The potential impact of intensification on forest productivity under different climate change scenarios

Alba Cabrera Berned[a*] and Maarten Nieuwenhuis[a]

Abstract

The intensification of forest management, using fast-growing species well-adapted to future climate conditions is seen as a solution to guarantee a sustainable increase in the domestic timber production, while avoiding or minimising any risks associated with climate change. This paper reports on the findings of a research project that assessed the productivity of Sitka spruce (*Picea sitchensis*) on a range of site types under different climate change scenarios and stand density control methods (i.e. planting spacings and thinning intensities). To this end, an integrated approach was developed through a link between the Irish dynamic yield models (Growfor) and the CLIMADAPT software, the Irish Ecological Site Classification System.

The results show that Sitka spruce is likely to produce yield class 14 or greater in most of Ireland by the end of the century, although its growth rate is expected to decrease in many parts of the country, especially in the south-east and some areas in the western regions, and alternative species may have to be used there. In general terms, stands planted at close spacings (1.7 m square) and thinned at light intensities (60-80% of marginal thinning intensity (MTI)), using a 5-year thinning cycle, would produce the greatest volume. When the management objective was to maximise the profitability rather than yield, applying light thinning intensities (up to the MTI) and planting a 3 m square was the best approach.

Keywords: *Growfor, CLIMADAPT, Sitka spruce, intensive forest management, climate change.*

Introduction

Demand for wood fibre in Ireland already exceeds the capacity of Irish forests to supply it and it has been forecasted to further increase by 40% by the end of the decade, much of this coming from the expanding bioenergy sector (COFORD 2011). However, strong pressure to support conservation, agriculture and housing may limit the land available for future afforestation plans to meet the increased demand for wood (COFORD 2016). According to Farrelly and Gallagher (2015), only 0.43 million ha of wet grassland and unimproved land have real potential for afforestation plans in Ireland. At the same time, future climate conditions, which will be marked by higher temperatures, changes in precipitation patterns and an increase in the frequency

[a] UCD Forestry, School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4.
[*] Corresponding author: a.c.berned@gmail.com

of extreme events (Dunne et al. 2008), are expected to impact on the way forests develop and the goods and services they can provide (Ray et al. 2008). Under these circumstances, the intensification of forest management practices, using fast-growing species well-adapted to the future climate conditions has been advocated as a solution in order to sustainably increase the domestic supply of raw material (Binkley 1997, Sedjo and Botkin 1997).

This study focused on Sitka spruce, which is the most important species of Irish forestry (accounting for 52.4% of the total forest estate according to the latest National Forest Inventory (NFI) in 2012) and the main pillar of the wood processing industry, due to its suitability to a wide range of climatic and edaphic conditions, its rapid growth rate and the versatility of its wood.

Intensive forest management

Intensive commercial forest management, undertaken on small existing and newly afforested areas in a sustainable and resilient manner, is seen as a possible solution to the increasing demand for wood fibre without the use of much more land. Concentrating timber production on the best-suited and adapted sites, where high growth rates can be achieved in the shortest possible time, requires a smaller amount of land to meet the demand for forest products and may allow large areas of forest to be given priority for other uses (e.g. biodiversity, protection and recreation) (Fox 2000).

This project focused on the increase in timber production through the intensification of forest management using stand density control methods, such as the initial planting, spacing and thinning intensity. The amount of growing space available to an individual tree will affect not only the size, shape and structure of its stem and its branching characteristics, but also the growth of the stand through the rate of site utilisation (Joyce and OCarroll 2002). Since the 1960s, several spacing, respacing and thinning studies in coniferous crops have been carried out in Ireland to examine the effect of growing space on tree and stand characteristics (Gallagher 1980, Gallagher 1985). Research has shown that close spacing results in inter-tree competition and high mortality, displaying slower tree diameter growth, longer rotations and lower rates of return (Thornhill 1956). High stocking densities also increase planting and operational costs and, as there is more root and crown competition, the dangers of windthrow, especially after thinning (Cremer et al. 1982). Wider spacings, on the other hand, allow trees to grow more rapidly and guarantees greater crown development leading to larger individual tree dimensions in a shorter period. This rapid growth of trees is offset by a reduction in the potential total volume production (Joyce and OCarroll 2002) and affects many timber characteristics (Moore et al. 2009). Close spacing promotes good clean stems with reduced side branching and knottiness, higher timber density, elasticity and tensile strength, resulting in high-quality timber (Simic et al. 2016).

Thinning treatments are an effective way to accelerate tree growth, reduce mortality and increase overall timber yield. They also increase the overall timber revenue by increasing the volume production of sawlog and provide a periodic income for the owner. The thinning influence on the volume growth varies with thinning intensity, frequency of thinning and, to a lesser extent, the length of rotation (Hummel 1957).

Traditionally, empirical growth and yield models have been the principal modelling tools used by foresters to make decisions on initial establishment spacing, when and how heavy to thin and the rotation length. Broad and Lynch (2006) developed a dynamical yield modelling system to represent forest growth in Ireland called Growfor. Growfor is used in Irish forestry to forecast the outcome of a wide range of silvicultural practices in terms of user-defined thinning regimes and different initial spacings (McCullagh 2013).

Climate change and forestry

Forests are particularly sensitive to climate change because the long lifespan of trees does not allow for rapid adaptation to a rapid rate or large magnitude of environmental change (Lindner et al. 2010, Keenan 2015). Higher temperatures, changes in precipitation patterns and rising atmospheric CO_2 concentrations are expected to have a significant effect on tree growth rates (Lindner et al. 2010). These climatic changes will indirectly increase the biotic and abiotic disturbances, which not only impact on forest productivity (Cannon 1998, Parmesan 2006) but may also initiate changes in species composition and forest structure and shifts in vegetation distribution (Keenan 2015).

The forecasted changes in the Irish climate over the 21st century (Dunne et al. 2008) will be marked by rising temperatures (increasing by up to 3.4 °C towards the end of the century), especially in the south and east of Ireland, and autumn and winter seasons will become wetter, with precipitation increasing by 15-25% towards the end of the century. On the other hand, summers are expected to become drier, with a 10-18% decrease in precipitation towards the end of the century. Projections suggest that the climate will become more variable, with an increased risk of storm damage and flooding.

In sustainable forest management, it is of fundamental importance to ensure that the tree species selected for a specific site are suited to the site conditions. CLIMADAPT, a multi-factor forest site classification system, which brings together climatic and edaphic factors that influence tree growth, is used in Ireland for guidance on species choice according to site type and future climate change scenarios (Ray et al. 2009).

Materials and methods

Effect of climate change on growth

CLIMADAPT was used to assess Sitka spruce suitability and yield in 100 sites around Ireland under current and future climates. The sites included in this study were selected randomly from the permanent forest sample plots used in the second cycle of the NFI (provided by J. Redmond, Forest Service 2017). In order to facilitate the analysis of CLIMADAPT outputs, the sites have been arranged in 7 geographical sub-divisions based on the Regional Authorities Establishment Order, 1993: East Coast, South-East, South-West, Midlands, West, Mid-West and Border.

For each selected site, CLIMADAPT stand analysis was performed using the system's default soil characteristics (SMR and SNR) and for four climate change scenarios: baseline (period 1961-1990), 2050 A2, 2050 B1 and 2080 A2. The future climate data (for the years 2050 and 2080) used in CLIMADAPT were calculated based on projections of the future greenhouse gas emissions scenarios A2 and B1 (SRES) described by the Intergovernmental Panel on Climate Change (IPCC) (Ray et al.2009). The output of the system provides an indicative yield class (YC) for each species/site combination and indicates whether a particular species is Very Suitable (YC >20), Suitable (YC 14 to 20) or Unsuitable (YC <14).

To assess the sensitivity of the results to the default soil assumptions built into CLIMADAPT, the modelling was also carried out for the 12 plots located in the South-East region, but using accurate soil data obtained from the NFI.

Effect of forest management on timber yield and revenue

The indicative yield class provided by CLIMADAPT was applied to typical regimes in the 1981 Forestry Commission Yield Tables (Edwards and Christie 1981), defined by the top line of each table (consisting of age, top height, mean DBH, stocking and BA). These top line data were the inputs required to run the simulations by Growfor. Growfor was used in this research project to analyse the volume production obtained under different forest management regimes and to analyse the income associated with the production of different assortments.

Greatest volume production

The simulations were carried out for each yield class from YC 10 to YC 24. The goal was to identify the management regime that produced the maximum cumulative volume to 7 cm top diameter. Thinning intensity was defined in terms of the marginal thinning intensity (MTI) which is the maximum intensity which can be maintained without causing loss of volume production. The British Forestry Commission (FC) models are based on the assumption that MTI equals 70% of the respective YC

(Edwards and Christie 1981). For this study, thinnings were controlled by the intensity of the volume reduction (expressed as a percentage of MTI) and the thinning cycle. A 5-year thinning schedule was adopted as the default. The thinning yields were calculated as a product of thinning intensity, YC and thinning cycle. The rotation lengths were based on the maximum mean annual increment (MMAI). When this point was reached, the maximum cumulative volume production was determined.

The potential production of timber in Sitka spruce stands was determined under the following scenarios:

- Thinning intensity: Heavy (120% MTI), Marginal (MTI i.e. 70% of MMAI), Light (80% MTI), Very Light (70% MTI), Super Light (60% MTI) and No thinning.
- Square spacing between trees: 1.7 m, 2 m, 2.4 m and 3 m.

The age of first thinning in each case, which was the earliest age at which thinning could take place without losing cumulative volume production, was based on Table 2 (average growing stock levels) in the Forestry Commission Booklet 48 (Edwards and Christie 1981). As the Forestry Commission models and Table 2 of Booklet 48 are based on stands thinned at MTI, it was necessary to interpolate these average growing stock levels for the other thinning intensities considered in this study.

Corrections to thinning intensity to account for the slow down of stand growth with age have not been included in order to keep the analysis manageable.

Greatest revenue

Growfor was also used to assess the harvest revenue based on the assortment production for YC 10 to YC 24. The same forest management regime in terms of thinning intensity, planting spacing and 5-year thinning cycles as described in the previous section, have been considered in the financial approach. In this analysis, the goal was to identify the management scenarios that maximise the profit based on short-term standing assortment prices (Table 1).

The Growfor model provides the assortment volume production for any age of the stand as well as the thinning yields. By applying the assortment prices to these volumes, the total revenue (main crop and thinnings) was calculated. The discounted

Table 1: *Timber assortment defined by small end diameter (SED) and large end diameter (LED) and their standing prices (2015).*

Assortment	**SED** (cm)	**LED** (cm)	**Price** (€ m^{-3})
Pulpwood	7	14	6
Palletwood	14	20	8
Small sawlog	20	24	32
Large sawlog	24	>24	41

Source PTR Ltd., 2015.

revenue (DR) for the main crop and thinning yields was calculated using a standard discount rate of 5%. To present the forest management's profitability, the net present value (NPV) was quantified. The NPV represents the net costs and revenues incurred throughout the rotation, expressed at current value. For the aim of this research, only the establishment cost differences were considered, it was assumed that other costs did not differ significantly between scenarios (as the analysis was based on standing prices). In determining the NPV, the standard investment formula for a timber stand with some modifications was applied (Eq. 1).

$$\mathrm{NPV} = -C_0 + \sum_{n=0}^{N} \frac{V_n}{(1+r)^n} + \frac{H_N}{(1+r)^n} \qquad [1]$$

where:
C_0 = initial investment (i.e. the establishment costs);
V_n = value of thinning removal in n years' time;
H_N = value of clearfell in N years' time;
r = interest rate expressed as decimal;
n = the year number;
N = life of the project;
$1/(1 + r)^n$ = the discount factor.

Finally, to allow comparisons between the profitability of the different forest management alternatives (with different rotation lengths), the NPV was expressed by its equivalent annual value (NAE), see Eqs. (2) and (3). For each management regime, the maximum NAE and the age at it which occured (optimal rotation length) were determined.

$$\mathrm{NAE} = \mathrm{NPV} \times \text{Annuity factor} \qquad [2]$$

$$\text{Annuity factor} = \frac{r\,(1+r)^n}{(1+r)^n - 1} \qquad [3]$$

where:

NAE= net annual equivalent;
NPV= net present value;
r = interest rate expressed as decimal;
n = the year number;
$1/(1 + r)^n$ = the discount factor.

Harvest residue production

The revenue obtained for each forest management regime when including residual biomass harvesting into the financial analysis was also estimated. To determine the residual biomass production in each scenario, biomass expansion factors (BEFs) were used. These are multiplication factors used to expand merchantable tree stem volumes to account for non-merchantable biomass components (Tobin and Nieuwenhuis 2007).

The BEFs were calculated on the basis of 2002 survey data from managed Sitka spruce forests in Ireland (supplied by B. Tobin, UCD 2016). The data used to construct them consisted of the biomass content of the tree components (live and dead branches, tip and stem) and the correspondent DBH of a series of harvested trees. Equation 4 was used to calculate single tree level BEFs:

$$\mathrm{BEF} = \frac{\text{Aboveground biomass (branches and tip)}}{\text{Timber biomass}} \qquad [4]$$

The BEFs were arranged in five DBH groups and the average BEF for each group was calculated. The first DBH category started at 10 cm, as thinnings start to take place at an early stage in the stand growth simulations. Based on the study by Tobin and Nieuwenhuis (2007), which determined that BEF values are close to constant for DBHs greater than 30 cm, all stands with an average tree DBH exceeding 30 cm were included in the same group. The corresponding BEF values for each DBH group were: 10-15 cm: 1.48; 15-20 cm: 0.49; 20-25 cm: 0.44; 25-30 cm: 0.41; 30 cm and above: 0.37.

The revenue obtained from selling the residual biomass assortment was calculated by applying a standing price of €4.30 m^{-3} (D. Little, pers. comm. November 2016) and the NAE for each scenario was estimated. As the biomass price has not been long established in Ireland, the financial analysis was also run using double and triple the biomass price to assess NAE trends of scenarios with higher future biomass prices.

This assessment was carried out considering that all residual biomass was removed from site and sold after thinning and final clearfell operations. The impacts of making this material unavailable as a brash mat to support harvesting machinery and the impact of the loss of nutrients on future stand development were not evaluated. The amount of brash available to be sustainably removed from a site for biofuel markets will depend on the soil type and other site factors, marketing opportunities and restocking objectives (Moffat et al. 2006), and this practice should only be carried out on sites where such risks have been evaluated by the forest manager.

Results

Effect of climate change on growth

CLIMADAPT simulations for the baseline period showed that Sitka spruce was well-suited to the prevailing Irish climatic conditions and was capable of growing at YC 14 or greater in most of Ireland (97%) and YC 20 or greater in 67% of the territory. The mean YC at a national level was estimated at 20 m^3 ha^{-1} yr^{-1} and the most productive regions appeared to be located in the Border, West and Mid-West of Ireland, achieving YCs greater than 20. Limitations to the growth in the baseline scenario were mainly due to the species' sensitivity to moisture deficits (MD), the strong winds affecting the south-west of the territory and the poor soil conditions where they occurred.

When Sitka spruce suitability and productivity were examined under medium and long-term future climate change scenarios, CLIMADAPT indicated that the species was likely to continue to be suitable and productive by the middle (in 84% of the territory in scenario B1 and 70% in scenario A2) and the end of the century in the majority (66%) of the country, for the medium-high carbon emission scenario A2. However, the predicted changes in the climate and site quality are likely to greatly affect the species growth rate, reducing its productivity, on average, by up to 5 YCs at a national level over the course of the current century (Table 2). By the end of the century, the main limiting growth factors predicted by CLIMADAPT will be MD and soil moisture regimes.

The areas more likely to suffer from droughts, where the MD was predicted to increase over the course of the present century, will become less favourable for the growth of Sitka spruce. The areas most affected were located along the south-east coast of Ireland, where Sitka spruce growth could be reduced on average by up to 6 YCs by 2080 (becoming unsuitable with productivity levels lower than YC 14). The productivity of Sitka spruce plantations in the north-west, west and south-west of Ireland were predicted to decrease considerably, on average by up to 5 - 7 YCs. In this case, the main reasons behind the forecasted reduction were the very wet conditions (i.e. waterlogging of the soil), combined with poor soil quality and effect of strong winds that were expected to occur in the long-term scenario.

Although the vast majority of plantations where Sitka spruce is grown are expected to experience a decrease in the growth rate by the end of the century, areas where growth factors other than temperature will not be limiting will experience the maintenance or an increase in the productivity of Sitka spruce forests. These areas are located in some parts of the Midlands and inland parts of the western regions.

When running the simulations using detailed soil data from the NFI as inputs in CLIMADAPT, no big differences in average YC were found in the South-East region compared to the results obtained using the default soil characteristics. The same average YC (16) was forecasted for the baseline scenario under both methodologies, although an increase of one to two YCs was predicted for the mid and long-term scenarios when considering more accurate soil data. This analysis also indicates that Sitka spruce is likely to be suitable in this region by 2050 (average YC 14 under the climate change scenario A2 and YC 17 under the scenario B1), although its productivity might be reduced by up to 5 YCs by the end of the century, resulting in it being no longer suitable in the region (YC 11 on average). The slight increases in

Table 2: *Sitka spruce productivity (average YC) forecasted for three scenarios (2050 B1, 2050 A2 and 2080 A2) and compared with the current baseline, for the seven geographical regions considered in the study. The reduction in productivity by the end of the century for the 2080 A2 scenario in comparison to the baseline was also included.*

Scenarios	Ireland total	East coast	South-east	South-west	Mid-lands	West	Mid-west	Border
Baseline	20	19	16	21	18	21	21	22
2050 A2	16	18	12	16	15	17	19	16
2050 B1	18	20	16	17	18	19	20	16
2080 A2	15	16	10	14	14	18	16	17
Reduction by 2080 A2	5	3	6	7	4	3	5	5

YC were a result of an improvement in the soil conditions when using NFI soil data.

Effect of forest management on timber yield and revenue

<u>Greatest volume production</u>

All YCs showed higher cumulative volume production when stand thinning was lighter than at MTI. The volume of timber removed when using the MTI was too large for the stands to recover after the thinning and resulted in the reduction of potential volume production for all YCs. These reductions were greater as the thinning intensity (120% MTI) and the spacing between trees increased, indicating that sites were not being fully utilised.

For low YCs (10, 12 and 14), the light thinning (80% MTI) and very light thinning (70% MTI) intensities were the ones that guaranteed the highest cumulative volume, whereas the super light and unthinned treatments resulted in a reduction in volume production. However, when higher YCs were considered (i.e. YC 16 to 24), the volume of timber removed in each thinning operation was larger than in smaller YCs and lighter thinning intensities, such as super light thinning intensity (60% MTI) achieved the objective of producing the maximum cumulative volume, especially when wider spacings were considered (Figure 1).

The results reflect a significant effect of initial spacing on the growth and volume production of stands. The overall productivity of a stand was lower in widely spaced stands than in closer spaced ones. It was also noticeable that the actual total harvest volume for the lighter thinning scenarios did not differ very much for low and high YCs, although the rotation lengths needed to produce these volumes were quite different. Obviously, rotations for the same cumulative volume were considerably shorter when the YCs were higher, regardless of the forest management regime, signifying higher volume production in the same amount of time.

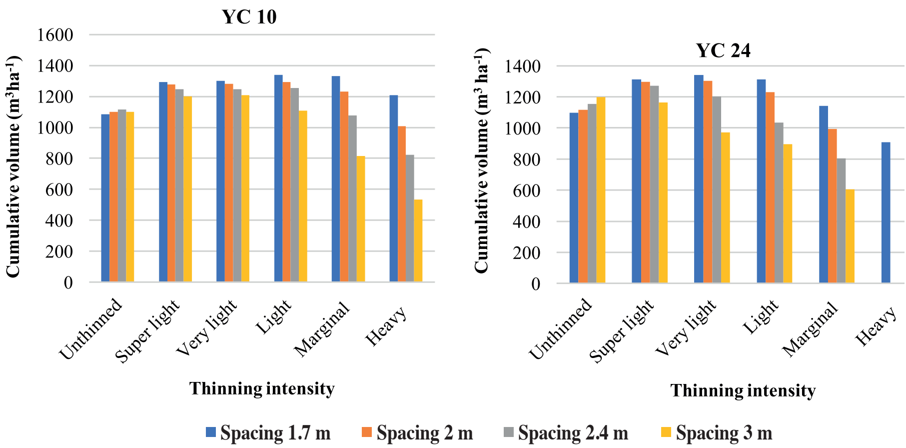

Figure 1: *The effect of different thinning intensities and planting spacings on maximum cumulative volume for yield class (YC) 10 and 24, in Sitka spruce stands. Note: where cumulative volume values are not represented in the graph it is because the Growfor simulations could not be completed (i.e. final stocking in the stand was too low or thinning yield was too high).*

Greatest revenue

The highest net annual revenue achieved in each scenario was determined according to assortment production and prices. Thinned stands were more profitable than unthinned ones as they produced higher proportions of more valuable larger timber when clearfelling and because of the contribution that early thinnings made to the present value. Stands that had been planted at wide spacings, which required lower establishment costs than higher stocking rates, produced larger timber quicker and, therefore, resulted in greater income over the rotation. No big differences were found between stands thinned at different intensities. However, in the higher YCs, the marginal and heavy thinning intensities were too severe for stands, resulting in a reduction of the timber volume production and, therefore, also a drop in the associated net discounted revenue. The stands thinned up to marginal thinning intensities generally generated higher NAEs. However, for lower YCs (for example, YC 14 and 16), the introduction of more intense thinnings resulted in the higher production of large sawlog and associated higher income, especially when the stands were planted at close spacings. The analysis indicates that it is not worth planting Sitka spruce forests on sites that cannot achieve at least YC 14; lower YCs would result in economic losses. The results indicate that the scenario which guaranteed the greatest revenue was planting at 3 m square spacing and applying very light or light thinning intensities (Figure 2).

In unthinned stands, less sawlog but higher proportions of pulp and pallet wood (which could potentially be used as energy wood) were produced. Similarly, low YCs produced more volume of smaller assortments than high YCs, and consequently less volume of larger timber.

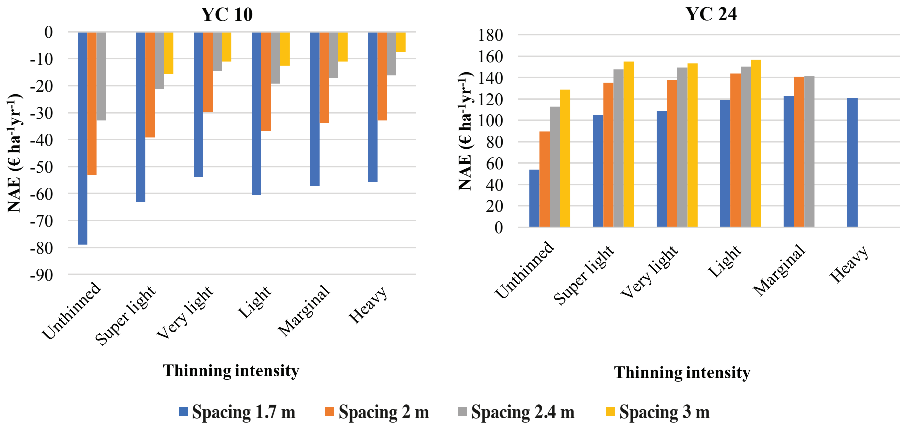

Figure 2: *Maximum NAE based on tree assortments, for Sitka spruce yield class 10 and 24, under different management scenarios. A 5% discount rate was applied.*

When residual biomass production was included in the simulations, the results showed that close spacings produced higher residual biomass volumes than wider ones (Figure 3). The overall volume production increased by about 200 m^3 ha^{-1} in unthinned stands and 300 m^3 ha^{-1} for thinned scenarios, for all YCs. However, as the biomass price per cubic metre is still very low in Ireland, its inclusion in the financial analysis results in an increase of only around €20 per year for high YC and about €10 annually for lower YCs. Although close spacings produced more volume of biomass material, wide initial spacings still resulted in greater net revenue for most of the thinning treatments and YCs, because the establishment costs were much lower for wide spacings. However, it is noticeable that the annual income for 2.4 m and 3 m square spacing was almost similar for most YCs when the stand was thinned. In higher yield classes, especially for light and heavier thinning intensities, the NAEs for 2 m square spacing was close to the net annual income when planting was at wider spacings.

Discussion

Effect of climate change on growth

According to both the NFI and CLIMADAPT outputs for the baseline scenario, Sitka spruce is currently growing at high growth rates in Ireland (YC 20 on average). However, climate change forecasts for the end of the century indicate that climate in Ireland will be marked by higher temperatures and changes in precipitation patterns (Dunne et al. 2008), resulting in significant effects on Sitka spruce growth rates. The changing climatic conditions will impact differently on Sitka spruce growth depending on the change between the old and new site characteristics, mainly on the level of water availability.

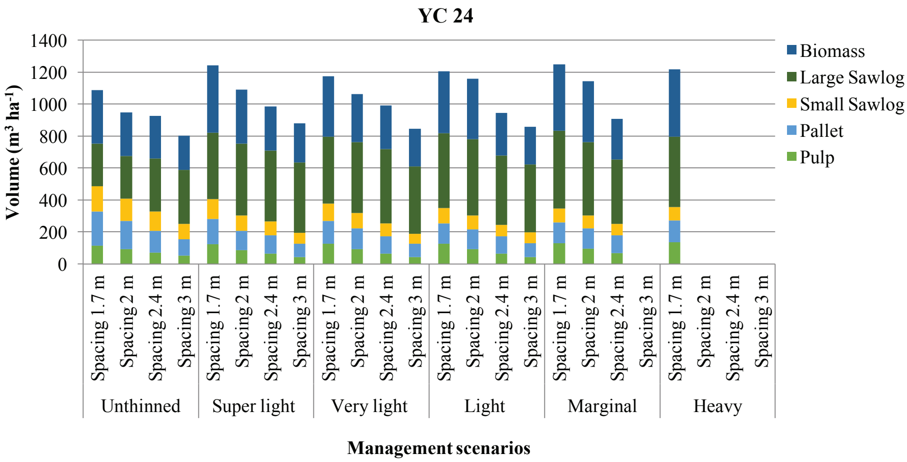

Figure 3: *Volume production per assortment, including harvest residues, over the financial rotation of YC 24 Sitka spruce stands, under different management scenarios.*

Cameron (2015) indicated that Sitka spruce requires a relatively high soil moisture status for good growth, together with an annual precipitation typically around 1,000 mm or higher. A dendroclimatological study, conducted on Sitka spruce in Avoca (Co. Wicklow), showed that large reductions in radial growth were associated with MDs above 180 mm (Tene et al. 2009). However, the maritime climate of the country and the fact that Sitka spruce has largely been confined to soils with high water storage capacity or soils with high seasonal water tables (Farrelly et al. 2009) explain why MDs have rarely been encountered in plantation forestry in Ireland. Nevertheless, extended and frequent drought periods are expected in central, southern and east-coastal parts of the country, especially in summer, increasing to more than 7 droughts per decade towards the end of the century (Dunne et al. 2008, Ray 2008). Actually, the baseline scenario indicated that Sitka spruce planted along the south-east coast is already growing at medium growth rates (YC 16 on average) because of limitations in water availability. The future increases in temperature, evapotranspiration levels and summer MD levels expected in this area will reduce its productivity by up to 6 YCs by the end of the century. This indicates that the species will no longer be suitable on sites in the southeast with freely draining soils (and high MDs). Most of the sites in the midlands and along the east coast will also be sensitive to a future drier climate and are likely to experience, but to a lesser extent than the southeast, a reduction in timber yield by 2080.

Although the increase in warmth (when moisture, nutrients or other growth factors are not limiting) is expected to positively affect forest productivity (Cannell 2002, Black et al. 2010), CLIMADAPT only predicts a slight increase or a maintenance of Sitka spruce productivity in some inland sites in the western regions. A study carried out by

Tene et al. (2009) indicated no significant relationship between temperature and Sitka spruce growth in Ireland and the UK. Therefore, the improvement in water availability in these few areas in the west seems to be a factor behind the forecasted increase in Sitka spruce yield.

Most of the areas located in the south-west, west and north-west coast of Ireland will experience a drastic decline in productivity because of the increase in moisture in the soil expected over the next number of decades. The soils located in these areas are expected to experience waterlogging conditions by the middle and end of the century. Different field studies have shown a reduction in Sitka spruce growth when growing in environments with excess water - in wet and very wet soil moisture regimes (Coutts and Philipson 1978, Farrelly et al. 2011).

The default soil characteristics in CLIMADAPT are based on a model that uses a soil map as the basis and, as a result, are only indicative. However, as this study aimed to assess general trends in the country, focusing on the average productivity class obtained in different regions, the system's default soil characteristics were considered sufficient. Nevertheless, to assess the sensitivity of the outcomes based on the default soil characteristics, the simulation was repeated using NFI soil data for the plots located in the South-East region. This additional analysis was carried out for this area not only because it was considered to be the most sensitive region to the potential impact of climate change, but also because the results obtained using the default options differed from the results found in another study (Farrelly et al. 2009) which identified higher productivity rates in this region due to more favourable soil qualities for Sitka spruce. When running the simulation using more accurate data, no big differences were found in the forecasted YC for Sitka spruce compared to those obtained using the default settings, especially in the long-term scenario. Despite the small differences in the results, to provide the most robust predictions of growth, the use of CLIMADAPT in further analysis of the impact of climate change on the productivity of the Irish forest estate should be based on field data (obtained during a site visit by identifying soil type, topography, local management practices and carrying out vegetation surveys).

The influence of other factors, such as CO_2 fertilisation, nitrogen deposition, or other secondary effects of increasing temperatures (e.g. pests and diseases and forest fire) may also affect Irish forest productivity (Ray et al. 2008). However, these factors have not been included as variables in CLIMADAPT because it is still not clear how they interact with the main climatic and soil quality variables used in the model predictions.

The warmer and drier climate that is predicted for the end of the century in Ireland may offer the possibility of extending the range of species that are currently less common in Irish plantations, especially in areas where Sitka spruce is likely not to grow sustainably at higher rates. Diversifying tree species and increasing the genetic diversity of the forests may be a strategy to cope with climate change impacts (Mason et al. 2012, Pawson et al. 2013, Cameron 2015).

Effect of forest management on timber yield and revenue

Growfor models were used to simulate the effect of different management regimes to identify the scenario that produced the greatest volume production and revenue. As the stand growth and production are determined by the models, it is important to be aware of their compatibility. First of all, the Forestry Commission yield tables and Growfor models are not based on the same dataset. In addition, the climate and typical forest treatments applied to the research plots in Ireland are not identical to those in Britain. McCullagh et al. (2013) concluded that Growfor generally forecasts significantly lower volumes than those in the Forestry Commission yield tables for different species growing in Ireland, but Sitka spruce deviated from the main trend. Gallagher (1972) showed that the volume in unthinned Irish Sitka spruce stands was greater than the figures displayed in the Forestry Commission yield tables, which supports the view that Sitka spruce volumes forecasted by Growfor were close to those predicted in the Forestry Commission tables (McCullagh et al. 2013). Broad and Lynch (2006) carried out extensive work to ensure the statistical validity of the Growfor models.

Greatest volume production

The simulations of volume production indicate that stands planted at close spacings and thinned at light to moderate intensities (60-80% of the MTI) result in the greatest volume production through the optimal utilisation of space on a site. It would not be recommendable to thin at MTI (70% of the respective YC) or at heavier intensities for any YC as this results in volume losses. This is consistent with results from a study conducted in Ireland which showed that the volume extracted when thinning Sitka spruce stands (YC 24) at the MTI was too large since the main crop that remained did not produce the maximum or even a sustainable volume increment (McCullagh et al. 2013).

Since the volume of timber removed in thinnings was fixed throughout the rotations, it may have resulted, in some cases, in a stocking reduction to a level that caused a loss of cumulative volume production. In some cases, when applying high thinning intensities in understocked stands, more volume was removed than the remaining stand could sustainably support. Such cases resulted in Growfor terminating the simulation (because of low stocking projections). In practice, the specified thinning yields are intended for use with fully stocked stands and reductions in yields are necessary for stands that are understocked (Rollinson 1988).

On the other hand, results from this study also indicate that leaving a stand unthinned would reduce the volume production through inter-tree competition and mortality. Similar results were found in a thinning intensity experiment in Sitka spruce stands (YC 24) established at Avoca forest, Co. Wicklow, which indicated that the greatest volume production was achieved when stands were thinned at a moderate intensity (55% of the MTI removed), whereas the unthinned stands accounted for the greatest reduction in volume because of the restricted growing space (Joyce and OCarroll 2002).

This analysis demonstrates a significant effect of initial spacing on the growth and volume production of stands. The overall productivity of thinned stands was lower in widely spaced stands than in closer spaced ones (with an opposite trend for unthinned stands). Producing similar results, a respacing experiment established in Baronscourt, Northern Ireland, in Sitka spruce plantations (YC 20) indicated a sharp decline in total crop volume for stocking densities lower than 1,450 stems ha^{-1}, with greatest total volume production when planting at densities between the two closest spacings (2,900 and 1,450 stems ha^{-1}) (Joyce and OCarroll 2002).

Greatest revenue

The financial analysis was based on the NPV, which represents the net costs and revenues incurred throughout the rotation, expressed in today's money. Results indicated higher financial returns when high YCs were considered, as they produced more valuable timber in shorter financial rotations (revenues discounted over shorter periods of time) than lower yield classes.

Thinned stands were more profitable than unthinned ones, as supported by several studies carried out in Ireland (Thornhill 1956, Joyce and OCarroll 2002), which show how thinned stands can produce a higher proportion of more valuable large timber when clearfelling than unthinned stands. Furthermore, thinning not only produces a periodic income starting early in a rotation, but also higher net present values, as the early thinning revenues are discounted over shorter periods of time than the clearfell revenue obtained from unthinned stands. Those stands that have been planted with wider spacings will also produce larger timber assortments quicker, reaching higher values over the rotation than those planted at close spacings. However, when the growing space available is not fully utilised, the rapid growth of trees may be offset by a loss in potential volume production, which explains why thinning at the MTI or heavier would result in lower volume production and reduced economic returns compared to lighter thinning intensities. Although the effect on timber prices due to changes in timber quality was not assessed in the analysis, it is important to keep in mind that wide planting spacing may also affect a number of intrinsic timber properties (i.e. straightness, larger branch and knot size, larger proportions of juvenile core and lower wood density, elasticity and tensile strength), which may result in lower quality timber (Simic et al. 2016, Moore et al. 2009) and a lower associated value.

When including harvest residues in the financial simulations (and not taking quality considerations into account), the stands thinned and planted at the widest spacing (3 m square) achieved the highest net revenue, even though higher harvest residue volumes were produced at the closer spacings. This is explained by the current low price associated with the biomass assortment in Ireland and by the higher establishment costs of planting at high stocking densities. Actually, when doubling and tripling the biomass price, the scenarios that resulted in greatest net revenue were planting at 2 m square spacing and by applying light or marginal thinning intensities. The commercialisation of clearfell harvest residues could become realistic in a natural regeneration scenario, where establishments costs would be greatly reduced.

Climate change and forest management

Future afforestation plans should result in new Sitka spruce forests on those sites where the species is forecasted to be suitable, producing high growth rates, considering the climate change expected to occur over the next decades.

In the previous sections, the optimal combinations of planting spacings and thinning intensities were identified for stable Sitka spruce stands. However, it may be necessary to adapt these practices to the specific site conditions to avoid timber volume and/or financial losses. For example, the prediction of stronger wind events expected for the next decades will especially affect Sitka spruce forests growing on soils with very high moisture regimes, which may render the trees unstable and susceptible to windthrow (Ray et al. 2008). Changes in forest management regimes and methods of site preparation, such as site drainage and mounding to prevent waterlogging and anaerobic conditions, have been shown to favour a stand's stability (Paterson and Mason 1999). Traditionally, no-thinning regimes were seen as a solution to increase stand stability as no gaps are created in the canopy, but as the results presented in this study indicate, stands left unthinned result in a drastic reduction in commercial volume production and in financial losses. Therefore, as suggested by other authors, stands growing on sites that present a windthrow risk should be thinned early, applying low thinnings and a short thinning cycle to provide enough growing space for the residual trees without creating major openings in the canopy (Joyce and OCarroll 2002). At the same time, close spacing also results in greater dangers of windthrow than wider spaced stands as there is more root and crown competition (Cremer et al. 1982). Equally, in regions where high MDs are forecasted for the next decades, reducing tree densities through silvicultural thinning is seen as a strategy for minimizing forest drought vulnerability as the soil moisture availability to the remaining trees of a stand is increased (D'Amato 2013) and because suppressed trees (in dense stands) become more vulnerable to damage caused by drought (Cameron 2015). A series of forest management recommendations have been developed from these considerations and are proposed as guidance for foresters on how to establish and thin Sitka spruce stands in Ireland, to either maximise volume production or revenue, under current and future climatic conditions (Table 3).

Table 3: *Forest management recommendations for Sitka spruce under current and future climate conditions, for different geographical regions in Ireland.*

Region	Time frame	Sitka spruce growth under climate change forecasts	Management recommendations
East-Coast and Midlands	Mid-term	Current high growth rates will be maintained or suffer a slight reduction by mid-century.	To maximise volume production, initial spacing of 1.7 m square and moderate to light thinnings (60-80% of MTI) on a 5-year cycle, managed on rotations of 60-65 years, should be applied. To achieve greatest revenue from the stand, initial minimum spacing of 2 m square and thinnings up to MTI for rotations of 40-45 years should be considered. Thinnings of 60% of MTI and a 3-year thinning cycle should be preferable in those stands located close to the east coast, which are exposed to higher windthrow risks.
	Long-term	Stands will continue to be productive although productivity may be considerably reduced, due to the increase in MD levels.	To reduce drought vulnerability, the reduction in tree densities through thinning (apply 80% of the MTI to get higher timber volumes or MTI to maximise the revenue) and planting at wider spacings (i.e. 2 m square spacing when the aim is to maximise timber yield, or 2.4m/3m square when maximizing profit and not taking quality into consideration) would be recommended.
South-East	Mid-term	Already growing at medium growth rates because of the presence of freely draining soils and limitations in water availability.	To ensure that more water is available for remaining trees, plantations should be thinned at the maximum thinning intensity possible without damaging the potential stand's productivity (80% of MTI) using rotations of 70-75 years, to reach the greatest volume production; or thinned to MTI and using rotations of about 50 years, to maximise profit.
	Long- term	The forecasted increase in drought episodes is likely to cause a great reduction in productivity (no longer suitable in the region).	When establishing new forest plantations, replace Sitka spruce with other species that are more drought tolerant or, when possible, to plant mixed species stands.
Western regions	Mid-term	Current high productive classes, which will be slightly reduced by mid-century.	Stands currently growing in these regions should be thinned at moderate to very light thinning intensities (60% -70% of MTI), especially on those sites with high risk of windthrow, and managed using rotations of 60-65 years if the aim is to get the greatest volume production, or 40-45 years if the aim is to maximise revenue.
	Long- term	A dramatic drop in productivity is expected (especially in the South-West), due to a large increase in soil moisture.	Stands (re)established on soils with poor drainage should be planted at wide spacings (2.4 2/3.0 m square), thinned at super light thinning intensities (60% of MTI) and thinned on a 3-year cycle, to reduce the risk of windthrow. As the YC is expected to be lower in the future, longer rotations will be necessary to maximize volume production or revenue. Intensive methods of site preparation (i.e. drainage and mounding) and/or planting other species more suitable to the new climate conditions, should be considered.
		Some inland sites where growth factors will be less limiting, may experience a maintenance of or increase in productivity.	More intensive practices, such as closer planting spacings and heavier thinning intensities (80% of MTI) may be adopted, using shorter rotations (less than 40 years to achieve maximum income).

Conclusions and management recommendations

This study revealed that the future climatic conditions in Ireland are likely to impact on Sitka spruce growth rates. The species is expected to continue to be suitable in the vast majority of the country, but its productivity levels will be significantly reduced at a national level over the course of the present century and some regions will become less favourable for its growth (i.e. the south-east of Ireland and the western regions). Therefore, even applying more intense management may not lead to increased production. It also appears that current management, based on 2 m square spacing and thinning less than MTI, is close to optimal so little gain can be made. Overall, a reduction in timber output can be expected.

This research has demonstrated that to maximise both production and revenue from stable Sitka spruce stands, foresters should apply thinning to 60 - 80% of MTI for most YCs. No thinning or thinning to MTI or heavier would result in reduced volume production. When assessing the optimal planting spacing, the overall productivity was lower in widely spaced stands than in closer spaced ones, although the financial analysis indicated higher profits, not taking changes in timber quality into consideration, when wider spacings were considered.

To adapt the Irish forest estate to climate change and to guarantee a sustainable development, forest management practices should be adapted to the new climate and soil conditions. To this end, a series of forest management recommendations have been proposed to guide foresters on how to establish and thin Sitka spruce stands in Ireland (see Table 3). The recommendations should only be used for guidance and a site visit, the use of risk assessment models and an analysis of the timber market are suggested before deciding which silvicultural practices to apply.

References

Binkley, C.S. 1997. Preserving nature through intensive plantation forestry: the case for forestland allocation with illustrations from British Columbia. *Forestry Chronical* 73: 553-559.

Black, K., Xenakis, G. and Ray, D. 2010. Climate change impacts and adaptive strategies. *Irish Forestry* 67: 66-85.

Broad, L. and Lynch, T. 2006. Growth models for Sitka spruce in Ireland. *Irish Forestry* 63: 53-79.

Cameron, A.D. 2015. Building Resilience into Sitka spruce (*Picea sitchensis* (Bong.) Carr.) forests in Scotland in response to the threat of climate change. *Forests* 6: 398-415.

Cannell, M. 2002. Impacts of climate change on forest growth. In *Climate Change: Impacts on UK Forests*. Ed. Broadmeadow, M.S.J., Forestry Commission Bulletin 125. Forestry Commission, Edinburgh, UK.

Cannon, R.J.C. 1998. The implications of predicted climate change in the UK, with emphasis on non-indigenous species. *Global Change Biology* 4: 785–796.

COFORD Roundwood Demand Group. 2011. *All Ireland Roundwood Demand Forecast 2011-2020*. COFORD, Department of Agriculture, Food and the Marine. Dublin, Ireland.

COFORD Land Availability Working group. 2016. *Land Availability for Afforestation. Exploring Opportunities for Expanding Ireland's Forest Resource*. COFORD, Department of Agriculture, Food and the Marine. Dublin, Ireland.

Coutts, M.P. and Philipson, J.J. 1978. Tolerance of Tree Roots to Waterlogging. I. Survival of Sitka Spruce and Lodgepole Pine. *New Phytologist* 80: 63-69.

Cremer, K.W., Borough, C.J., McKinnell, F.H. and Carter, P.R. 1982. Effects of stocking and thinning on wind damage in plantations. *New Zealand Journal of Forestry Science* 12: 244-268.

DAFM. 2013. *The Second National Forest Inventory - Republic of Ireland - Results*. Department of Agriculture, Food and the Marine. Dublin, Ireland.

D'Amato, A.W., Bradford, J.B., Fraver, S. and Palik, B.J. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecological Applications* 23: 1735-1742.

Dunne, S., Hanafin, J., Lynch, P., McGrath, R., Nishimura, E., Nolan, P., Venkata Ratman, P., Semmler, T., Sweeney, C., Varghese, S. and Wang, S. 2008. *Ireland in a Warmer World- Scientific Predictions of the Irish Climate in the Twenty-First Century*. Community Climate Change Consortium for Ireland (C4I). Dublin, Ireland.

Edwards, P. and Christie, J. 1981. *Yield Models for Forest Management*. Forestry Commission Booklet 48.

Farrelly, N., Ní Dhubháin, Á., Nieuwenhuis, M. and Grant, J. 2009. The distribution and productivity of Sitka spruce (*Picea sitchensis*) in Ireland in relation to site, soil and climatic factors. *Irish Forestry* 66: 51-73.

Farrelly, N., Ní Dhubháin, Á. and Nieuwenhuis, M. 2011. Modelling and mapping the potential productivity of Sitka spruce from site factors in Ireland. *Irish Forestry* 68: 23-40.

Farrelly, N. and Gallagher, G. 2015. The potential availability of land for afforestation in the Republic of Ireland. *Irish Forestry* 72: 120-138.

Fox, T.R. 2000. Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management* 138: 187-202.

Gallagher, G. 1972. Some patterns in crop structure and productivity for unthinned Sitka spruce. *Irish Forestry* 29: 33-52.

Gallagher, G. 1980. Crop structure studies in Ireland. In Growing space in coniferous crops, Supplement to *Irish Forestry*. *Irish Forestry* 37: 5-32.

Gallagher, G. (Ed). 1985. *The Influence of Spacing and Selectivity in Thinning on Stand Development, Operations and Economy*. Proceedings of the meeting of IUFRO Project Group P.4.02.02. Dublin, Ireland. 24 – 28 September 1984. Forest and Wildlife Service: 108-113.

Hummel, F.C. 1957. Yield regulation and forecasts of production. *Irish Forestry* 14: 100-107.

Joyce, P. and OCarroll, N. 2002. *Sitka Spruce in Ireland*. COFORD, Department of Agriculture, Food and the Marine. Dublin, Ireland.

Keane, T. and Collins, J.F. 2004. *Climate, Weather and Irish Agriculture*. 2nd ed. AGMET, Met Eireann, Dublin.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbatie, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J. and Marchetti, M. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management* 259: 698-709.

Local Government Act. 1991. *Regional Authorities, Establishment Order, 1993*. Dublin, Ireland.

Mason, W.L., Petr, M. and Bathgate, S. 2012. Silvicultural theories for adapting planted forests to climate change: from theory to practice. *Journal of Forest Science* 58: 265-277.

McCullagh, A., Hawkins, M., Broad, L. and Nieuwenhuis, M. 2013. A comparison of two yield forecasting methods used in Ireland. *Irish Forestry* 70: 7-17.

Moffat, A.J., Jones, W.M. and Mason, W.L. 2006. *Managing Brash on Conifer Clearfell Sites*. Forestry Commission Practice Note 13. Forestry Commission, Edinburgh.

Moore, J., Achim, A., Lyon, A., Mochan, S. and Gardiner, B. 2009. Effects of early re-spacing on the physical and mechanical properties of Sitka spruce structural timber. *Forest Ecology and Management* 258: 1174–1180.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution and Systematics* 37: 637–669.

Pawson, S.M., Brin, A., Brockerhoff, E.G., Lamb, D., Payn, T.W., Paquette, A. and Parrotta, J.A. 2013. Plantation forests, climate change and biodiversity. *Biodiversity and Conservation* 22: 1203–1227.

Paterson, D.B. and Mason, W.L. 1999. *Cultivation of Soils for Forestry*. Forestry Commission Bulletin 119. Forestry Commission, Edinburgh.

Ray, D. Xenakis, G. Semmler, T. and Black, K. 2008. The impact of climate change on forests in Ireland and some options for adaptation. In *Proc. from COFORD Conference Forestry, Carbon and Climate Change- local and international perspectives*, pp 23-34.

Ray, D., Xenakis, G., Tene, A. and Black, K. 2009. Developing a site classification system to assess the impact of climate change on species selection in Ireland. *Irish Forestry* 66: 101-122.

Sedjo, R.A. and Botkin, D. 1997. Using forest plantations to spare natural forests. *Environment* 39: 14-20.

Simic, K., Gendvilas, V., O'Reilly, C., Nieuwenhuis, M. and Harte, A. 2016. The effects of planting density on the structural timber properties of 23-year-old Irish-grown Sitka spruce. Paper presented at the Civil Engineering Research in Ireland (CERI 2016) conference. Galway, Ireland.

Tene, A., Tobin, B., Ray, D., Black, K. and Nieuwenhuis, M. 2009. Adaptability of forests species to climate change. *TRACE (Tree Rings in Archeology, Climatology and Ecology)* 8: 62-68.

Thornhill, J.J. 1956. Planting spacings. *Irish Forestry* 12: 68-70.

Tobin, B. and Nieuwenhuis, M. 2007. Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. *European Journal of Forest Research* 126: 189-196.