kronoberg approach. When over-yielding is expressed as MAI, delta MAI of spruce under the Kronoberg approach was ca. 1.4 m^3 ha^{-1} yr^{-1} at rotation (Tables 1A and 3A). This is considerably lower than the increase in MAI of 4.3 m^3 ha^{-1} yr^{-1} for Norway spruce as reported by Johansson (2003) but consistent with results published by Klang and Eko (1999). These authors report an increase in MAI of 34% (a delta MAI of 1.34) for Norway spruce grown as a mixture with birch, when compared to pure stands. The difference in the over-yielding response may be due to various factors such as differences in management, nutritional status of sites and exposure to frost. Sitka spruce is considered to have a lower tolerance to shade than Norway spruce (Horgan et al., 2004) so an earlier intervention may be required earlier for Sitka spruce when using the Kronoberg approach. Evidence from the literature would suggest that the performance of a mixture is dependent on the different functional traits of component species, such as shade tolerance (Mason and Connelly 2020). Although birch and Sitka spruce may be considered to have different shade tolerance traits, the over-yielding response is also influenced by other interactive effect such as nutrition and changes in the interaction between the species over time. Masson and Connolly (2020) show that a decline in over-yielding may occur when the nurse (facilitation) effect decreases over time or if the light demanding species outcompetes the component species at a later stage of stand development. In addition, different silvicultural strategies may apply to sites with better potential productivity. In certain site types, such as nutritionally rich mineral soils, Sitka spruce can dominate the canopy after 30 years even if birch has regenerated in advance of the planting of spruce (Mason 2006). Therefore, the use of birch as a nurse species for spruce may be limited to nutritionally poor sites or sites prone to frost damage, or both, as is the case for afforested cutaway peatland sites.

Early silvicultural intervention by removing birch appears to be crucial to ensure that productivity of Sitka spruce is maximised (Figure 2). Results from measured stands in southern Sweden also report that growth, yield and NPV decrease with increasing birch proportion, but if the proportion of birch removed in subsequent thinnings is increased, the between-treatment differences are reduced (Fahlvik et al. 2011). Early intervention has also been reported to reduce whipping damage to spruce crowns, which may further decrease productivity (Fahlvik et al. 2011).

We propose that the application of the proposed KM approach to birch / spruce mixtures planted as a 50:50 mixture on cutaway bog sites could be considered as an option with some economic potential. Clearly, planting of pure Sitka spruce or a no management scenario for the mixture is not a commercial forestry option for nutritional poor cutaway peatlands under current market conditions. It should be noted that pure Sitka spruce stands would take considerably longer to reach rotation age than the Kronoberg approach, on these site types. However, it is difficult to compare NPV or discounted annualised returns when rotation ages are very different.

This analysis is largely based on model simulations, which have not been cross-validated for the proposed silvicultural management system. Pretzsch (2009) highlights the importance of species-specific interactions in mixed stand that may lead to modification of the species response to stand competition factors. Sitka spruce and birch species-specific interactions have not been tested or validated for the CARBWARE modelling framework. Moreover, the CARBWARE model does not have a natural regeneration function, so simulations do not consider how natural regeneration may influence economic outcomes. The feasibility of the Kronoberg system for planted mixtures needs to be investigated further in the existing cutaway bog experiments and in other peat sites, such as blanket peats, where the range of suitable tree species for commercial forestry in very limited.

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Appendix

Table 1A: *Mean stand and harvest attributes for the Sitka spruce no-thin management scenario (SS-NT). Abbreviations: SS = Sitka spruce, Ba = basal area; Cum. vol. = cumulative volume; MAI = mean annual increment; CAI = current annual increment.*

		Main crop						Cum. vol.	MAI	CAI
Age	**Species**	**DBH** (cm)	**H** (m)	**Ba** (m^2 ha^{-1})	**Vol.** (m^3 ha^{-1})	**Trees** (ha^{-1})	**Vol. tree^{-1}** (m^3)	(m^3 ha^{-1})	(m^3 ha^{-1} yr^{-1})	(m^3 ha^{-1} yr^{-1})
16	SS	6.7	5.1	8.3	10.6	2,347	0.005	10.6	0.7	9.7
21	SS	11.5	7.1	22.1	69.4	2,087	0.03	89.6	4.3	16.5
27	SS	15.2	9.6	34.9	179.9	1,924	0.09	228.9	8.5	19.1
34	SS	18.5	12.6	46.4	314.9	1,731	0.18	402.7	11.8	24.8
40[a]	SS	20.8	14.9	54.1	433.1	1,578	0.27	564.5	14.1	27.0

[a] Clearfell at 40 years for pulp market.

Table 2A: *Mean stand attributes of the mixed species crop under the mixed stand no-thin scenario (M-NT). Abbreviations BI = birch, SS = Sitka spruce, Ba = basal area; MAI = mean annual increment; CAI = current annual increment.*

Age	**Main crop**							**Cum. vol.**	**MAI**	**CAI**
(yrs)	**SPP**	**DBH** (cm)	**H** (m)	**BA** (m^2 ha^{-1})	**Vol.** (m^3 ha^{-1})	**Trees** (ha^{-1})	**Vol/tree** (m^3)	(m^3/ha)	(m^3 ha^{-1} yr^{-1})	(m^3 ha^{-1} yr^{-1})
16	Total	9.3	5.5	20.6	67	2,530	0.03	67	4.2	25.9
	BI	11.5	6.3	13.3	47	1,161	0.04	47	2.9	15.7
	SS	7.7	4.8	7.3	21	1,369	0.02	21	1.3	10.2
21	Total	12.2	8.2	35.0	172	2,530	0.07	172	8.2	20.9
	BI	14.7	9.3	21.9	117	1,161	0.10	117	5.5	13.9
	SS	10.2	7.4	13.1	56	1,369	0.04	56	2.6	7.0
27	Total	14.3	11.4	49.4	385	2,024	0.19	385	14.3	35.5
	BI	16.2	12.4	30.9	248	1,042	0.24	248	9.2	22.0
	SS	14.1	12.5	18.5	137	982	0.14	137	5.1	13.5
34	Total	19.3	18.4	60.3	622	1,339	0.46	622	18.3	33.8
	BI	20.7	19.2	41.2	433	833	0.52	433	12.7	26.4
	SS	14.8	17.7	19.1	189	506	0.37	189	5.6	7.5
40[a]	Total	23.1	22.3	68.6	692	1,131	0.61	692	17.3	11.7
	BI	25.3	23.4	50.3	520	685	0.76	520	13.0	14.5
	SS	14.7	19.0	18.2	172	446	0.39	191	4.3	0.3

[a] Clearfell at 40 years for bioenergy market (BI) and roundwood market (SS).

Table 3A: *Mean stand and harvest attributes for the Kronoberg management scenario (KM). Abbreviations: BI = birch, SS = Sitka spruce, Ba = basal area; MAI = mean annual increment, CAI = current annual increment.*

Age		Maincrop after thinning					Harvest				Before thinning					Cum. vol.	MAI	CAI
(yrs)	Spp.	DBH (cm)	H (m)	Ba (m^2 ha^{-1})	Vol (m^3ha^{-1})	Trees (ha^{-1})	Ba (m^2 ha^{-1})	Vol (m^3ha^{-1})	Trees (ha^{-1})	Vol/tree (m^3)	DBH (cm)	H (m)	Ba (m^2 ha^{-1})	Vol (m^3ha^{-1})	Trees (ha^{-1})	(m^3 ha^{-1} yr^{-1})	(m^3 ha^{-1} yr^{-1})	(m^3 ha^{-1} yr^{-1})
16	Total	8.4	4.0	12.7	29	1,994	7.9	29	536	0.05	9.3	5.5	20.6	67	2,530	58	3.6	25.9
	BI	10.1	4.3	5.3	12	625	7.9	29	536	0.05	11.5	6.3	13.3	47	1,161	41	2.6	15.7
	SS	7.7	4.2	7.3	17	1,369					7.7	4.8	7.3	21	1,369	17	1.0	10.2
21	Total	11.6	6.1	24.1	77	1,994										106	5.0	9.6
	BI	13.2	6.6	9.2	31	625										60	2.8	3.7
	SS	11.0	5.8	14.9	46	1,369										46	2.2	5.9
27	Total	17.4	12.1	27.3	179	1,071	19.2	120	923	0.13	16.1	11.4	46.4	299	1,994	328	12.2	37.1
							17.6	112	625	0.18	18.1	12.2	17.6	112	625	141	5.2	13.6
	SS	17.4	12.1	27.3	179	1,071	1.6	8	298	0.03	15.3	11.1	28.9	187	1,369	187	6.9	23.5
34	Total	29.9	17.1	37.8	315	536	15.9	125	536	0.24	24.6	15.9	53.7	440	1,071	588	17.3	37.2
	BI															141	0.0	0.0
	SS	29.9	17.1	37.8	315	536	15.9	125	536	0.24	24.6	15.9	53.7	440	1,071	448	13.2	37.2
40	Total	36.3	19.3	55.4	487	536	55.4	487	536	0.91						760	19.0	28.6
	BI															141	0.0	0.0
	SS	36.3	19.3	55.4	487	536	55.4	487	536	0.91						619	15.5	28.6

Table 1B: *Economic analysis based on net present value (NPV) at discount rates of 2 to 6% for the pure Sitka spruce stand under a no-thin scenario (SS-NT).*

Operation	Year	Revenue[a]	Cost	Cashflow	Net Present Value				
		(€)	(€)	(€)	2%	3%	4%	5%	6%
Establishment cost	1		-3,650.00	-3,650.00	-3,578.43	-3,543.69	-3,509.62	-3,476.19	-3,443.40
	16								
	21								
	27								
	34								
Clearfell	40	8,666.33		8,666.33	3,924.90	2,656.72	1,805.10	1,231.01	842.56
NPV (€)					**346.47**	**-886.97**	**-1,704.51**	**-2,245.18**	**-2,600.84**
AE (€ yr^{-1})					**12.67**	**-38.37**	**-86.12**	**-130.84**	**-172.86**

[a] Standing timber price at clearfell was €23 m^{-3} for log size category 0.27 m^3 tree^{-1}.

Table 2B: *Economic analysis based on net present value (NPV) at discount rates of 2 to 6% for the mixed species stand under a no-thin scenario (M-NT).*

Operation	Year	Revenue[a]	Cost	Cashflow	Net Present Value				
		(€)	(€)	(€)	2%	3%	4%	5%	6%
Establishment cost	1		-3,650.00	-3,650.00	-3,578.43	-3,543.69	-3,509.62	-3,374.94	-3,343.10
	16								
	21								
	27								
	34								
Clearfell	40	24,984.49	-15,454.80	9,529.69	4,315.91	2,921.39	1,984.93	414.97	284.02
NPV (€)					**737.47**	**-622.30**	**-1,524.68**	**-2,959.97**	**-3,059.08**
AE (€ yr^{-1})					**26.96**	**-26.92**	**-77.03**	**-172.50**	**-203.31**

[a] Standing timber price at clearfell was €40 m^{-3} for log size category 0.39 m^3 tree^{-1}.

Table 3B: *Economic analysis based on net present value (NPV) at discount rates of 2 to 6% for the Kronoberg management scenario (KM).*

Operation	Year	Revenue[a] (€)	Cost (€)	Cashflow (€)	Net Present Value 2%	3%	4%	5%	6%
Establishment cost	1		-3,650.00	-3,650.00	-3,578.43	-3,543.69	-3,509.62	-3,374.94	-3,343.10
	16	1,050.37	-856.46	193.91	141.26	120.84	103.53	88.83	76.33
	21								
	27	4,275.92	-3,486.52	789.40	462.48	355.38	273.78	211.44	163.70
	34	2,499.81		2,499.81	1,274.97	915.04	658.83	475.85	344.75
Clearfell	40	24,432.17		24,432.17	11,065.10	7,489.85	5,088.95	3,470.48	2,375.35
NPV (€)					**9,365.37**	**5,337.42**	**2,615.48**	**871.67**	**-382.97**
AE (€ yr^{-1})					**342.36**	**230.91**	**132.14**	**50.80**	**-25.45**

[a] Standing timber price at clearfell was €23 m^{-3} for log size category 0.27 m^3 $tree^{-1}$.