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# Drought risk in Scottish forests

Tom Locatelli, Kate Beauchamp, Mike Perks, Georgios Xenakis, Bruce Nicoll, James Morison, Forest Research

February 2021

DOI: https://doi.org/10.7488/era/1292

## 1 Executive summary

### 1.1 Context

Drought, as a significant risk to Scottish forests, is likely to be exacerbated by the changing climate. In light of increased drought events in recent years, we were asked to review the available evidence, and report on current drought-related research activities relevant to the forestry sector in Scotland.

This report summarises the current state of research, describes ongoing projects and identifies knowledge gaps and potential research directions. Considerations around the policy and practice implications are made, taking into account the available information.

### 1.2 Key findings

- UKCP18 projections point to increasingly drier summers and more severe and frequent droughts in the UK, including Scotland. Findings in the latest Climate Change Risk Assessment (CCRA3) are that a very dry summer like the one in 2018 will become the norm by 2050.
- There is high confidence that especially in east, central, and south Scotland the direct effects of severe droughts are likely to be felt primarily in forest productivity and carbon sequestration. Some reductions in timber quality are expected, and any gains in forest productivity driven by temperature or $CO_2$ increase can be rapidly counteracted by losses due to drought. There is limited evidence on how long adverse impacts are likely to persist following drought events.
- Large-scale tree mortality due to drought in Scotland has not yet been observed. However, several studies report severe damage to forests in Scotland, the UK and continental Europe after the 2003 and 2018 droughts, due to their intensity and duration. There is also limited evidence of mortality at establishment resulting from spring droughts.
- With extreme summer droughts becoming more common, established forests in Scotland will be exposed to intense and prolonged drought stress. This might cause extensive mortality (low confidence).

- Tree species are known to differ in their vulnerability to drought impacts. The productivity of Scots pine, Douglas fir, and Sitka spruce can be heavily impacted by severe droughts, with higher mortality in Sitka spruce than Douglas fir. Trials of different species provenances have shown that there can be as large a variation in drought susceptibility between provenances as between species.
- Drought effects are the result of the complex interplay between climate extremes, many different components of forest ecosystems and other biotic and abiotic disturbances. All these elements will be affected by climate change in ways that cannot be confidently projected, which makes predicting the interactions between them even more difficult.
- There is medium confidence that applying dendrochronology (the study of annual growth increments, or tree rings) alongside remote sensing and drought indices, such as the Standardised Precipitation Evapotranspiration Index (SPEI), could help understanding of the risk of large-scale drought impacts.

## 1.3 Policy and practice implications

- Drought impacts can, in some cases, be mitigated through management practices such as thinning, underplanting, and Continuous Cover Forestry (CCF). We found medium confidence that stands with high species diversity may be more resilient to drought impacts.
- More flexibility on the seasonal timing when new trees are planted, based on continuous monitoring of temperature and precipitation patterns and forecasts, can reduce the risk of early drought damage.
- Evidence about the complex dynamics between drought, forest ecosystems, and other disturbances is scarce, and not strong enough to delineate clear implications for policy and practice.

## 1.4 Next steps

- It is important that negative effects of drought on the carbon stocks of Scotland’s forests and on the quality and quantity of Scottish timber products are carefully monitored.
- Further research is urgently needed into the effect of drought on different species and provenances to inform the use of the most suitable plant material and silvicultural practices for critical sites in Scotland. This could underpin further investment in forest nurseries to support healthy, vigorous, and drought-resilient seedlings.
- Additional research and guidance for Sitka spruce on drought-prone soils and sites, especially in the Scottish regions at the highest risk of severe droughts, would be beneficial to sustain timber productivity.
- We found a need for data collection to inform management practices. We recommend an ‘extensive’ approach based on dendrochronology surveys across existing networks of forested plots to assess prior response to climate, along with more frequent remote sensing data acquisition (especially from airborne LiDAR) over Scottish forests. This will bring the additional benefit of better understanding other environmental risks to Scottish forests.

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# 2 Glossary

| | |
|---|---|
| Accumulated Temperature | the difference between mean temperature and a reference value (typically 5ºC), summated over the course of a year. It is routinely used in forestry and agriculture as a predictor of crop growth |
| Adaptive Capacity | in this context, the ability of forested ecosystems, and institutions responsible for their management, to adjust to potential damage, take advantage of opportunities, and respond to consequences |
| CCF (Continuous Cover Forestry) | a compendium of sustainable forest management practices whereby stands with complex vertical structures and multiple species are promoted |
| Crown dieback | the dying back of branches and branch tips, often an indication of environmental stress |
| Dendrochronology | suite of techniques for dating tree growth rings and identifying growth patterns and trends during the lifetime of a tree. Non-destructive sampling is performed by extracting thin (0.5 - 1cm) cores from the stem |
| ESC (Ecological Site Classification) | Forest Research's decision support system to support species selection based on site characteristics and local climate conditions |
| Indurated soil | a heavily compacted soil horizon that limits rooting depth and impedes drainage, often causing higher water tables. Also called hardpan |
| LiDAR – Light Detection And Ranging | a remote sensing method used to quickly and efficiently capture large amount of data about the different surfaces of the Earth. The technology has become very popular in forestry because of the possibility of correlating canopy imaging with stress levels |
| Lock-in | irreversible state of a system caused by delay or failure to implement early adaptation actions before impacts actually occur. Consequences of lock-in are increased damage from climate change, and higher opportunity and repair costs such as loss of ecosystem services, premature harvesting, and replanting |
| Maladaptation | actions that may lead forests to experience increased risk of climate-related damage, increased vulnerability to climate change, now or in the future |
| Pole stage | the developmental stage of trees between sapling and maturity. Trees at this level of development often resemble poles |
| RAPM - Risk Adjusted Performance Measurement | risk-induced reductions in productivity (Yield Class) |

| | |
|---|---|
| RCP8.5 | see UKCP09 High Emission Scenario (A1F1) |
| Scopus | a popular abstract and citation database used for literature searches |
| SMD – Soil Moisture Deficit | a measure of soil water scarcity, defined as the difference between the amount of water in the soil and the maximum water capacity of the soil |
| SPEI - Standardised Precipitation Evapotranspiration Index | a widely used drought index, that provides a measure of the effect of increased temperatures on water demand by combining information on precipitation and evapotranspiration – that is, the combined evaporation of water from the land's surface, and the metabolic transpiration of vegetation |
| UKCP09 – UK Climate Projections 2009 | a set of climate projections for the UK published in 2009 by the United Climate Impacts Programme and Defra. Recently superseded by UKCP18 |
| UKCP09 High Emission Scenario (A1F1) | the high emissions scenario of the IPCC used in UKCP09 alongside the low and medium emission scenarios. It is the most similar to the RCP8.5 emission scenario, where greenhouse gas emissions continue to grow unmitigated. Both the A1F1 and the RCP8.5 are regarded as worst-case scenarios, but do not specifically look at climate extremes |
| UKCP18 – UK Climate Projections 2018 | the most recent set of climate projections released by the Met Office Hadley Centre Climate Programme |
| YC – Yield Class | the maximum achievable average rate of annual volume increment in a forest stand (measured in $m^3$/ha/year). It depends on site characteristics and silvicultural practices |

# 3 Introduction

## 3.1 Scope of this report

This document describes the current state of research on drought impacts on Scottish forests, describing recent and ongoing projects and their findings, and identifying knowledge gaps and potential research directions. These findings and recommendations are described within the context of relevant and recent trends of drought-related research at UK, European, and global levels.

## 3.2 Background & sources of information

Drought in Scottish forests has been identified as a significant risk that is expected to be exacerbated by a changing climate. Recent research has examined the evidence for this growing risk, including a paper by Davies *et al.* [1], titled “Drought risk to timber production – A risk versus return comparison of commercial conifer species in Scotland”, that was published in August 2020. In light of the increased occurrence of episodes of drought in recent years, and their impacts on Scottish and UK forests, Scottish Forestry commissioned Forest Research through ClimateXChange to review the available evidence, and report on the recent and current drought-related research activities relevant to the forestry sector in Scotland.

This report is based on an extensive literature review complemented with content from semi-structured interviews with Forest Research scientists involved in drought-related research. The complex nature of the topic and the compound effects of drought and other biotic and abiotic disturbances are reflected in the many specialist forest disciplines that this report draws from. Because of the difficulty of addressing drought impacts in isolation, silvicultural measures intended to reduce risk of drought damage are often the same as forest adaptation measures aimed at wider resilience. Further details of our approach are set out in Appendix 1.

# 4 Current state of knowledge relevant to Scotland’s forests

Large-scale tree mortality due to drought in Scotland has not yet been observed in Scottish forests (either pole stage or mature trees). Consequently, the number of published studies on drought impacts on Scottish forests is very limited. In this section, the few published studies will be used as examples around which we discuss the state of knowledge on relevant drought impacts in Scotland, drawing from studies from the broader UK, Europe, and temperate North America.

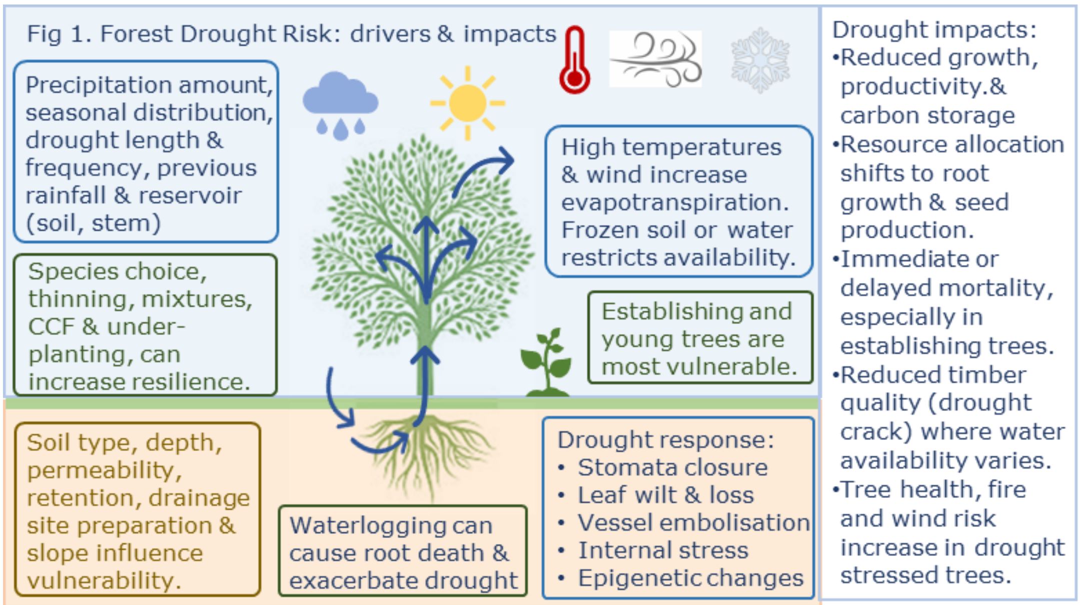
When relevant, the information reported in this section will be accompanied by the associated, colour-coded level of confidence (High – Medium – Low) in square brackets at the end of each statement/paragraph.

## 4.1 Definitions of ‘drought’, impacts and tree responses

Defining drought in a forestry context is not straightforward as it depends on several issues.

1. Scale aspects characterise levels of drought damage: from cells, to tissues, organs, individual trees, whole stand and soil strata, to complex landscapes [2, 3] ***[HIGH]***.
2. Different drought characteristics need to be considered: severity, duration, frequency (inter and intra annual), and timing in relation to tree phenology and physiology [4, 5, 6] ***[HIGH]***.
3. Different species exhibit different vulnerabilities to drought impacts [7], and different 'coping strategies' which can be grouped in two categories [8]: drought-avoidance and drought tolerance ***[HIGH]***.

The drivers and impacts of drought are summarised in Figure 1.




Damage levels can vary greatly, from foliage discoloration or loss of foliage, to partial crown dieback. Short-term and legacy drops in productivity and carbon uptake have been observed, as have timber defects (cracks and fungal staining). Extreme and prolonged droughts can eventually cause mortality – either immediate to delayed – at local and landscape scales [9, 10, 11, 12, 13] ***[HIGH]***. Critically, ascribing any of these types of damage to drought is particularly difficult due to frequent interactions with other disturbances and stressors: pests and disease, wind, fire, and climate change [12, 14, 15, 16, 17] ***[HIGH]***.

From a climatic perspective, different 'drought indices' have been used to characterise drought conditions in forest ecosystems and are commonly found in the literature [18]. Among these indices, the Standardised Precipitation Evapotranspiration Index (SPEI, [19]) has gained popularity [20] because of its relative simplicity and sensitivity to climate change ***[HIGH]***.

The frequency of severe droughts (and the patterns of temperature and precipitation between these events which may or may not enable recovery) are key in determining the extent, severity, and persistence of impacts on trees and forests. Trees have a degree of resilience that allows them to react to disturbances such as drought. The level of drought resilience and adaptive capacity depends on tree species, site conditions (soil nutrient and water holding capacity, exposure, slope), silvicultural treatments (stand structure, thinnings), and exposure to previous climatic conditions. When available, trees mobilise stored resources in response to drought to repair damaged organs (e.g. water conducting and root systems) and may partially compensate for drought-induced reductions in growth as shown by Ovenden *et al.* [21] for Scots pine grown in Scotland. When trees are exposed to closely repeated severe droughts, these resources can rapidly become depleted, causing a decrease in trees' adaptive capacity and resulting in 'legacy effects' [22] such as lasting damage to timber and productivity, and ultimately causing early mortality [3] ***[MEDIUM]***.

Results from the first assessment of the large species and provenance trials of the REINFFORCE [1] European consortium across a long Atlantic seaboard transect confirm the vulnerability of young trees (4-year old) to drought. Correia *et al.* [23] report that mortality in the broadleaves was driven by the size of the difference between precipitation in the native and non-native ranges, while conifer survival was affected by elevated accumulated temperature. For broadleaved species, this suggests that precipitation levels in the region of the source seed material need to be carefully compared with those of the intended planting location. For conifers it is important to ensure that the differences in temperature and the length of the growing season between the source and target locations are kept to a minimum. This study identified a strong negative correlation between tree height and a drought index derived from accumulated temperature and precipitation. Conifers were more heavily impacted than broadleaves, despite the latter being more susceptible to unfavourable soil properties than conifers ***[LOW]***.

## 4.2 Co-stressors & disturbances

Drought impacts on trees and forests are often compounded by other disturbances (biotic and abiotic). The most reported interactions in the literature are with pests and diseases ***[HIGH]***. This can be seen as counterintuitive for fungal infections since moisture is essential for the germination of, and infection by, fungal spores. However, except for extreme cases of severe droughts, the flexibility of pathogens to reductions in water availability in plant tissues is typically superior to that of trees, which can result in more severe infections under moderate drought stress as seen in young Norway spruce [24]. The mechanisms of drought-pathogen interactions can be quite complex, ranging from direct and indirect effects of drought on pathogens, or mediated through the physiology of the host trees.

Drought can increase a tree's susceptibility to biotic attacks, or pathogens, as well as being a simultaneous stressor on trees [15]. Green and Ray [25] proposed a theoretical assessment of the compound risk of drought and disease on Scottish forests. They suggested that the frequency and severity of diseases caused by *Armillaria* spp. and *Heterobasidion annosum* is likely to increase on vulnerable tree hosts growing in drought-prone regions in Scotland with increased droughts ***[MEDIUM]***, based on the fact that pathogens are often already present in a non-harmful form on tree hosts, and that the compound effect of another stressor such as drought triggers the pathology ***[HIGH]***. *Armillaria* are ubiquitous in Scotland and may cause decay of the root system of a wide range of conifers and many broadleaves. *H. annosum* is equally widespread and can cause root and butt rot in many conifer species including Sitka spruce, Norway spruce and Scots pine. Drought can also increase the vulnerability of trees to insect attacks, as seen in Scots pine and Larch with their associated bark beetle species [26, 27].

[1] REINFFORCE - Resource INFrastructures for monitoring, adapting and protecting European Atlantic FORests under Changing climatE - https://efi.int/projects/reinfforce-resource-infrastructures-monitoring-adapting-and-protecting-european-atlantic

## 4.3 Drought damage in Scotland

Multiple studies report particularly severe damage to forests in Scotland, the UK and Europe after the 2003 drought because of its intensity and duration ***[HIGH]***. Green *et al.* [10] report that the exceptional drought of 2003 had caused mortality to as much as 22% of trees in plots of pole stage Sitka spruce located in Deeside. Nearby Douglas fir plots showed considerably less damage. Younger Sitka spruce plantations in the area were undamaged, suggesting that established early rotation Sitka trees may be more resilient than older trees. Damage was largely on indurated soils which are known to have lower water availability during dry spells and are prone to waterlogging in wet periods; sustained and frequent winter waterlogging can kill fine roots and limit their vertical development, thus leaving trees maladapted in drought conditions [7, 28] ***[MEDIUM]***.

The Douglas fir plots described by Green *et al.* [10] were found to be largely unaffected, especially when compared to Sitka spruce. This suggested that this species may be less vulnerable to drought impacts in Scotland. Growth patterns of Douglas fir in its natural range are largely controlled by water and nutrient availability [29]. Evidence from the 2003 drought in France shows that whole tree mortality in Douglas fir stands was uncommon and localised to areas with unfavourable soils (low nutrients, high drainage), while less severe modes of damage (e.g. defoliation and limited crown dieback), and a substantial decrease in growth rate (~30%) were more common and widespread [30] ***[MEDIUM]***.

Significant mortality may occur at establishment, as recently seen in a large Sitka spruce plantation in Galloway, where up to 50,000 seedlings were lost to an unexpected hot spring that had resulted in very dry soils. Extensive replanting may be needed if a severe drought were to affect a recently restocked site, as was the case of for Sitka spruce plantations in Harwood forest, Northumberland, described by Xenakis *et al.* [13]. Similar impacts have been reported by private sector forest managers after both 2018 and 2020 droughts for both restocked sites and newly planted seedlings. ***[MEDIUM]***.

## 4.4 Climate projections & future impacts

In the recently published “Independent Assessment of UK Climate Risk” advising the UK Government on the outcomes of the UK’s third Climate Change Risk Assessment (CCRA3) [31], four key messages resonate strongly with the forestry sector and fittingly apply to drought risk. Firstly, adaptation measures for the level of drought impacts expected with a 2°C mean temperature increase need to be integrated into policy, and risks for a 4°C future need assessed. Secondly, the risk of maladaptation leading to ‘lock-in’[2] is high and needs to be avoided with early adaptation practices that consider long-term drought risks. Thirdly, adaptation measures to mitigate drought damage need to allow the forestry sector in Scotland to prepare for unpredictable extremes. Lastly, tipping points need to be identified for drought risk, and adaptive measures designed and implemented to reduce the risk of lasting and severe damage, and of adverse consequences of lock-in.

Climate change models indicate that the frequency of severe droughts is likely to rise in the future with increasing impacts on forests [4, 32] ***[MEDIUM]***. The role of climate and soil properties on the likelihood and severity of drought impacts on forests can help

[2] Example of lock-in for the forestry sector: Selecting tree species that are mismatched with future climatic conditions in a given site, or the wrong design of forest management interventions can cause maladaptation at different stages through the life-cycle of a forest stand. This loss of resilience is likely to result in higher losses and incur in opportunity and repair costs due to adverse climate impacts (e.g. recurrent, intense droughts).

identify locations in Scotland where the most damaging drought consequences can be expected. Using baseline climate and climate projections available at the time [3] and data on soil drought potential [4], Green and Ray [25] identified forests in the east of Scotland as the most vulnerable to drought impacts. Subsequent work by Petr *et al.* [33] using UKCP09 data extended these areas to include central and south Scotland to the list of regions with highest drought impact potential ***[MEDIUM]***.

The natural range of Sitka spruce is restricted to a humid and oceanic climate with high precipitation (1,000 – 3,000mm/year). Current planting guidelines for Sitka in Scotland indicate that the species is expected to perform well in areas with annual precipitation above 1,000mm, although it is known to perform adequately on some sites as low as 700 to 800mm – provided that sufficient soil water is available. That is, in the absence of sustained and severe soil moisture deficit (SMD), Sitka spruce can be expected to have good productivity as reported by Davies *et al.* [1]. ESC assessments indicate that Sitka spruce is intolerant of SMD larger than 180mm [34] ***[HIGH]***. In North Deeside in the summer of 2003, SMD exceeded this threshold for four consecutive months [10], causing the substantial damage to Sitka spruce described in the previous section.

Recently planted and establishing stands are more vulnerable to drought impacts. However, widespread forest dieback caused by drought alone is believed to be unlikely in established forests in the near future. In Scotland, direct effects of severe droughts are likely to be felt primarily on forest productivity. Ovenden *et al.* [21] report a substantial reduction in radial stem growth of Scots pine in Scotland for a period of approximately 5 years after a drought event. Similarly, in their study of the effects of the severe 2018 drought on Sitka spruce plantations in Harwood, Xenakis *et al.* [13] show that sustained droughts can substantially impact stand productivity ***[HIGH]*** and cause mortality to seedlings ***[MEDIUM]***. Effects of severe drought on the productivity and strength of the carbon sink of European forests (including Nordic countries) have been reported with increased frequency, regardless of their average climate conditions. These studies confirm that the gains in productivity due to increased temperatures and atmospheric $CO_2$ concentrations can be quickly offset, and even reversed in severe cases, by long and hot droughts [3, 6,11] ***[HIGH]***, with differences in drought resilience between species being more evident in some cases (e.g. [35]) ***[MEDIUM]***.

## 4.5 Forest management and adaptive practice

Drought impacts may, in some cases, be mitigated with silvicultural practices such as thinning, underplanting, and Continuous Cover Forestry (CCF). Recommending the most appropriate silviculture is not straightforward as local site conditions and management history (e.g. thinning intensity) need to be considered ***[MEDIUM]***. Thinning can allow more precipitation to reach the soil thus increasing soil water availability [36] and reduce competition between trees in a stand [37]. This potentially allows for the development of larger root systems which may increase future resilience to drought [38]. However, thinning may also promote the growth of ground vegetation and thus competition for soil water; more ground vegetation growth also increases the risk of wildfire spread. In some cases, thinning the overstorey can increase air temperature and reduce humidity at canopy level, which may increase tree water loss [38].

It should be noted that silvicultural studies in the UK have mostly focussed on general resilience and impacts on forests' adaptive capacity, rather than on drought alone, which makes drought-centred considerations difficult. Recent evidence suggests that forests with high structural and species diversity are more resilient and better adapted to climate

[3] From UKCP02
[4] Derived from soil drainage capacity and presence or absence of induration

change impacts [39, 40]. Silvicultural strategies such as underplanting (planting seedlings of shade-tolerant species such as western hemlock, Douglas fir, and western red cedar, in an established stand with sufficient space and an established overstorey) and CCF can increase forest diversity and are often cost-effective ways of maintaining stock levels on a site. The additional structural complexity provided by these practices can have positive effects on drought resilience, often via mechanisms completely opposite to those of thinning, i.e. reducing air temperatures and wind speed, and increasing humidity in the multi-storey stand structure [41], improving forest adaptation. Sheltered conditions can favour seedling establishment in extreme weather events including droughts [42] ***[MEDIUM]***.

Increasing species diversity in a stand can also benefit from using a financial risk management approach as done by Davies *et al.* [1] with RAPM. Stands with high species diversity may be more resilient to drought impacts, especially when species are selected based on their physical characteristics and susceptibility to drought, therefore increasing adaptation by reducing risk in an approach similar to financial hedging [5] [43] ***[MEDIUM]***. The upcoming UK Climate Change Adaptation Practice Guide produced by Forest Research summarises these adaptive practices and puts their effectiveness in the context of other risks to forestry operations.

# 5 Knowledge gaps, on-going and future research

As shown in the previous section, only a handful of studies have focussed specifically on drought impacts on Scottish forests, concentrating on the severe droughts of 2003 and 2018. The upland Sitka spruce forests in Harwood are representative of typical forestry in Scotland (Argyle would be the analogue region in terms of climate, soils, and silviculture), but not of Scottish regions where drought impacts on forests are expected to increase in severity [33, 44] ***[MEDIUM]***. Similarly, while the findings of current experiments of controlled soil drought and waterlogging on oak in south England [6] will improve our understanding of compound impacts of precipitation extremes on forests, their immediate transferability to forestry in Scotland is likely to be limited ***[LOW]***.

The only recent study on drought impacts on the decline of productivity in Scottish forests after the 2018 drought [21] indicates that drought impacts on commercial forests in Scotland may follow similar trends to those observed in central and north European countries after the severe drought of 2018 [3, 6, 11] ***[LOW]***. The complexity of drought impacts on trees and stands, and the vulnerability of different species are confounded by the fact that published studies rarely monitor tree and stand health and vitality for extended periods of time. The application of dendrochronology to investigate legacy effects of past droughts has recently increased [17, 18, 21, 30] and has shown good potential to inform drought risk forecasting and modelling. Dendrochronology studies on Scottish forests are however very limited in numbers and mostly focus on conifer species. The application of dendrochronology alongside remote sensing (e.g. LiDAR) and drought indices such as SPEI can identify tipping points of tree mortality and provide information on a range of different environmental risks and climate change impacts [18] ***[LOW]***.

Beside the moderate mortality of older Sitka spruce trees reported by Green *et al.* [10], the 2003 drought may have promoted the occurrence of round wood defects (sometimes referred to as drought cracks). Forest Research, in partnership with Edinburgh Napier

[5] For instance, when newly-planted stands include species that are expected to flourish under very different future climatic conditions, and species that are known to grow well in the current climate
[6] As part of the PuRpOsE project - https://www.forestresearch.gov.uk/research/protect-oak-ecosystems-purpose/

University and the University of Aberdeen, are investigating the emergence of these defects in Sitka spruce plantations. Cameron *et al.* [45] report on the extent and severity of stem cracks in pole stage Sitka spruce, noble fir, and grand fir grown in north east Scotland, the latter species being most affected. The authors ascribe the cracks to the 2003 drought and suggest a compound effect with wind action on the stems ***[LOW]***. Exploratory work at Forest Research investigating the relationship between the occurrence of drought cracks and a derivation of SPEI reports similar propensity of firs and spruces to form drought cracks, with firs tending to develop discrete, annual small cracks, while spruces are more prone to more extensive, lengthwise cracks ***[LOW]***.

As described previously, there is some evidence that Douglas fir shows drought resistance. A further study of mature Douglas fir stands [46] identified that high wood density and high late-wood to early-wood ratio are associated with lower likelihood of drought-induced mortality in affected stands. These relationships suggest that these traits are correlated with resistance to drought ***[LOW]***, but the mechanisms involved remain poorly understood. Similar relationships between wood density and vulnerability to drought impacts have been reported for Norway spruce [47]. These findings may be relevant to the timber sector both for forest management (e.g. aiding identification of retained trees during thinning operations) and sawmill operations.

The extensive network of existing field experiments in Scotland and across the UK may provide useful information on drought impacts to Scottish forests. Analyses of Forest Research's extensive datasets from Long-Term Experiments, Operational Species Trials, and an ongoing project to assess the establishment success of emerging species across Scotland, may provide useful information on susceptibility to drought stress. However, none of these experiments have a specific focus on drought, but rather focus more generally on resilience and forests' adaptive capacity, and often derive species suitability assessments from ESC which does not capture the dynamic intra-annual influence of droughts. Isolating the effectiveness of silvicultural practices such as thinning, underplanting, and CCF on drought impacts is therefore currently difficult.

To allow forest managers to make informed decisions about implementing drought-reducing silvicultural practices, the forecasts of drought-related risks to growth and productivity of Scottish forests estimated by Petr *et al*. [33] and adopted by Davies *et al*. [1] will require higher spatial resolutions, and a better representation of the fundamental interactions between forest stands, soils, and climate.

Forest Research will remain involved in the REINFFORCE experiment to observe and compare survival and productivity of a range of broadleaf and conifer species along the Atlantic coast of European countries. Monitoring whether drought remains a significant driver of reduced growth and increased mortality in these experimental plots beyond the juvenile stage will supply much needed data on the vulnerability of early tree developmental stages. Climate data and dendrochronology data would allow matching any drought event to changed patterns in tree growth and development. However, a potential constraint lies in the location of plots on the west coast which is a lower risk area ***[LOW]***.

## 5.1 Next steps

The low confidence associated with the findings reported above suggests a strong need for improved datasets. These data will contribute to informing forest management decisions for resilient Scottish forests, and to fine-tune climate-responsive models of growth to predict impacts of future drought, utilising probabilistic climate projections data (e.g. UKCP18). Two approaches can be suggested to meet these large data requirements. One approach (the 'intensive approach') would be to introduce a strong drought focus in existing and new networks of continuous monitoring and experimental studies of drought impacts on Scottish forests. An alternative 'extensive' approach would be to use dendrochronology across existing networks of forested plots to assess prior response to climate.

The extensive dendrochronology-based approach may be supplemented with 'extreme' drought experiments (e.g. greenhouse or designed multi-site experiments, and investigating the use of gels / biochar to aid water retention / availability) and targeted application in mature stand phase to look at the drivers of growth reduction and mortality. Because the costs of this latter type of field experimentation – of droughting a forest and measuring its response – are high and the value of the data would be 'specific' to the site and trees within the manipulation, it may be sensible to focus on Sitka spruce as the primary commercial species in Scotland. These experiments would provide data on Sitka spruce's drought tolerance and would enhance vulnerability mapping of Sitka spruce to drought. The experimental plots could then undergo a Phase II to explore the effect of interventions (e.g. thinning) in more detail.

The geographical distribution of drought risk regions in Scotland that were identified with UKCP09 data [33] has been largely confirmed by the recent UKCP18 project [44] ***[MEDIUM]***. However, recent evaluation of extreme climate scenarios (H++, [48]) indicate that future conditions may be more severe than the UKCP09 worst case scenario used in Davies *et al.* [1] ***[LOW]***.

Drought events remain difficult to forecast; this suggests that a probabilistic framework combined with process-based modelling of stand productivity and vulnerability to drought is required to improve our ability to support the forestry sector with growth and risk forecasts. Although some advice and general projections are available on climate change risks (e.g. [33, 49]), the limited scientific evidence and high and unquantified uncertainty around outcomes restricts the practical decisions that forest planners and managers feel confident in implementing [50]. UKCP18 climate data are probabilistic, so lend themselves to statistical assessments of uncertainty in future projections of forest response to environmental change. These approaches allow tailoring risk metrics at the stand to regional scale to inform planning and decision-making and for comparing management options over future rotations. The present FR/UKCEH NERC-funded PRAFOR project [7] combines novel risk assessment methods [51, 52] with process-based modelling of forest growth using the latest UKCP18 climate projections to predict drought risk, deriving information on tree and stand climate response from dendrochronology and greenhouse gases flux studies. The proposed analysis and incorporation of outcomes into the FR decision support platform (e.g. ESC) will provide improved spatial and temporal patterns of drought-driven growth reductions for two principal Scottish conifer species (Sitka spruce and Scots pine).

The PRAFOR approach will represent an advance on the work of Davies *et al.* [1] improving quantification of the level of risk in terms of hazard and exposure at much improved spatial (1km$^2$) and temporal (monthly) scales, enabling intra and inter-annual impacts to be represented ***[HIGH]***. Additional advantages of process modelling such as that employed in PRAFOR are that, by dynamically interacting with climate and soil, management interventions postulated to improve stand-level resilience (e.g. thinning, species mixtures) can be tested ***[MEDIUM]***. This will encompass the likelihood of legacy impacts of drought on tree and stand-level performance, as evidenced from tree ring studies (e.g. [21]).

Compound drought effects are the result of complex interplay between climate extremes, components of forest ecosystems (e.g. soils and trees) and abiotic and biotic

[7] PRAFOR - Probabilistic drought Risk Analysis for FORested landscapes - https://landscapedecisions.org/prafor-probabilistic-drought-risk-analysis-for-forested-landscapes/

disturbances. All these elements will be affected by climate change in ways that cannot be confidently projected to follow linear trends, which makes predicting the interactions between them even more difficult. Investigations into the effect of alternate precipitation extremes (cycles of very dry and very wet years) are increasing. Serra-Maluquer *et al.* [17] report that drought-stunted trees can recuperate growth losses during years with higher precipitation. However, they might "overshoot" and thus become more vulnerable to the next period of intense droughts [8] ***[MEDIUM]***. Additionally, a succession of very wet winters may inhibit root development, hindering drought resilience potential in subsequent dry summers. ***[LOW]***

# 6 Conclusions

The most likely drought impacts for forests in Scotland are reduced productivity and carbon sequestration in east, central and south Scotland, reduced timber quality of Sitka spruce on drought prone sites, and mortality in very young, establishing stands in drought years. Further modelling of drought risk using probabilistic UKCP18 climate data and high emissions climate scenarios will help understand drought risks to productivity and inform decision making. Additional research into roundwood defects is underway, and further research and guidance for Sitka spruce on drought prone soils and sites would be beneficial.

There is a need to further explore and document the experiences of forest managers who have experienced drought-induced mortality in establishing stands, in order to obtain a better understanding of the extent of the issue, and to assess which adaptive measures are being trialled.

Improving understanding amongst forest managers of spring drought risk could help prevent maladaptation, and encourage managers to explore the trade-offs of autumn planting on sites that are at low risk of autumn frost. This could help with the establishment of drought-vulnerable seedlings, for example on sites with low deer-browsing pressure which can be an issue in the winter following autumn planting. Further research into whether any beneficial impacts exist of exposing seedlings to early drought would be useful.

When implemented successfully, CCF and underplanting can increase drought resilience in establishing stands. Building knowledge on the principles of drought vulnerability and the complex factors driving drought risk on vulnerable sites needs to be coupled with forest managers' first-hand experience of local conditions and the history of a site. This combined approach can help forest managers avoid lock-in by assessing the suitability of the type, timing and extent of adaptive silvicultural practices. Existing tools (e.g. ESC, Climate Matching Tool) and guidance can support forest managers' decisions, but do require to be updated with much-needed information on drought impacts. For instance, for silvicultural treatments to be most effective, further research is needed into the effect of drought on different species and provenances to inform the use of the most suitable plant material for critical sites.

Despite the confirmation that central, south, and east Scotland remain the regions at higher drought risk, there are indications that the frequency and severity of extreme climatic events may increase further in the upcoming decades. These concerns together with the inherent difficulty in forecasting drought events, suggest that the further development and application of a probabilistic risk assessment framework would be useful to support the Scottish forestry sector. The development and support of research aimed at updating the widely used ESC decision support system to incorporate sensitivity to climate extremes such as drought would benefit greatly the public and private forest sectors in Scotland.

The complexity of drought impacts due to species differences, compound effects with other disturbances and stressors, and the often-delayed impacts observed in Scottish and European forests, indicate that studies covering extended periods of time are necessary to assess drought risk. Dendrochronology methods are routinely used to investigate the effect of disturbances over the lifespan of a tree and often can be performed non-destructively on standing trees. Their recent use in a study on drought impacts on a Scots pine forest in Scotland has shown promising results that would need to be corroborated by further research on different species. Dendrochronology has good potential to be used in conjunction with modelling studies to forecast drought risk in Scottish forests.

Bringing together a dendrochronology approach with climate data and risk modelling to assess and forecast risk to large, forested areas is likely to require the use of remote sensing techniques such as airborne LiDAR. These tools can generate large amounts of data and are cost-effective in providing periodical monitoring of forest health status; they are highly flexible and applicable across a multitude of risks to forests (e.g. of drought, pests and disease, and wind). These features suggest that it would be beneficial to the Scottish forestry sector if airborne LiDAR coverage of Scottish forests was available at regular intervals to assess environmental risks and climate change impacts at a large scale, and at high resolution.

Forestry is a sector for which the timescale between initial investments and returns (e.g. timber production) is inherently very long [54]. This poses two major risks to any new forestry project: (a) the risk of ‘locking-in’ with unsuccessful practices (e.g. species and site selection, forest management decisions); (b) the risk to the permanence of products and services (e.g. carbon sequestration) that can be exacerbated by maladaptation to an uncertain climate, and by climate extremes whose timing is very hard to predict. Coupled with the large uncertainty due to the scarcity of available information from drought-specific studies in Scotland, it is very difficult to suggest specific approaches to improve practice and policy. However, increasing forest managers’ familiarity with the general principles of drought vulnerability will be essential, together with a good understanding of specific site conditions and their relevance to drought damage.

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# Appendix 1

The report first summarises the Davies *et al.* [1] article, to provide necessary context. It then describes the methodology adopted in this report. This is followed by a description of the current state of knowledge on drought impacts to forests in relation to a changing climate and the potential to mitigate impacts through silviculture – including the susceptibility of different tree species and the suitability of management approaches. This is complemented by a discussion of the identified gaps in current knowledge, and the research activities that Forest Research is undertaking to address some of these. Other important areas of drought-related research are recommended where they are relevant to forestry policy and the future of Scotland's forests.

## Methodology

### Davies *et al.* (2020) paper

Davies *et al.* [1] adopt a financial tool for risk management (Risk Adjusted Performance Measurement, RAPM) to isolate and quantify the risk of drought-induced reductions in productivity for twenty commercial conifer species in Scotland. Productivity is expressed as Yield Class (YC), i.e. the maximum achievable average rate of annual volume increment in a forest stand, dependent on-site characteristics and management practices [52]. Average soil moisture deficits for representative lowland and upland areas were used in Forest Research's Ecological Site Classification model (ESC, [33]) to calculate average YC values for the different species in a 100 $km^2$ grid covering Scotland's public forest estate. From this the productivity of the different species throughout a typical 50-year rotation of commercial conifers in Scotland was estimated using Forest Research's ForestYield model [52]. Future climate conditions were derived from UKCP09 data for the high emissions scenario (A1F1) using the approach of Petr *et al.* [32].

One of the key conclusions of the paper is that Sitka spruce, because of its considerably greater YC potential, is still projected to provide higher yields and return on investment than other commercial conifer species for the next few years, despite its higher sensitivity to drought. This is the case even in regions where drought conditions are expected to increase in severity (i.e. central, eastern, and southern Scotland). The paper also identifies alternative conifer species that are expected to have comparable – although lower – productivity with that of Sitka spruce in regions with the highest forecasted drought risk, typically firs (Douglas and noble), western hemlock, coastal redwood and in some cases Norway spruce. Some of the limitations in the paper's methodology need to be understood in assessing the conclusions. Primary issues are spatial (100 $km^2$ grid) and temporal resolution (decadal reporting) and related issues of the use of yield models for predictions that are based on an outdated climate envelope and future growth predictions which have limitations in terms of climate sensitivity. Importantly, the paper does not consider climate change impacts on soil properties and presents regional scale estimates accounting for temperature and moisture limits on growth.

### Literature review and interviews

This report is based on a rapid review of the available evidence on drought impacts on Scotland's forests. We drew on findings from two approaches: a search of peer-reviewed literature, and semi-structured interviews with researchers across Forest Research.

Two searches of scientific literature and other evidence-based reports were undertaken on Scopus in December 2020. The first using search terms: (Drought AND Scotland) OR (Drought AND Scottish), and the second using search terms: (Drought AND forest*) OR

(Drought AND tree*). The first search yielded 146 publications, of which 12 were directly relevant to Scotland, and 10 were forestry related. Small numbers of articles focussed primarily on past or future climate (5), on peatland and forestry (3), and agricultural crops with some relevance to forestry (2). Only one study investigated drought impacts on soils with relevance to forestry.

As expected, the second search yielded many more results, with a total of 20,723 publications. The recent steep increase in popularity of drought and forestry studies, driven by more frequent drought events (e.g. [12]), can be seen in the over 1,800 papers published on this topic in 2020 alone. The search showed a predominance of European studies, North American studies, Asian (esp. China and Japan) studies, and to a lesser extent South American studies. Studies on tropical ecosystems are also present. Within Europe, approximately equal numbers of studies focus on countries in Atlantic, Central, and Nordic regions, as in Mediterranean countries. Approximately equal numbers of studies focus on coniferous as on broadleaved species. Within the results of this search, only a relatively small number of papers investigated interactions between drought and other disturbances, with fire and pests the predominant co-stressors in these studies.

Between December 2020 and February 2021, we also conducted semi-structured interviews to explore previous, ongoing and planned work with 12 researchers at Forest Research, encompassing a broad range of forestry expertise: climate change, tree ecophysiology, plant health, silviculture, and timber properties. The topics discussed in the interviews informed subsequent searches which identified an additional number of papers, reports, and grey literature. The compound nature of drought impacts and resilience with other stresses emerged as a strong thread through all the interviews. Consequently, we included additional articles which reference drought obliquely (e.g. general resilience studies) to capture the complexity of the issue. In total we reviewed 46 papers. The broad spectrum of forestry expertise represented by Forest Research scientists involved in, or interviewed for this report, gives us confidence that we have assessed the most pertinent evidence.



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+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

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