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LETTER

Adapting Scotland's forests to climate change using an action expiration chart

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Supplementary material for this article is available online

Abstract

The inherent uncertainty of climate change impacts is one of the main challenges for adaptation in environmental management. The lack of knowledge about climate impacts on ecosystem services at high spatial and temporal resolution limits when and what adaptation measures should be taken. We addressed these limits by assessing four ecosystem services—forest production, tree growth, sequestered carbon, and tourism potential—under drought or climate change. To support adaptation, we adapted the existing concept of 'dynamic adaptive policy pathways' for forest management by developing an action expiration chart, which helps to define expiry dates for forestry actions using ecosystem services delivery thresholds. We assessed services for Sitka spruce, Scots pine, and pedunculate oak on the National Forest Estate in Scotland for the next 80 years using probabilistic climate change data from the UKCP09 weather generator. Findings showed that drought would have an overall long-term negative impact on the provision of three services with a decrease up to 41%, whereas climate change has a positive impact on tourism potential with up to five times higher frequency of good climate conditions during summer months. Furthermore, the results highlighted when forestry actions, mainly in the lowlands, will reach their environmental limits during the next 80 years. Our findings reduce knowledge uncertainty and highlight when and where adaptation should be implemented to ensure the provision of future forest ecosystem services in Scotland.

1. Introduction

Natural and human ecosystems have a long history of adaption to changing climate conditions and its variability. But expected rapid climate change will undoubtedly harm these ecosystems (Fischlin *et al* 2007, Ciscar *et al* 2011) calling for adaptation that can minimize these impacts (Hall *et al* 2012, Jones *et al* 2012). The essential components of climate change adaptation are how, where, and when to adapt (Smit *et al* 1999), and to what climate stimuli. Many studies have investigated adaptation measures to potential climate change impacts on multiple ecosystems in Europe (Schroter *et al* 2005, Lindner *et al* 2010) and in the UK (Read *et al* 2009, Bateman *et al* 2013). However, these studies lack the level of spatial and temporal detail necessary for medium to long-term management, such as decadal information, and what future adaptive pathways might exist. To overcome these issues, improvements in climate change modelling have resulted in climate data at higher spatial and temporal resolutions, such as the climate change projections in the UK (Murphy *et al* 2009). By building upon recent research on adaptation strategies providing choices, relevant actions, and pathways while considering uncertainty (Hallegatte 2009, Denton *et al* 2014, Haasnoot *et al* 2013), then new adaptive management pathways for forestry can be created.

In forestry, climate change adaptation is a long-term process as trees grow for decades. Adaptation involves having information when and where climate change impacts are serious enough to initiate changes in forest management. Different adaptation approaches to climate change exist based on forest management, such as 'silvicultural adaptation measures' (Mason *et al* 2012), and adaptive strategies including resistance, resilience, and natural response (Millar *et al* 2007, Stephens *et al* 2010); or sociological approaches like 'risk perceptions' (Williamson *et al* 2005). Still, these studies lack detailed information about when and where forest managers should start to adapt and what limits their adaptation. A novel approach of dynamic adaptive policy pathways found in the literature for water management (Haasnoot *et al* 2013) seems a promising new approach, which when modified, can support spatially oriented climate change adaptation in forestry. The essential component for these pathways is to define an expiry date for each action—e.g. raising of dykes—described as a 'sell-by date' beyond which the plan's objectives will fail. Furthermore, expiry dates define boundaries for a set of adaptation pathways considering different objectives and problem understandings. To assess these pathways and their actions, quantified ecosystem services are needed.

Not only do natural ecosystems have a long history of adapting to changing climate conditions, human ecosystems have also been searching for means to adapt. Therefore, the societal perspectives on the environment and its values have been changing. These values are well expressed in the environmental or ecosystem services that society appreciates. In the past, for instance, forests were appreciated mainly for wood production, but in the last few decades they became appreciated and valued also as sources of biodiversity, tourism revenue, and carbon storage (Quine *et al* 2011). These multiple forest benefits—ecosystem services—increase the value of forests to the public.

Corresponding to these changes in societal appreciation of the environment, ecosystem services assessments emerged in the last decade at a global (Millennium Ecosystem Assessment 2005) and at a national scale (UK National Ecosystem Assessment 2011). Traditionally, in forestry, the main services have been forest production and contribution to the local economy, but recently new services emerged, such as carbon sequestration and recreation (Quine *et al* 2011). Numerous sophisticated models exist for assessing traditional services, such as forest production (Metzger *et al* 2008, Hanewinkel *et al* 2012), and carbon sink and sequestration (Pan *et al* 2011, Morison *et al* 2012). However, only a limited number of models are available to assess newer services, such as recreation (Mieczkowski 1985), especially when incorporating climate change impacts (Bateman *et al* 2013). Therefore, forest managers need information about climate change impacts on these services because they provide vital benefits to the public. Furthermore, to support broader climate change adaptation multiple ecosystem services should be evaluated to inform environmental management (Bateman *et al* 2013).

This paper aims to quantify resilience of managed forests with four forest related ecosystem services (tree growth potential, forest production, carbon sequestration, and tourism potential) under climate change and to incorporate them into an action expiration chart, for the case of Scottish public forestry. We address two research questions: (a) How much will drought and climate change reduce the delivery of forest ecosystem services in the future under different emissions scenarios? and (b) Which forestry actions, and by when should forest planners choose to support the continuous provision of ecosystem services under climate change ? To assist future forest transitions while reducing climate change uncertainty, we explored when, where, and how to adapt. We assessed changes in ecosystem services on the National Forest Estate (NFE) in the lowlands and uplands based on probabilistic climate change projections (UKCP09) (Murphy *et al* 2009). To assist climate change adaptation in forestry and its intrinsic uncertainty, we incorporated information about ecosystem services into an action expiration chart.

2. Materials and methods

We used a climate stress testing framework (figure 1) as guidance for our assessment of ecosystem services and the development of an action expiration chart.

2.1. Data collection

Simulated climate data were obtained from the weather generator (WG)—with 5 km spatial resolution—available from the UKCP09 climate projections (Murphy *et al* 2009, Jones *et al* 2009). To calculate moisture deficit (MD)—as a drought proxy—we used key climate variables: precipitation (mm) and potential evapotranspiration for grass (PET) (mm d^{-1}). To calculate a tourism climatic index (TCI) (Mieczkowski 1985) we used: maximum daily temperature (°C), mean daily temperature (°C), mean daily relative humidity (%), precipitation (mm), and sunshine (h d^{-1}). The WG data lacked wind speed data, hence we used the MetOffice gridded observation dataset with monthly averages for the climatic period 1971–2000 at 10 m height (Jenkins *et al* 2008). WG data were available for the baseline period (1961–1990), for seven 30-year overlapping time periods from the 2020s (2010–2039) until the 2080s (2070–2099), and for three IPCC emissions scenarios: low (B1), medium (A1B), and high (A1FI).

We modified the sampling of WGs sites experiment of Petr *et al* (2014) to increase the density of sites and to expand the coverage across forested areas on the NFE in Scotland. Sampling was random with one WG site within two strata: (a) UKCP09 25 km grid cell overlaying the NFE, and (b) within the lowlands or

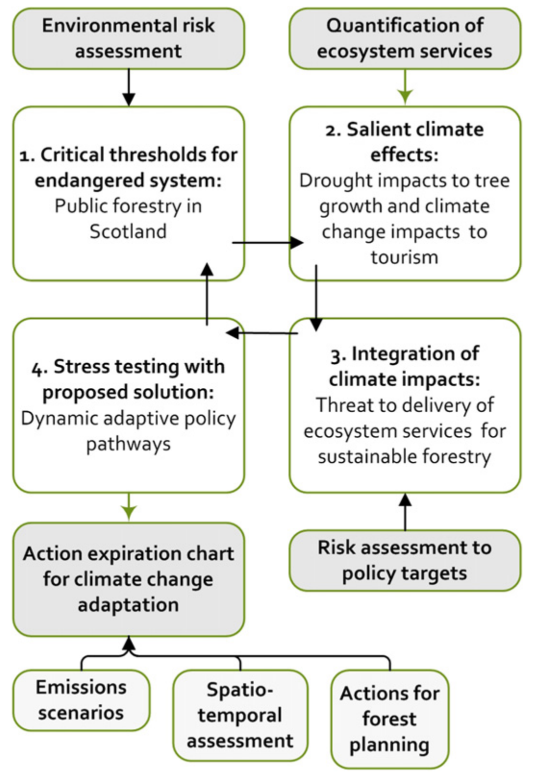

Figure 1. Climate stress testing framework guiding the assessment of ecosystem services and action expiration chart —in grey boxes (modified from (Swart et al 2013)).

uplands. We chose 25 km grid cells to have a regular block design and because WG sites at this scale have the same set of change factors for climate data (Jones et al 2009). The lowlands represents drier and warmer conditions and the uplands colder and wetter climate zones (Petr et al 2014). The Forestry Commission database provided forestry data about species, stand area and age, available in supporting information. Our final climate data sample consisted of 215 WG sites with 92 in the lowlands and 123 in the uplands, see figure A2 in supporting information for the WG spatial distribution.

2.2. Methods for estimating ecosystem services

We first estimated drought impacts on tree growth, forest production, and carbon sequestration, and then climate change impacts on tourism. We defined drought using a climatic MD index (Petr et al 2014) and climate change as impacts of multiple climate variables, e.g. temperature and precipitation. For each ecosystem service we calculated an indicator using models developed either for British conditions—drought risk assessment or carbon—or for international conditions—tourism (table 1).

We assessed the drought impacts on tree growth (stand yield class) for Sitka spruce (*Picea sitchensis*), Scots pine (*Pinus sylvestris*), and pedunculate oak (*Quercus robur*). For the future periods we adjusted the baseline yield class (1961–1990) with a drought risk impact measure (Petr et al 2014) for each tree species by the relative future yield class change factor within each 25 km grid cell. Using an adjusted yield class we calculated the potential mean stand yield class for spruce, pine, and oak stands weighted by stand area. Then, we computed the potential forest production multiplying the adjusted mean stand yield classes by the forest area, assuming the same future forest extent. Next, we estimated cumulative sequestered carbon stocks for stands using the freely available Woodland Carbon Code calculator[3] based on the CSORT model (Morison et al 2012). For each species we calculated the sequestered carbon based on: tree age, adjusted stand yield class, tree spacing, and with standard forest management. The cumulative carbon values represent sequestered carbon in biomass and debris.

Finally, we calculated a tourism potential for forests with the TCI representing human comfort (Mieczkowski 1985, Perch-Nielsen et al 2010). We used daily climate data from the WG to calculate five monthly sub-indices required for TCI: daytime comfort index, daily comfort index, precipitation, sunshine, and wind. The only missing climate variable was minimum daily relative humidity, which we substituted with the mean daily relative humidity similarly as (Perch-Nielsen et al 2010). All climate variables were available for the baseline period (1961–1990) except for wind data (available for 1971–2000), which still provided a good proxy for the baseline. To calculate changes in tourism potential between the baseline and the future, we used the number of ‘good days’ with TCI > = 60 indicating suitable conditions for light tourism (Perch-Nielsen et al 2010). We analysed changes in the average number of good days in summer (June, July, and August) when the highest visitor numbers in Scottish forests occur. The supporting information contains the detailed calculation steps for ecosystem services.

2.3. Method for the action expiration chart

We expanded the dynamic adaptive policy pathways developed for water management with spatial and temporal evaluations of forestry actions and created the action expiration chart. Following the first five analysis steps by Haasnoot et al (2013), we (1) described the study area, (2) specified the problem related to forest adaptation in Scotland, (3) provided a list of relevant forestry actions, (4) assessed these actions, and (5) proposed an action expiration chart with two sets of threshold values.

2.3.1. Study area—Scottish public forestry

We analysed three major tree species on the NFE (481 000 hectares) in Scotland (Forestry Commission 2012b). In the lowlands and uplands, Sitka spruce as the major production species covers more than 50% of forest area; Scots pine covers approximately10%; and pedunculate/sessile oak

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[3] http://www.forestry.gov.uk carboncode

Table 1. Indicators for assessment of ecosystem services.

Type of service from UK NEA classification[a]	Ecosystem services	Indicators (units)	Models
Provisioning–trees for timber	Tree growth	Weighted mean stand yield class (m^3 ha^{-1} yr^{-1})	Drought risk assessment (Petr *et al* 2014)
Provisioning–trees for timber	Forest production	Volume of available timber (m^3 yr^{-1})	Drought risk assessment (Petr *et al* 2014)
Regulating–climate	Carbon sequestration	Carbon sequestration [$tCO_{2equivalent}$]	Woodland carbon code and CSORT model (Morison *et al* 2012)
Cultural–environmental settings	Tourism potential	Tourism climatic index (no. of 'good' d $month^{-1}$)	Tourism climatic index (Mieczkowski 1985)

[a] Quine *et al* (2011)

covers approximately 1% (table A1). The climatic conditions in Scotland have changed with an increase in mean annual temperature by 0.8 °C over the last three decades and with summer precipitation changes in a range between −5% and 4.6% in contrast to winter precipitation with an increase between 35.9% and 65.8% from 1961 to 2006 (Jenkins *et al* 2008). From the forest policy perspective, Scottish Government has specified broad policy aspirations, such as an increase in the woodland area from 17% to 25%, an increase in carbon sequestration, and a contribution to public health benefits (Forestry Commission Scotland 2006); and another target for delivering a smooth annual production of at least three million cubic metres of softwood timber over the next 50 years (Forestry Commission Scotland 2013).

2.3.2. Problem for Scottish forestry

Climate change and its potential impacts are one of the main threats to the future delivery of key forest ecosystem services in Scotland (Forestry Commission Scotland 2006). The problem for forest managers is to know when and where they should adapt and by what means. Opportunities exist, such as woodland expansion on suitable sites, or choosing more resilient tree species. Vulnerabilities also exist, such as growth rate reduction due to drought (Allen *et al* 2010).

2.3.3. Relevant forestry actions

We chose three forestry management actions important for sustainable forest management for which we can quantify ecosystem services delivery into the future. Three forestry actions are: keep the current tree species, adjustment of forest recreation facilities, and forest area expansion. We classified these into three groups: forest management of current tree species, potential forest tourism, and forest area expansion. In each group we split the actions into the lowlands and uplands, and for forest management we also split them by the three species.

2.3.4. Evaluation of forestry actions

Each action was evaluated by the quantity of ecosystem service delivery with and without climate change, similar to the scorecards by (Haasnoot *et al* 2013). We used quantified ecosystem services to define expiry dates (by decades) after which actions will stop delivering the required amount of service and a need for adaptation starts. To compare differences among ecosystem services we used relative values. Moreover, we specified two sets of threshold values: a 10% and a 20% reduction values indicating a decline in the amount of services. Once an action reaches the threshold value, this defined its expiry date or a 'stop' point. For tourism we defined different threshold values with a 100% and 200% increase in the number of 'good days' as climate change should have a positive impact. The example in figure 2 shows two reduction rates of ecosystem services, with various widths of vertical bars indicating the number of services (from one to three) reaching its expiry date. The horizontal coloured bars connecting vertical bars depict a 'window of necessity' indicating how much time forest managers have left before the remaining services reach their expiry date. The black horizontal lines indicate no expiry dates.

2.3.5. Action expiration chart

Having a set of forestry actions with expiry dates at two threshold values, we defined windows of necessity and incorporated these into an action expiration chart. Expiry dates specify which action a forest planner may still follow and define limits for possible adaptive pathways. Consequently, these dates are part of the uncertainty that forest planners have to face now and into the future. Planners do not know how society will value ecosystem services, and this would influence forest management objectives. Stated another way, planners have to deal with this ambiguity (Brugnach *et al* 2008). Consequently, we offer two threshold values for consideration –10% and 20% for traditional services. By combining forestry actions with their expiry dates we were able to create spatial (lowland and upland) action expiration chart for forestry. This chart can help foresters and policy makers to draw possible adaptation pathways and outline where (in the lowlands or uplands), when (for seven time periods), and under which future (emissions

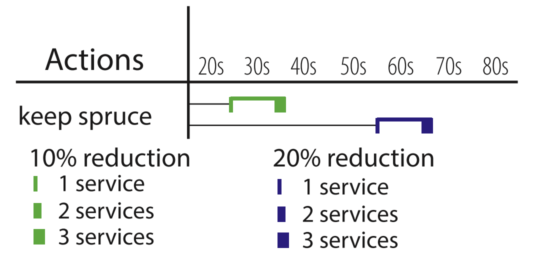

Figure 2. Illustration of a forestry action and accompanying 10% and 20% threshold values with expiry dates for one, two, and three ecosystem services (forest production, stand yield class, and carbon sequestration). The seven decades range from the 2020s (20s) until 2080s (80s).

scenarios) adaptation should start. Furthermore, an action expiration chart offers information about evaluated reasonable adaptation choices: forest area expansions or orientations to forest tourism.

3. Results

3.1. Spatiotemporal assessment of ecosystem services

Figure 3(a) shows that total future forest production combined for spruce, pine, and oak in both the lowlands and uplands reduces compared with the baseline (1961–1990) climate. Spruce contributed the most to this decrease with 664 000 $\mathrm{m^3\,yr^{-1}}$, followed by pine with almost 12 times smaller contribution of 57 000 $\mathrm{m^3\,yr^{-1}}$, and oak contributed with a marginal increase of 900 $\mathrm{m^3\,yr^{-1}}$ assessed for the A1FI emissions scenario in the 2080s. The forest production for spruce reduces 1.6 times more in the uplands than in lowlands in the 2080s for the A1FI scenario.

Figure 3(b) demonstrates that calculated weighted mean stand yield classes mostly decrease compared to the baseline. Spruce has a higher growth potential in the lowlands than in the uplands but both decline compared to the baseline. However, in the 2080s for the A1B scenario and from the 2060s for the A1FI scenario the spruce yield class in the uplands overtakes the yield class in the lowlands. Spruce yield class decreases from 14.7 to 10.6 $\mathrm{m^3\,ha^{-1}\,yr^{-1}}$ in the lowlands for the A1FI scenario in the 2080s. Pine has a yield class approximately half that of spruce in the baseline, but has a smaller absolute reduction in yield class, from 8.1 to 5.7 $\mathrm{m^3\,ha^{-1}\,yr^{-1}}$ in the lowlands in the 2080s. Pine switches to a higher yield class in the uplands compared with the lowlands in the 2050s. In contrast to spruce and pine, oak yield class increases from the baseline over the next 80 years. Projected drier conditions help oak to increase its yield class from 2.9 to 3.5 $\mathrm{m^3\,ha^{-1}\,yr^{-1}}$ in the lowlands by the 2080s.

Figure 3(c) shows that in Scotland, spruce dominates with the total amount of sequestered carbon in biomass in both the lowlands and uplands, and this is almost five times more than pine and 173 times more than oak. For spruce, drought impacts result in a reduced sequestered carbon that is noticeable from the 2020s, with the largest reduction of 17 502 000 [tCO$_2$e] in the 2080s for the A1FI scenario compared with the baseline. The largest reduction in sequestered carbon for pine totals 3 400 000 [tCO$_2$e] in the 2070s for the same scenario. Surprisingly, the largest reduction in sequestered carbon for oak is 160 000 [tCO$_2$e] in the 2060s for the B1 scenario. Age distribution and species rotation lengths explain the 's' shape curve of sequestered carbon.

And finally, the figure 3(d) demonstrates that the climate conditions should become more favourable for light tourism in both the lowlands and uplands in Scotland. The mean number of 'good days' (TCI $> = 60$) during summer months increases almost by three times in the lowlands and a five times in the uplands over the next 80 years compared to the baseline climate. A slightly steeper increase in the number of good days occurs in the uplands than in lowlands. Also, the absolute difference between the lowlands and uplands reduces from about 8 good days in the 2020s to 5 good days in the 2080s. The baseline representing standard climate period 1961–1990 clarifies the sharp increase in the number of good days to the 2020s.

3.2. An action expiration chart

Building upon the quantified ecosystem services (traditional: forest production, mean yield class, and carbon sequestered; and the tourism potential separately) we developed an action expiration chart for the NFE in Scotland. This chart defines the threshold values with expiry dates for all forestry actions in the lowlands and uplands, and for three emissions scenarios. For a 10% reduction value of traditional ecosystem services–the expiry dates occur in the lowlands first for pine action already now, and for spruce action after the 2030s (figure 4). Second, in the uplands the expiry date for spruce action occurs in the 2050s for the B1 or in the 2040s for the A1FI scenario, and for pine action in the 2060s for the A1FI scenario. For a 20% reduction value of ecosystem services in the lowlands the expiry dates for spruce and pine actions occur in the 2050s or 2070s for the A1B and A1FI scenarios, respectively. However, no expiry dates exist for actions in the uplands. Orientation to forest tourism or forest area expansion in the uplands can provide future benefits and added values to forestry, which can partially compensate for losses in values and the delivery of forest production, mean yield class, and carbon sequestration. Furthermore, our findings show how the 'window of necessity' changes and also shows the urgency to take an action. Combining information about expiry dates for all forestry actions, we also

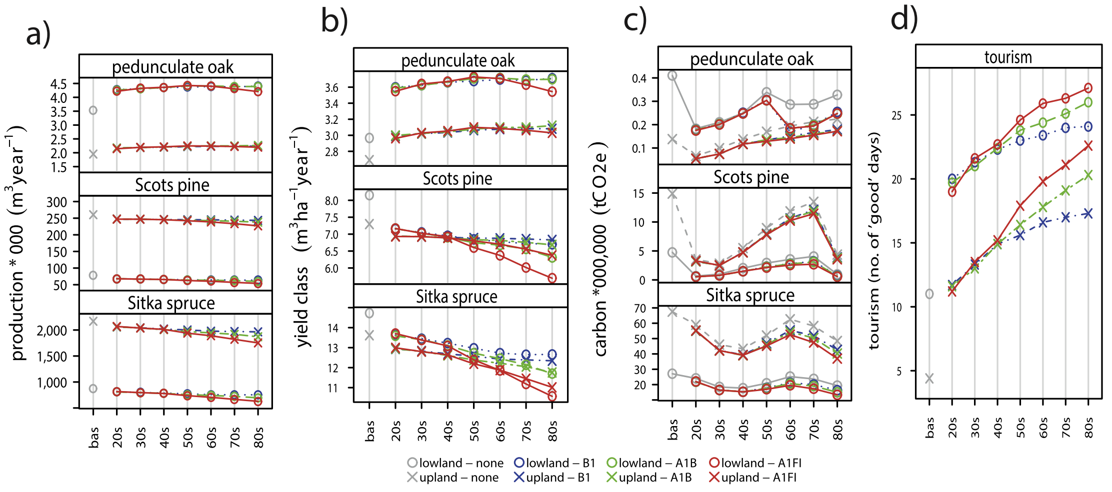

Figure 3. Estimated (a) potential forest production; (b) potential weighted mean stand yield class; (c) potential sequestered carbon; and (d) tourism potential for the number of 'good days' (tourism climatic index >60), due to drought and climate change impacts in Scotland for the lowlands and uplands; for the B1, A1B, and A1FI emissions scenarios where 'none' represents no climate change; and for the baseline (1961–1990) and seven time periods (2020s until 2080s).

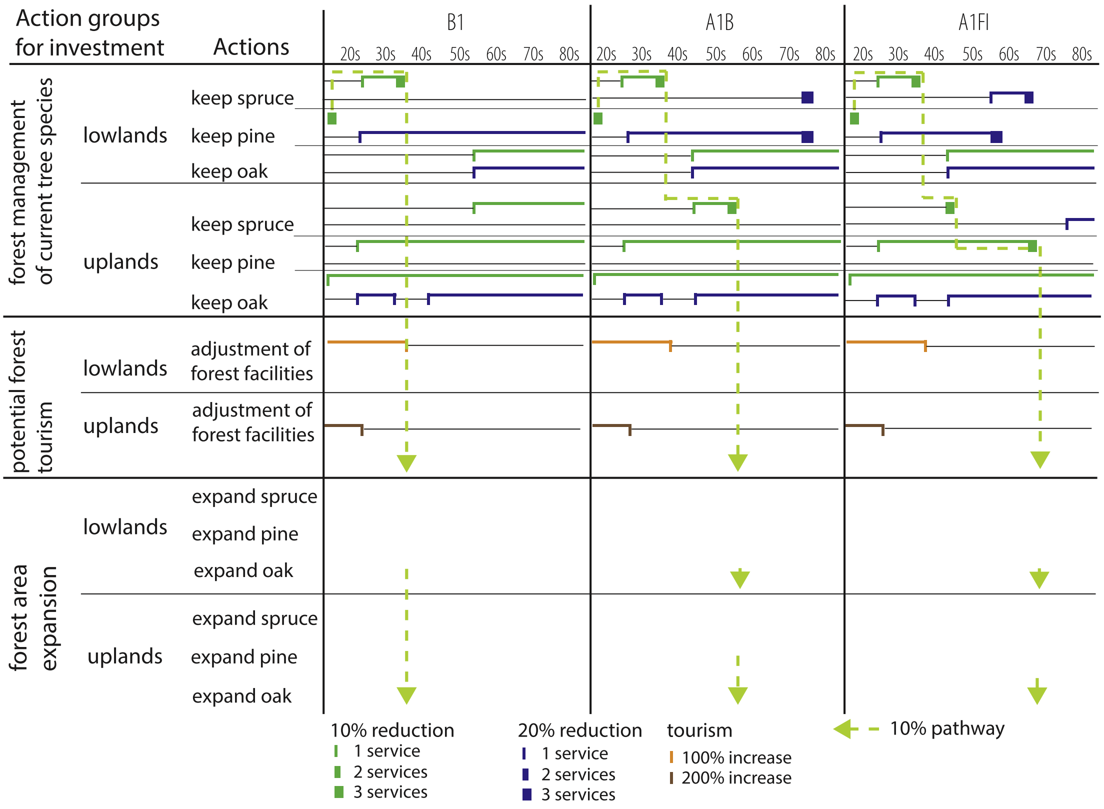

Figure 4. Action expiration chart for the National Forest Estate in Scotland with an example of manually drawn pathways in light green dashed line for 10% reduction. Chart shows expiry dates for a 10% (green) and a 20% (blue) reduction of ecosystem services; expiry dates for potential tourism for a 100% (orange) and a 200% (brown) increase; for three emisssions scenarios, and over the next seven decades (the 2020s until 2080s).

illustrate adaptation pathways for a 10% threshold value across three scenarios in dashed green line (figure 4). They indicate when each forestry action reaches its expiry date and where other actions can still provide sufficient services while partially compensating for other losses.

4. Discussion and conclusions

4.1. Spatiotemporal assessment of ecosystem services

The findings for the major Scottish tree species show that future droughts could largely reduce the provision of key forest ecosystem services (forest production, mean yield class, and sequestered carbon), and climate change could increase tourism potential. Drought impacts on species could result in forest production losses by 270 000 $m^3 yr^{-1}$ in the lowlands (28.3% of total production) and by 450 000 $m^3 yr^{-1}$ in the uplands (18.5%) in the 2080s. Forest managers can minimize these impacts by applying relevant adaptation measures, such as a choice of drought tolerant species and adjusting silviculture management. Although forest management can have a higher impact on wood production compared to climate change (Schroter *et al* 2005), still climate change will have a continuous and large effect. For example, the modelling study by Ray *et al* (2014) demonstrated that depending on the forest management practice, such as species diversity and business as usual, we can expect positive and negative impacts on the provision of ecosystem services under climate change. Therefore, when comparing their observations with ours, we can expect that species diversification can increase the amount of key forest ecosystem services and postpone the expiry dates whereas business as usual will most likely follow our negative impacts. Additionally, study by Brang *et al* (2014) summarized a list of both effective and ineffective silviculture practices for climate change adaptation, with, for example, reduced rotation length possibly mitigating high-risk stands and associated delivery of forest services. This practice can delay a need for new species, in our study management action, while providing a same amount of ecosystem services. At a national scale, other studies have shown a relatively small reduction in wood production by 2050–2080 across Scotland generalized for Atlantic north stratum (Metzger *et al* 2008), whereas production forecasts for softwood timber availability for Scotland showed a steep decline by 2036 by about 21.8% (Forestry Commission 2012a) and production decrease by 42% by the 2080s across the Great Britain (Petr *et al* 2014). Based on our study and these papers, we conclude that impacts on forest production on the NFE in Scotland will be substantial in the lowlands, especially in the second half of the 21st century.

Relative change in stand yield classes was similar to forest production. For spruce in the lowlands it reduced by 4.16 $m^3 ha^{-1} yr^{-1}$ (28.2% of yield class) and in the uplands by 2.6 $m^3 ha^{-1} yr^{-1}$ (19.1%) in the 2080s. These results can have a long-term impact on sustainable spruce timber production, with an average 50-year rotation period. Other studies have shown similar degree of drought impacts from a 30% reduction of gross primary productivity across Europe after the 2003 heat-wave (Ciais *et al* 2005), worldwide forests' vulnerability due to hydraulic failure (Choat *et al* 2012), and negative modelled drought impacts on growth of Scots pine in Scotland (Xenakis *et al* 2011). Future climate conditions, including extreme events, are thus likely to reduce forest productivity for the three species.

Sequestered carbon in the standing trees will decrease. For spruce, estimated carbon in the lowlands reduced by 6 $MtCO_2e$ (31% of total carbon) and in the uplands reduced by 11.5 $MtCO_2e$ (41%) in the 2080s for the A1FI scenario. These reductions can turn forests into carbon sources as reported after the 2003 heat-wave in Europe (Ciais *et al* 2005); after extreme events, such as wind-throw with estimated 30% reduced carbon balance (Lindroth *et al* 2009); and from a combination of stem increment reduction and an increase in number of natural events (Nabuurs *et al* 2013). Additionally, estimates of the carbon sink in Britain's forests, including Scotland, indicate large reductions from 10.5 $MtCO_2 yr^{-1}$ in 2005 to 5 $MtCO_2 yr^{-1}$ by 2020 (Read *et al* 2009).

The tourism potential index indicate a positive climate change effect with a high increase by 16 'good days' (equivalent to 250%) in the lowlands and up to 19 'good days' (equivalent to 520%) in the uplands for the 2080s and the A1FI scenario. This would result in a high demand for forest recreation in Scotland with a need for new facilities and infrastructure to accommodate this increase. Using the same index but different climate datasets, other studies reported a northward shift of 'good' days to southern Scotland in the 2060s or 2080s (Hein *et al* 2009, Perch-Nielsen *et al* 2010), and an increase in the frequency of good days by about 5 d in 2071–2100 (Perch-Nielsen *et al* 2010). Our results show more positive climate change effects, probably due to use of more detailed climate dataset. Even though absolute reduction in provision of ecosystem services is smaller in the lowlands while relative reduction is smaller in the uplands, forests in the uplands are more resilient to drought.

4.2. An action expiration chart

We found that climate change adaptation in Scottish forestry should start in the lowlands immediately or in the next two decades. This implies accepting a 10% reduction of services provision for forestry actions of major tree species—spruce and pine. For a 20% reduction, the same actions in the lowlands reach their expiry dates but this happens later from the 2050s. Our two threshold values with expiry dates provide a direction for possible adaptation pathways, opportunity space for adaptation, and contribute to resilient forests. But the pathways choice will depend on planners' risk attitudes and perceptions. The planners' risk perceptions will most likely drive choices of forestry actions, as a study by O'Connor *et al* (2005) has demonstrated that this was the case for water managers. Furthermore, planners and managers need to consider the amount of future ecosystem services at stake, for example with spruce covering more than 43% of forested area in Scotland, and their objectives. Opportunities exist for adding more benefits from several services, either with added value by and a shift to forest tourism or with offsetting losses in the lowlands by forest area expansion in the uplands. Essentially, a better future climate conditions for tourism will offer the public more opportunities for recreation and a better growth in the uplands will allow forest managers to partially compensate for losses in values of forest ecosystem services. These opportunities offer managers new options for adaptation while retaining the values of the public forest, but they also result in a need for trade-offs among ecosystem services (Schwenk *et al* 2012). Finally, our findings with changes in tourism potential could justify advanced studies into the perceptions and preference of tourists regarding the Scottish landscape and its forests.

Proposed action expiration chart can provide information about when and where actions can reach their expiry dates helping managers to define necessary lead time—supporting adaptation—with knowledge about their financial, human, and technical resources. As previous research demonstrated, a lack of knowledge exist among forest experts about agreement of effective adaption options for protecting key forest ecosystem services (West *et al* 2012). An action expiration chart with pathways addressing climate change uncertainty can also supports new types of climate change policies with specific recommendations when, where, and how much forests should change. This can help managers to make informed decisions while avoiding inappropriate adaptation measures that can make forests more vulnerable (Barnett and O'Neill 2010). The detailed information about the climate change impacts on ecosystem services should be used as a guidance for operational forest management, such as helping with transition of re-planting with new suitable tree species and shift to new locations (Millar *et al* 2007).

The study strengths are the assessment of multiple forest ecosystem services into the future at high spatial and temporal resolution with probabilistic climate data, and the development of an action expiration chart. Additionally, new understanding about climate change and ecosystem services can improve proposed flexible action expiration chart and provide coherent information to forest planners. To improve this work, future research should incorporate other ecosystem services impact models to reduce epistemic and ambiguity uncertainty. Overall, our study was limited to a description of assessed ecosystem services and future pathways, and that preferences and choices, such as recreational preferences and associated trade-offs, could not be studied, but these could certainly be interesting for further research using our action expiration chart.

5. Conclusions

For the first time multiple forest ecosystem services were assessed at a high spatial and temporal resolution, which until now has been missing at a regional scale, in combination with an action expiration chart. Overall, drought impacts should reduce the provision of the traditional forest ecosystem services more in the lowlands than in the uplands. However, climate change brings opportunities for forestry with a shift to new ecosystem services being tourism or to forest expansion preferably in the uplands. Additionally, assessed services enabled us to develop an action expiration chart with quantified expiry dates while offering directions for adaptation in forestry. This chart, when modified, can allow other sectors to identify future needs for adaptation. Finally, this study offers a new way of reducing climate change uncertainty by incorporating quantified ecosystem services into an action expiration chart for Scottish forestry.

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References

Allen C D *et al* 2010 A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests *Forest Ecol. Manag.* **259** 660–84

Barnett J and O'Neill S 2010 Maladaptation *Glob. Environ. Change* **20** 211–3

Bateman I J *et al* 2013 Bringing ecosystem services into economic decision-making: land use in the United Kingdom *Science* **341** 45–50

Brang P *et al* 2014 Suitability of close-to-nature silviculture for adapting temperate European forests to climate change *Forestry* **87** 492–503

Brugnach M *et al* 2008 Toward a relational concept of uncertainty: about knowing too little, knowing too differently, and accepting not to know *Ecol. Soc.* **13** 16

Choat B *et al* 2012 Global convergence in the vulnerability of forests to drought *Nature* **5** 4–8

Ciais P *et al* 2005 Europe-wide reduction in primary productivity caused by the heat and drought in 2003 *Nature* **437** 529–33

Ciscar J-C *et al* 2011 Physical and economic consequences of climate change in Europe *Proc. Natl Acad. Sci. USA* **108** 2678–83

Denton F *et al* 2014 Climate-resilient pathways: adaptation, mitigation, and sustainable development ed C B Field *et al* *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (Cambridge: Cambridge University Press) pp 1101–31

Fischlin A *et al* 2007 *Ecosystems, their properties, goods, and services. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed M Parry *et al* (Cambridge: Cambridge University Press) pp 211–72

Forestry Commission 2012a 25-year forecast of softwood timber availability *National Forest Inventory Report* Edinburgh, Scotland, UK

Forestry Commission 2012b *Forestry Statistics* (Edinburgh: Forestry Commission)

Forestry Commission Scotland 2013 *The Role of Scotland's National Forest Estate and Strategic Directions 2013–2016* (http://scotland.forestry.gov.uk/managing/plans-and-strategies/national-forest-estate-strategy)

Forestry Commission Scotland 2006 *The Scottish Forestry Strategy* ed F C Scotland (Edinburgh: Forestry Commission)

Haasnoot M *et al* 2013 Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world *Glob. Environ. Change* **23** 485–98

Hall J W *et al* 2012 Proportionate adaptation *Nat. Clim. Change* **2** 833–4

Hallegatte S 2009 Strategies to adapt to an uncertain climate change *Glob. Environ. Change* **19** 240–7

Hanewinkel M *et al* 2012 Climate change may cause severe loss in the economic value of European forest land *Nat. Clim. Change* **2** 1–5

Hein L, Metzger M J and Moreno A 2009 Potential impacts of climate change on tourism; a case study for Spain *Curr. Opin. Environ. Sustainability* **1** 170–8

Jenkins G J, Perry M C and Prior M J 2008 *The Climate of the United Kingdom and Recent Trends* (Exeter: Met Office Hadley Centre)

Jones H P, Hole D G and Zavaleta E S 2012 Harnessing nature to help people adapt to climate change *Nat. Clim. Change* **2** 504–9

Jones P D, Kilsby C G, Harpman C, Glenis V and Burton A 2009 *UK Climate Projections Science Report: Projections of future daily climate for the UK from the weather generator* University of Newcastle

Lindner M *et al* 2010 Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems *Forest Ecol. Manag.* **259** 698–709

Lindroth A *et al* 2009 Storms can cause Europe-wide reduction in forest carbon sink *Glob. Change Biol.* **15** 346–55

Mason W, Petr M and Bathgate S 2012 Silvicultural strategies for adapting planted forests to climate change: from theory to practice *J. Forest Sci.* **2012** 265–77

Metzger M J *et al* 2008 A spatially explicit and quantitative vulnerability assessment of ecosystem service change in Europe *Reg. Environ. Change* **8** 91–107

Mieczkowski Z 1985 *Tourism Clim. Index: Method Eval. World Clim. Tourism* **29** 220–33

Millar C I, Stephenson N L and Stephens S L 2007 Climate change and forests of the future: managing in the face of uncertainty *Ecol. Appl.* **17** 2145–51

Millennium Ecosystem Assessment 2005 *Ecosystems and Human Well-being: Synthesis* (Washington, DC: Millennium Ecosystem Assessment)

Morison J *et al* 2012 Understanding the carbon and greenhouse gas balance of UK forests *Forestry Commission Research Report* Forestry Commission, Edinburgh i–vi, pp 1–149 (www.forestry.gov.uk/pdf/FCRP018.pdf/$FILE/FCRP018.pdf)

Murphy J M *et al* 2009 *UK Climate Projections Science Report: Climate Change Projections* (Exeter, UK: Met Office Hadley Centre)

Nabuurs G *et al* 2013 First signs of carbon sink saturation in European forest biomass *Nat. Clim. Change* **3** 792–6

O'Connor R E *et al* 2005 Feeling at risk matters: water managers and the decision to use forecasts *Risk Anal.: Off. Publ. Soc. Risk Anal.* **25** 1265–75

Pan Y *et al* 2011 A large and persistent carbon sink in the world's forests *Science* **333** 988–93

Perch-Nielsen S L, Amelung B and Knutti R 2010 Future climate resources for tourism in Europe based on the daily Tourism Climatic Index *Clim. Change* **103** 363–81

Petr M *et al* 2014 A spatial and temporal drought risk assessment of three major tree species in Britain using probabilistic climate change projections *Clim. Change* **124** 791–803

Quine C *et al* 2011 Woodlands *UK National Ecosystem Assessment Technical Report* (Cambridge: UK National Ecosystem Assessment, UNEP-WCMC)

Ray D *et al* 2014 Comparing the provision of ecosystem services in plantation forests under alternative climate change adaptation management options in Wales *Reg. Environ. Change* 1–3

Read D J *et al* 2009 Combating climate change—a role for UK forests *An Assessment of the Potential of the UK's Trees and Woodlands to Mitigate and Adapt to Climate Change* (Edinburgh: The Stationary Office)

Schroter D *et al* 2005 Ecosystem service supply and vulnerability to global change in Europe *Science* **310** 1333–7

Schwenk W S *et al* 2012 Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis *Ecol. Appl.: Publ. Ecol. Soc. Am.* **22** 1612–27

Smit B *et al* 1999 The science of adaptation: a framework for assessment *Mitigation Adapt. Strateg. Glob. Change* **4** 199–213

Stephens S L, Millar C I and Collins B M 2010 Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates *Environ. Res. Lett.* **5** 024003

Swart R *et al* 2013 Beyond vulnerability assessment *Nat. Clim. Change* **3** 942–3

UK National Ecosystem Assessment 2011 *The UK National Ecosystem Assessment: Synthesis of the Key Findings* (Cambridge: UK National Ecosystem Assessment)

West J M, Julius S H and Weaver C P 2012 Assessing confidence in management adaptation approaches for climate-sensitive ecosystems *Environ. Res. Lett.* **7** 014016

Williamson T B, Parkins J R and McFarlane B L 2005 Perceptions of climate change forest-based risk to forest ecosystems and communities *Forestry Chronicle* **81** 710–6

Xenakis G, Ray D and Mencuccini M 2011 Effects of climate and site characteristics on Scots pine growth *Eur. J. Forest Res.* **131** 427–39