Research Report No. 1228

Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland, 2021-2040

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Summary

Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland, 2021-2040

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Keywords

Extreme drought; climate change; water scarcity; wetlands; SPEI; mapping

Background

Climate change is causing increases in extreme weather events, including storms, flooding and droughts, the effects of which are being felt across the world. However, in Scotland, much of the focus of extreme event research and mitigation has been on storms and flooding, despite increases in drought occurrence and severity throughout the country. Droughts, especially extreme droughts, can have substantial impacts on both built and ecological environments, particularly when occurring in combination with other extreme weather events. Water-table sensitive habitats such as wetlands are particularly at risk, and can be seriously affected by episodes of water scarcity.

This study therefore explores the likelihood of changes to extreme drought risk in Scotland in the near future, and considers potential impacts on wetland functions. Using modelled temperature and precipitation data from the UK Climate Projections 2018 (UKCP18) and the drought index Standardised Precipitation-Evapotranspiration Index (SPEI), changes in extreme drought were calculated for the near future (2021-2040) in comparison to a baseline period (1981-2001). These changes were then mapped to highlight areas and seasons with the greatest projected change, enabling identification of 'hotspot' areas that may be at most risk.

These results can be used to direct mitigation and management actions to these areas, enabling pre-emption of drought damage and facilitating improved resilience to extreme weather events. For wetlands in particular, identifying sites that may be at most risk from climate change-related reductions in water levels will enable focussing of conservation effort, with the aim of increasing resilience, improving site condition and protecting key ecosystem functions. NatureScot, and others in the sector, can therefore utilise this work to enable more effective and efficient use of resources, and contribute towards the wider goals of addressing the climate and biodiversity emergencies.

Main findings

- **Increases in extreme drought are likely throughout the country**; extreme drought increases were projected in all cells on a 12km grid across Scotland
- **Extreme droughts are likely to become more common**; the number of extreme drought events was projected to increase from an average of one event every 20 years in the baseline period, to one event every 3 years in the near future (2021-2040)
- **Extreme droughts are likely to be longer**; typical drought events were projected to be up to 2-3 months longer than during the baseline period, with an average of 11 extra drought months per decade
- **Increases are likely to be felt most in autumn**, with increases of up to 9.5 months across all autumns in the next 20 years, while spring showed the lowest increases of up to 5.5 months
- **Increases are likely to be highest in the east**, particularly in the Borders, Grampian, Caithness, Orkney, and Shetland, while the increases along the west coast and in the Western Isles were projected to be lower
- **These increases are likely to interact with other climate-driven changes and anthropogenic pressures**, creating feedback loops that can negatively impact built and ecological environments

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1. INTRODUCTION

1.1 Background

The most recent Met Office climate projections indicate that Scotland will experience warmer, wetter winters and hotter, drier summers as a direct result of changes to the global climate (Lowe *et al.*, 2018). A key impact of these projected changes is an increase in the occurrence of extreme weather events, as well as in the severity of those events (Seneviratne *et al.*, 2012). Although extremes of flooding are a commonly considered consequence of such changes globally (Milly *et al.*, 2002) and particularly in Scotland (Sayers *et al.*, 2016), water scarcity will likely also be affected; episodes of water scarcity and drought are predicted to increase in frequency and become longer and more severe, with similar potential to flooding for negative effects on ecology and society (Naumann *et al.*, 2018).

Water scarcity events have already been shown to have detrimental impacts in Scotland, with past droughts causing serious environmental, economic and social damage. Agriculture can be seriously affected (Brown *et al.*, 2011; Waajen, 2019; WWF, 2019), with crop yields negatively affected by the UK drought in 2003 (Wreford and Adger, 2010). Similarly, water availability in densely populated areas such as the Central Belt may be restricted during severe water scarcity, often impacting the most disadvantaged communities first (Benzie *et al.*, 2011). Increases in urbanisation and rural depopulation throughout Scotland could exacerbate these issues (Paterson *et al.,* 2015), and rural communities dependent on well water supplies are likely to also be affected, as they were during the drought year of 2018 (Rivington *et al*., 2020).

Ecologically, many habitats are highly sensitive to changes in hydrology. Wetlands are a key example, and some wetland habitats can be affected by even small changes in water levels, which can result in changes in the plant communities present (Dawson *et al*., 2003; Middleton, 2016). Individual site hydrology plays a role in the sensitivity of different wetland types; wetlands that are almost entirely dependent on rainfall, such as raised bogs, may be more immediately vulnerable to water scarcity, while surface or groundwater fed habitats such as fens may be more resilient in the short term, but may be negatively affected by frequent droughts or prolonged drought periods (Winter, 2000).

Drying may also exacerbate the effects on wetlands of other extreme weather events, or of anthropogenic disturbance. Dry periods have been connected with incidences of peat slides or bog bursts (Lindsay and Bragg, 2005; Dykes, 2008), which involve collapses of sections of peatland as drying creates cracks in the peat and renders it more vulnerable to impacts of heavy rains or floods. Drying can also reduce the capacity of the wetland to regulate water flows and act as a flood moderator (Acreman and Holden, 2013), as drier soil and less stable vegetation is more likely to erode (Li *et al*., 2018). Similarly, wetlands experiencing more frequent drought periods could be less able to reduce nitrogen and phosphorus loading of water due to a lack of healthy vegetative communities, which may have knock-on effects on the wider ecosystem as well as allowing more nutrients to enter water bodies downstream (Fisher and Acreman, 2004).

Each of these effects can negatively impact biodiversity and ecosystem functions within and around the wetland habitat, as well as downstream. However, wetlands are of particular interest to drought mitigation not only because of their status as vital habitats and water regulators, but also due to their role as carbon sinks. Healthy wetlands, especially peatlands, play a significant part in capturing and storing CO_2 emissions, thereby reducing global climate change (Mitsch *et al*., 2013; Leifeld and Menichetti, 2018; Nugent *et al.* 2019). In Britain, intact peatlands store more carbon than forests (Milne and Brown, 1997), but damaged sites are often far less able to do so. Dry peatlands erode easily through wind or flooding (Li *et al*., 2018), exposing the peat, which oxidises and releases CO_2 into the atmosphere. They may also reduce or stop storing new carbon, further contributing to climate warming (Moomaw *et al.*, 2018). Drought risk to Scottish wetlands therefore is both driven by climate change and exacerbates it, contributing to wider threats to ecosystem health in the process. Furthermore, Scottish peatlands have been estimated to store 1620 Mt of carbon, equating to 56% of the total carbon in Scottish soils (Artz and Chapman, 2016); and as Scottish blanket bogs make up 15% of blanket bog globally (Scottish Government, 2010), damage to Scottish peatlands has international implications.

Despite this threat, perceptions of Scotland as a largely wet country have resulted in a dearth of studies on the potential for increased water scarcity, with much work focussing on issues surrounding flooding (e.g. Black and Burns, 2002; Kenyon, 2007; Kay *et al.*, 2014; Iacob *et al.*, 2017). While some work has been done exploring the impacts of water scarcity on Scottish ecosystems (e.g. Jeffries, 1994; Petr *et al.*, 2014), few studies have developed projections of water scarcity specifically in Scotland. Spinoni et al. (2018) used a drought index and European climate projections to model drought likelihood across Europe; however, the scale is too coarse to draw meaningful management conclusions about impacts on Scotland specifically. Both Collett et al. (2018) and Visser-Quinn et al. (2019) have modelled changes in hydro-hazards throughout Britain, but these focussed on changes to river flows in the far future (2080s and 2071-2099 respectively) and do not cover the whole country. Similarly, Gosling developed drought indices to assess Scotland's vulnerability to climate change induced drought using river flows and precipitation changes, but focussed on specific sites and the period 2041-2070, using the UK Climate Projections 2009 (Gosling *et al.*, 2012; Gosling, 2014). Scotland's Centre for Expertise in Waters used the most recent UK Climate Projections (UKCP18) to explore changes in water scarcity in Scotland in response to the drought conditions in 2018, but only used precipitation deficits, and focussed on risk to private water supplies (Rivington *et al.*, 2020).

1.2 Objectives

This study therefore focusses on water scarcity in Scotland specifically, with the goal of providing a robust and meaningful set of projections highlighting likely changes to water availability throughout the country in the near future. Through mapping these projected changes, the study seeks to uncover geographic and temporal patterns that can be used to target water scarcity planning. These maps are intended to be easily accessible and understandable for use as a tool in developing mitigation strategies across multiple sectors, but particularly in the context of wetland management and conservation.

The specific aims of the project were:

- To calculate changes in likelihood of extreme drought between 2021-2040, in comparison with the baseline period 1981-2001, for the metrics of drought frequency and drought duration;
- To map these changes in a clear and understandable way;
- To briefly explore the application of these results to wetland functions in the most affected areas of the country.

2. METHODS

Due to the multiple different types of drought and subsequent lack of a single definition, there are numerous techniques available for quantifying drought. Indices are common, especially the Palmer Drought Severity Index and the Standardised Precipitation Index. This study uses the Standardised Precipitation-Evapotranspiration Index (SPEI) because of its inclusion of evapotranspiration, which accounts for the influence of changes in temperature as well as changes in precipitation (Vicente-Serrano *et al*., 2010). The SPEI also enables computation over different time scales, allowing control over the type of drought calculated.

2.1 Data

The inputs to the SPEI are temperature and precipitation data. These data were obtained from the UK Climate Projections 2018 (UKCP18) regional projections, which is an ensemble consisting of 12 model members. The data use a high emissions scenario, RCP8.5, therefore approximating a 'worst case' outcome and the upper end of potential impacts (Lowe *et al*., 2018). Temperature was in mean °C/month, and precipitation was mean mm/day, so was converted to mm/month for the purposes of SPEI calculation. All variables were modelled on a 12km grid across Scotland, covering the entire country, and data were obtained from the UKCP18 for 1981-2040 inclusive, to enable calculation of SPEI throughout the period.

2.2 Bias correction

Bias correction has been shown to improve the accuracy of modelled climate data (Christensen *et al.*, 2008; Teutschbein and Seibert, 2012); therefore, before calculating the SPEI, the climate model outputs were bias corrected using observational data obtained from the HADUK-Grid observational dataset, also on a 12km grid, for the period 1981-2000 inclusive (Hollis *et al*., 2019). The observations cover the majority of Scotland but do not extend fully to the coast, and the grid does not exactly overlay that of the model, so the grids were converted to location points and nearest-neighbour pairing was used to match each modelled value with the geographically closest observed value for both temperature and precipitation. Bias correction was performed using quantile mapping using local linear least square regression at a 0.11 quantile step (Gudmundsson *et al*., 2012). Each model member was corrected individually using the HADUK-Grid observations.

2.3 Calculation of SPEI

Once the data were bias corrected, the SPEI was calculated for each model member using 1981-2001 as the baseline, and 2021-2040 as the period of interest. The baseline was defined as June 1981-May 2001 because calculating the SPEI at a six-month time step results in NA values for January-May 1981, due to the lack of preceding data to aggregate for those months. This ensured an equal number of months in the past and future periods, while keeping the baseline as early as possible to form an accurate comparison with 'normal' conditions.

SPEI is a standardised drought index that uses precipitation and potential evapotranspiration (PET) to calculate a simple climatic water balance, which is then used to calculate likelihood of water scarcity over a time series (Vicente-Serrano *et al*., 2010). PET is subtracted from precipitation (P), giving a general indication of the climatic water balance (D) in a given area over a given time (Equation 1). For this study, Thornthwaite was used to calculate PET because other methods (e.g. Penman-Monteith) are demanding in terms of additional data requirements (Thornthwaite, 1948).

$$D_i = P_i - PET_i$$

Equation 1. Climatic water balance used to calculate SPEI values (Vicente-Serrano, et al.*, 2010).*

D_i can then be aggregated at different timescales to look at different types of drought. This study used a 6-month time step as the most relevant to the hydrological response times of wetland ecosystems. While these vary by wetland type depending on the primary water sources, most wetlands will experience effects of multi-season droughts, and these effects can be delayed by several months as shortages proceed through the system. The 6-month time step therefore detects inter-seasonal and delayed effects while still highlighting intra-seasonal patterns. Other scales are useful for other water systems; for example, a shorter time step of 1 or 3 months accounts for the quick responses of river flows to changes in precipitation, whereas time steps of a year or more can be more relevant for habitats dependent on groundwater.

Once D_i is calculated, a log-logistic cumulative probability distribution is fitted for the specified baseline period. The future period is then fitted and compared to this distribution, so that the SPEI value assigned to each month in the future period shows how likely the projected water level in that month would have been during the baseline period. The SPEI values are standardised to a mean of 0, such that positive values show increasing likelihood of wetness, and negative values show increasing likelihood of dryness (Figure 1). A value of -1σ or below is commonly defined as a drought event, with -2σ or below suggesting a high likelihood of an extreme drought event (WMO, 2012).

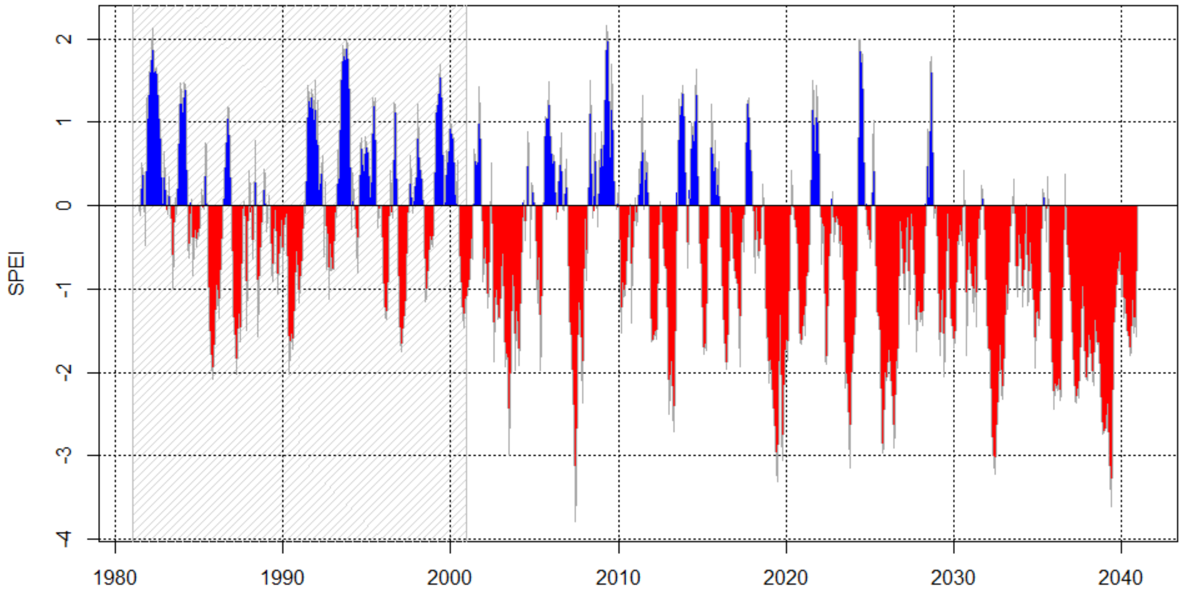

Figure 1. SPEI at an example site, Forsinard Flows National Nature Reserve, for one model member, 1980-2040. Red represents likelihood of dryness, while blue represents likelihood of wetness, with events ≤ -2 defined as extreme drought events. The hatched grey area indicates the baseline period.

2.4 Calculation of drought metrics

Once the SPEI was calculated, two drought metrics were computed based on the SPEI values for each grid cell: frequency of extreme drought, defined as the number of extreme drought events per period, and total duration of extreme drought, defined as the number of extreme drought months per period. Extreme drought was defined as any SPEI ≤ -2; therefore, one event is classed as any period during which each contiguous month has a 6 month SPEI of ≤ -2, and an extreme drought month is classed as any month with an SPEI value ≤ -2.

Drought duration was calculated both for the period as a whole and by season, to take into account seasonal patterns in temperature and precipitation, and the potential for climate change to increase differences in those patterns. Seasons were defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). However, splitting drought frequency into seasons is problematic, as many drought events last longer than three months; therefore, drought frequency was only calculated for the period as a whole.

These metrics were calculated for the baseline period and for the future period, after which the metrics for the baseline were subtracted from the future period to find the amount of projected change from baseline conditions. It is valuable to calculate both absolute projected future values and change from the baseline, as they reveal different impacts; absolute projected future values quantify which sites are likely to experience highest increases, whereas change from baseline highlights which sites may experience the greatest change from previous conditions. This also facilitates comparison between sites; as the same level of dryness can have different impacts on different sites, sites that experience the greatest change from the baseline may be most likely to suffer detrimental effects depending on local conditions.

2.5 Member combination and mapping

The number of extreme drought events per period (frequency) and the number of extreme drought months per period (duration) were calculated for each of the 12 members of the climate model ensemble. The 12 members were then combined by taking the median of each metric at each grid cell. This made the results more easily interpretable, as they could be displayed as one map rather than 12 separate ones. Figure 2 shows how many members agreed with the sign of their median for each grid cell – for example, if the median change for a given cell is positive (indicating an increase in drought), Figure 2 shows how many members out of 12 also gave a positive sign for that cell.

Once combined, the metrics were mapped using ArcGIS Pro. The metrics were mapped both seasonally and for the entire period to visualise the locations with the greatest projected change, as well as the locations with the greatest projected absolute likelihood of extreme drought in the near future.

All analyses were conducted in R version 3.6.0 (R Core Team, 2019), with bias correction using the package “qmap” (Gudmundsson, 2016), and figures and SPEI calculations using the package “SPEI” (Begueria and Vicente-Serrano, 2017). All maps were created in ArcGIS Pro version 2.5.1 (Esri 2020).

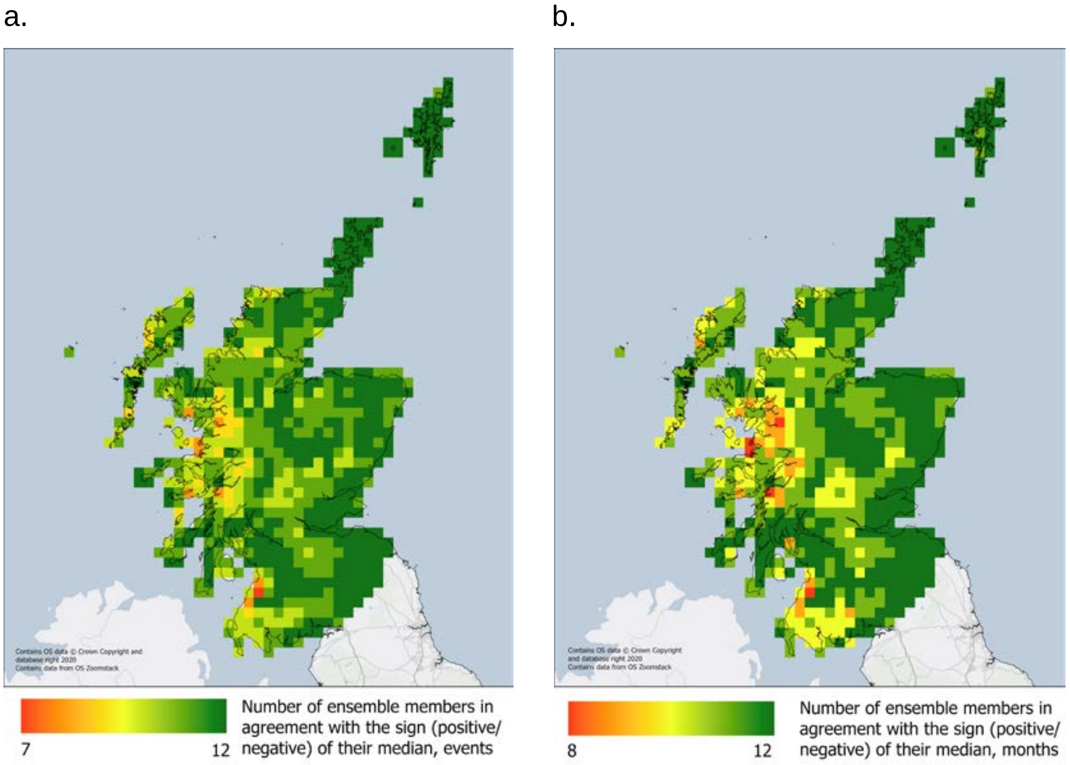

Figure 2. Number of UKCP18 ensemble members in agreement with the sign of their median, for a) change in extreme drought frequency, and b) change in extreme drought duration. © Crown copyright [and database rights] 2020 OS 100017908.

3. RESULTS

Both frequency and duration of extreme drought showed projected increases compared to the baseline, with all grid cells showing increases once all model members were combined. Both metrics were relatively consistent in geographic patterns, with ‘hotspots’ of increase primarily focused along the east coast, especially in the Borders, Aberdeenshire, Caithness, Orkney and Shetland. The west coast showed lower increases, but was still projected to be drier than during the baseline period. Both metrics also showed considerable seasonal variation by geographic distribution and degree of change, with autumn showing the greatest increases across the largest areas, and spring showing the smallest.

3.1 Observed baseline drought

Observed extreme drought during the baseline period was relatively low, with a maximum number of 4 extreme droughts per grid cell (Figure 3a), and a maximum duration of seven months of extreme drought per cell throughout the period (Figure 3b). Many areas experienced no extreme droughts at all. The geographic distribution for both metrics was different to the projections (Figures 4 and 5), with the driest areas along the west of the country and in the south. Spring and summer were the driest seasons, with fewer extreme droughts in autumn and winter (Figure 3c).

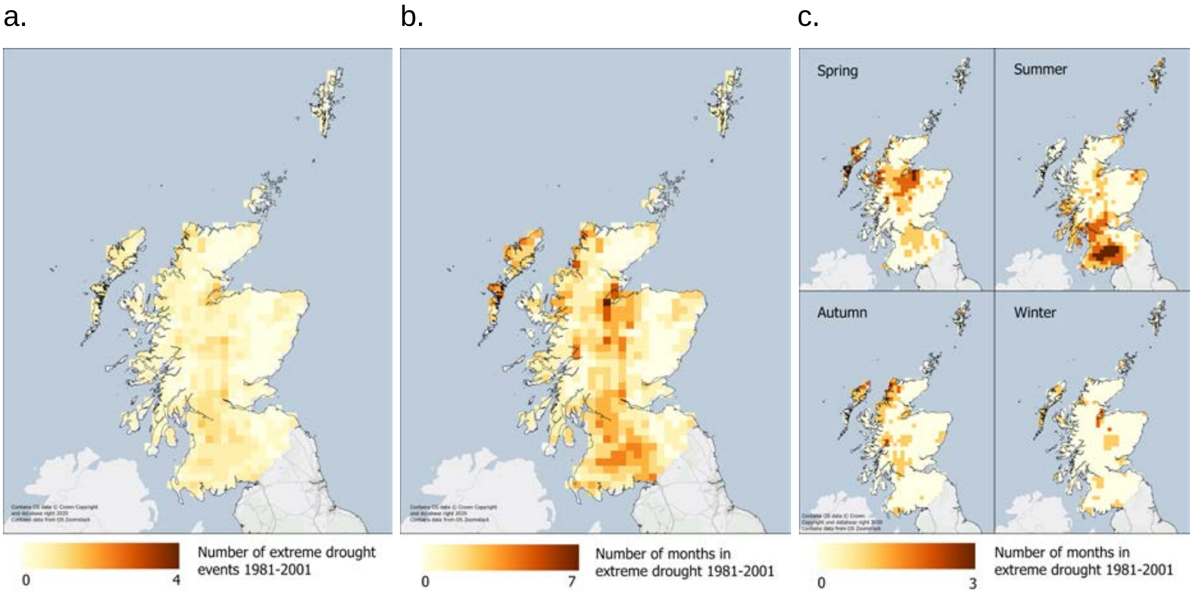

Figure 3. Observed drought patterns 1981-2001, for a) total extreme drought frequency, b) total extreme drought duration, and c) seasonal extreme drought duration. © Crown copyright [and database rights] 2020 OS 100017908.

3.2 Drought frequency

Dividing the projected number of extreme drought events during a period by the length of the period in years gives the return frequency of extreme events for the period in question. During the baseline period, the median return frequency of extreme drought events across all grid cells was one event every 20 years, up to one every 5 years in the driest areas. In contrast, in the future period, the median return frequency of extreme events was projected to be one every 3 years, up to one every 1.7 years in the driest areas (Figure 4a and b). In a very few grid cells these increases equate to an additional 9 events by 2040, in comparison to the baseline period.

Increases occurred across Scotland, with every grid cell showing an increase from the number of events modelled to occur during the baseline period. The majority of the smaller increases occurred along the Western Isles, with the highest increases concentrated in Shetland, Orkney, Caithness, Aberdeenshire, and the Borders.

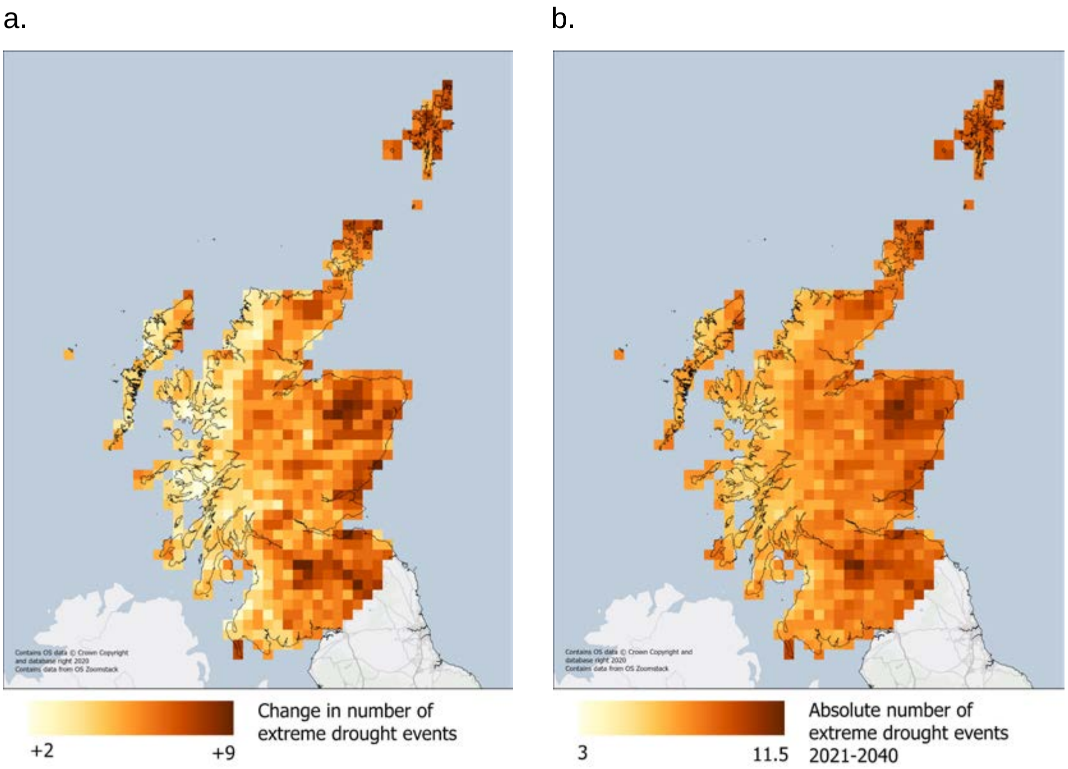

Figure 4. a) Projected change in extreme drought frequency by 2021-2040 in comparison to the baseline (1981-2001), and b) projected absolute extreme drought frequency 2021-2040. © Crown copyright [and database rights] 2020 OS 100017908.

3.3 Drought duration

Calculating total drought duration does not show length of individual events, but indicates the total number of months during the period in which drought conditions may exist. Dividing this by the number of projected events gives an estimate of change per event, with the caveat that events may vary drastically in length. For an area of high predicted change in both number of events and total duration such as the north east, a projected number of drought months between 2021-2040 of 23 divided by projected number of drought events of 10.5 gives an average of 2.2 months per drought event, whereas the same area during the baseline period had an average of 1 month per event.

The total increase in drought duration was up to 22.5 months between the baseline and future period, with every location showing increases (Figure 5a and c). Across all grid cells, this equates to a median likelihood of 4.2% that a given month during the future period will be in drought, in comparison to the baseline period median of 0.4%. Similarly to changes in frequency, the lowest increases occurred along the west coast and Western Isles. Following the same pattern, the greatest increases were in Aberdeenshire, the Borders and Caithness, with particularly strong impacts being seen in Aberdeenshire and in Caithness.

Additionally, dividing drought duration into seasons highlights the effect of seasonality on drought occurrence, which is impacted by changes in patterns of precipitation and temperature across the year (Figure 5b and d). The largest increases in drought duration 2021-40 were seen in autumn, with increases of up to 9.5 months in Aberdeenshire. This contrasts most strongly with spring, in which increases peak at 5.5 months. Spring also showed the greatest number of locations with no change.

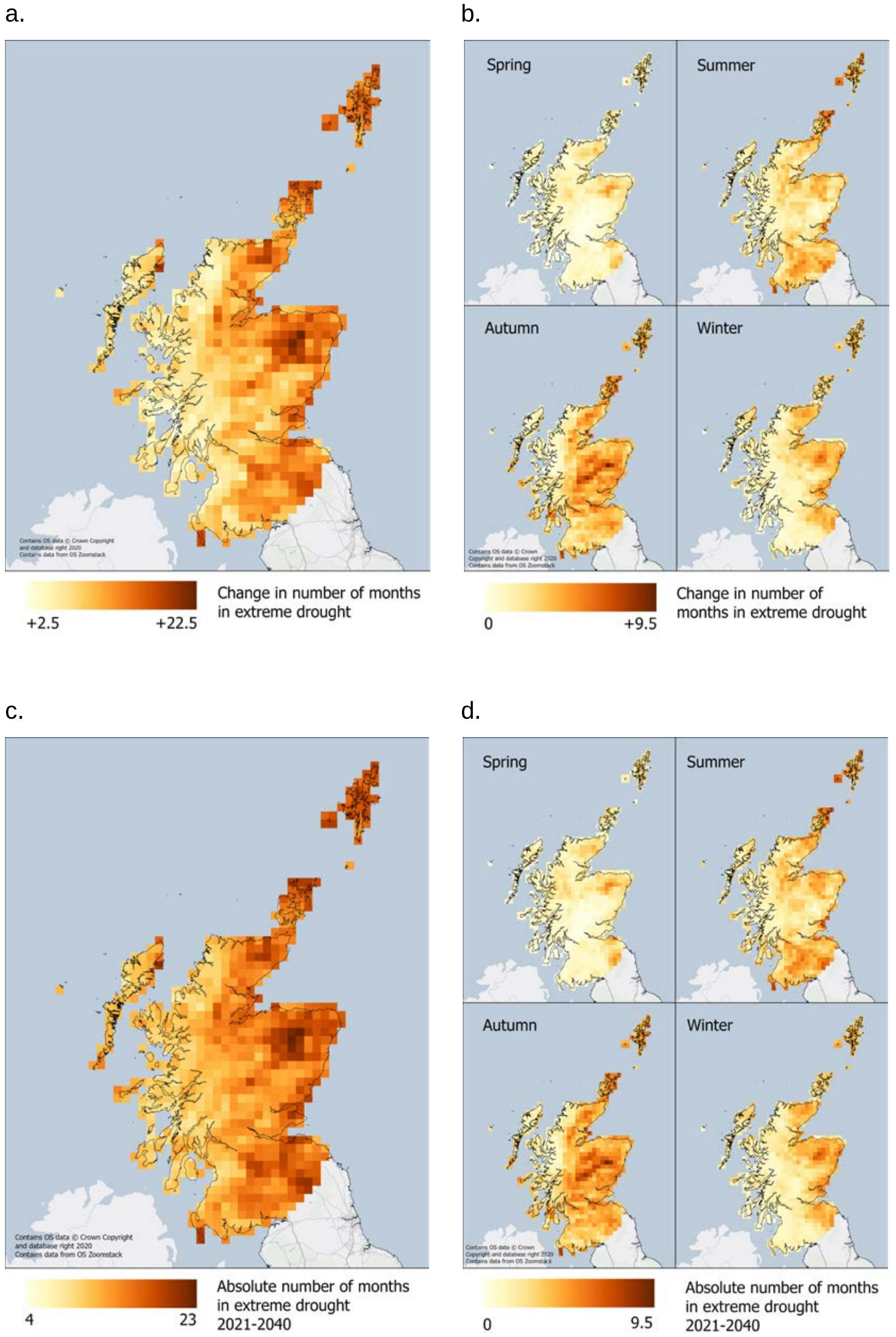

Figure 5. Projected change in extreme drought duration by 2021-2040 in comparison to the baseline (1981-2001), totally (a) and seasonally (b), and projected future absolute extreme drought frequency 2021-2040, totally (c) and seasonally (d). © Crown copyright [and database rights] 2020 OS 100017908.

4. DISCUSSION

In comparison with the baseline period, the increases in both extreme drought frequency and extreme drought duration suggest that extreme droughts in Scotland are likely to become longer and more common within the next twenty years. Changes in frequency will have different impacts to changes in duration, as multiple short drought events affect biota and ecosystems differently than fewer events that last longer. Nevertheless, increases in either type of extreme drought are likely to have negative impacts. Furthermore, the increases were found throughout the country and throughout the year, although the variation in both spatial distribution and between seasons indicates geographic and seasonal influences. This variation in drought type, location, and seasonality will influence the ways in which drought impacts manifest, with implications for management and mitigation strategies.

4.1 Geographic variation

The results highlight the potential for substantial geographic variation in patterns of extreme drought risk in Scotland over the next twenty years. These are consistent with Scotland's typical climatic patterns, with the east coast drier than the west due to the influence of the Atlantic Ocean and mountains in the Northwest Highlands, producing the well-known rain shadow effect to the east (McClatchey, 2014). However, these results indicate that while the west coast will remain wetter than the east, both areas are likely to experience increases in extreme droughts, with different implications for different areas based on habitat types and land use.

Substantial economic and social concerns fall within the areas highlighted as hotspots. Several key industries are dependent on water supplies that could potentially be disrupted by drought increases in the east, including whisky production, agriculture, and forestry, which are valued at £5.5 billion (Scottish Whisky Association, 2019), £672 million (Scottish Government, 2019) and £1 billion (Forestry Scotland, 2015) GVA per year respectively. The concentration of many distilleries on Speyside closely mirrors one of the key identified hotspots, an area that has already been forced to halt production due to drought during 2018 (The Guardian, 2019). Similarly, substantial agricultural interests fall within and near Aberdeenshire, one of the areas projected to experience the greatest changes in water availability, including livestock production, cereal crops and seed potatoes. Climate-related impacts on land use including agriculture are likely to be complex; Brown et al. (2008) projected expansion of prime agricultural land in the east and south as a result of climate change, but this expansion could be reduced by increases in extreme drought. Agro-forestry is also at risk, especially given the dominance of sitka spruce (*Picea sitchensis*), which has known vulnerability to drought conditions, and the location of major plantations along the east coast (Green and Ray, 2009). In addition, the water needs of rural populations are likely to be affected, as 30,000 and 40,000 people in Aberdeenshire and the Highlands respectively depend on wells for their water supply, which could be disrupted by frequent and prolonged lowering of the water table (Rivington *et al*., 2020).

However, while drought increases along the west coast are less substantial in scale, there is still potential for negative impacts on important ecosystems in those areas. The Scottish rainforest is an internationally recognised habitat along the west coast with globally rare species that thrive due to continually wet and mild conditions. The bryophytes, lichens and other epiphytes that form a key part of this ecosystem are especially sensitive to pollution and aridity, and can be damaged by even small decreases in water availability (Ellis, 2019). This demonstrates the potential impacts of even minor increases in drought conditions to vulnerable habitats.

4.2 Seasonal variation

The effect of seasonality on drought occurrence is consistent with climate projections for Scotland, which show increases in seasonal extremes of temperature and precipitation, with hotter, drier summers and warmer, wetter winters (Lowe, 2018). The emergence of autumn as the most drought-prone season may be due to the use of a 6-month time step when calculating the SPEI. As the SPEI values for autumn months therefore reflect the five months prior to them, a build-up of deficits during the spring and summer would manifest during the autumn period. This can be seen in Gosling (2014), which found drought increases by 2050 were greatest in spring and summer using a stream flow index at 1- and 3-month time steps; the shorter time steps show the immediate impacts of deficits, whereas the longer time step of this study pick up longer term processes. The deficits in autumn may therefore be due in part to a failure to recharge groundwater aquifers over that period, although this cannot be assumed based on SPEI alone. This also means that autumn – or any other season – could experience precipitation while also being in a period of water scarcity, if the deficit was substantial enough.

Such seasonal patterns have particular implications for water scarcity risk management strategies, for example focussing agricultural mitigation on specific autumn crops when the effects may be most damaging. For wetlands specifically, the seasonal timing of restoration work is known to affect the success of interventions, alongside the need to be sensitive to other seasonal occurrences such as breeding times (Similä *et al*., 2014). As dry conditions make it harder for drained areas to recolonize (Hinde *et al.*, 2010), these results therefore inform management planning to target interventions for the times of year when they are most likely to be successful.

4.3 Wetland impacts

As wetlands are especially sensitive to changes in water levels, these results have particular implications for impacts on wetland sites across Scotland. Many of the substantial number of designated wetland sites throughout the country, including 51 Ramsar sites, occur in the eastern areas projected to be most at-risk. This includes Sites of Special Scientific Interest (SSSIs) on Orkney and Shetland such as the West Mainland Moorlands, Rousay, Ronas Hill and Lochs of Spiggie and Brow, in Inverness-shire and Aberdeenshire such as the Cairngorms, Moss of Crombie and Reidside Moss, and Special Areas of Conservation (SACs) in the Borders, such as Whitlaw Moss and Branxholme. Additionally, the large projected increases in drought in Caithness are particularly concerning due to the potential impacts this could have on the Flow Country, 400,000 hectares of internationally important blanket bog covering much of Caithness and Sutherland that includes Caithness and Sutherland Peatlands SAC. While many wetland habitats and species are resilient to short term or low-level droughts, more frequent and/or more prolonged periods of water scarcity may result in long-term negative consequences, which could also reduce the ability of wetlands to fulfil their usual ecosystem functions (Middleton, 2012).

4.3.1 Ecosystem health and functions

Key changes that could occur due to drought stress include impacts on habitat provision, water management, and carbon sequestration. As wetland species are adapted to continual or frequent high water levels, many species could be negatively impacted by substantial or prolonged changes to these conditions. This could have serious implications for long term population health; for example, the breeding success of waders such as lapwing, redshank and snipe can be reduced by drying of surface water pools which provide invertebrates for their chicks (Burston, 2006), and frequent drought periods have been liked to population declines or losses in great crested newts (Miró *et al*., 2017). If conditions remain dry for long enough periods, succession can take place, transforming the original plant community to different, more drought tolerant community; fens may move to carr woodland, or

Schwingmoor vegetation may become anchored to the substrate (Wiegers, 1992; van Diggelen, 1997).

Similarly, if vegetative communities are damaged or even altered by dry periods, their ability to filter nutrients such as nitrogen or phosphorous from the remaining water may be reduced, potentially leading to eutrophication (Fisher and Acreman, 2004). Water management may also be further affected by low water levels, as damaged plant communities may be less able to control water flows when water levels return, especially over a short space of time; this can therefore cause flooding and erosion, within the site and downstream of it (Acreman and Holden, 2013; Li *et al.*, 2018).

In addition, peatland habitats in particular risk losing their ability to both sequester and store carbon. Peatlands form valuable carbon stores only when undamaged; damaged or deteriorating peatlands can become significant sources of CO_2 and methane emissions if left unrestored (Nugent, 2019). Low water levels prevent new peat from forming because dead sphagnum no longer remains in waterlogged, anaerobic conditions, but breaks down as in normal soil, releasing its carbon (Bengtsson *et al*., 2016). Alongside this, new sphagnum is unable to grow without high water levels (McNeill and Warrington, 2003), leading to the dominance of other non-peat forming species such as *Calluna vulgaris* (Bannister, 1964). Given the significance of peatland habitats to Scotland's carbon stores, the potential for carbon loss due to drought has serious implications for national carbon emissions, thereby contributing to global climate change.

4.3.2 Additional stressors and feedback loops

The impacts of drought on wetland functions are not limited to the direct effects of low water levels, but are exacerbated by feedback loops caused by additional stressors. Erosion is a key factor in degrading wetland systems; dry peatlands especially are prone to both wind- and flood-driven erosion (Li *et al*., 2018), which can break down the top vegetative layer of bog and expose the peat underneath, damaging the habitat and releasing the stored carbon. Fire is also a higher risk on dry peatlands, which can release massive amounts of carbon in addition to reducing water management and habitat provision (Stracher *et al*., 2015).

Bog bursts and peat slides are key examples of events caused by multiple stressors. Dry conditions can create cracks beneath the surface of a bog, weakening its internal structure such that heavy rain or floods permeate rapidly and can wash away large sections of habitat (Wilson and Hegarty, 1993). These events are often worst on slopes and near anthropogenic disturbance, with one meta-analysis finding artificial weakening of the peat structure to be a major factor in over 50% of peat slides studied (Dykes, 2008). Furthermore, dry conditions can make it harder for damaged habitats to recover from these events, potentially leading to longer-term impacts (Middleton and Kleinebecker, 2010).

The severity and consequences of these risks are determined partially by the condition of each specific site; wetlands in good condition – indicated by Site Condition Monitoring (SCM) for designated sites – may be more resilient to change than sites already in poor condition or hydrologically compromised. A wetland classified as 'favourable' in terms of its SCM status may have healthy plant communities, a functioning hydrology and appropriate management to maintain these conditions, for example appropriate levels of grazing or cutting; whereas sites classed as 'unfavourable' may have reduced hydrological functions, dominance by a particular species, and potentially the beginnings of succession. Therefore, wetlands in good condition may be more tolerant to high levels of change in water levels, whereas unfavourable sites may experience negative impacts with only small reductions in water availability. That being said, all sites are likely to have thresholds of water availability below which substantial change is highly likely regardless of condition (Middleton and Kleinebacker, 2010).

This sensitivity will also vary according to the plant communities present and the water supply mechanisms of each site, as well as any management techniques. As wetland hydrology can differ substantially by type, the site’s water source will strongly influence the effect of drought on a given area (Gilvear and McInnes, 1994; Middleton and Kleinebacker, 2010). Primarily rain water-fed wetlands may respond more quickly to reductions in precipitation, making them highly vulnerable to deficits (Winter, 2000); however, these wetlands may also experience short-term droughts relatively frequently due to seasonal precipitation patterns, and therefore may be initially resilient (Middleton and Kleinebacker, 2010). Wetlands supplied primarily by surface water are likely to respond more slowly as precipitation deficits begin to influence surface water levels, but may then be sensitive to localised changes to surface water flow dynamics. Finally, primarily groundwater-fed wetlands may be least affected initially, but also may be the slowest to recover, due to the long response times of groundwater processes (Winter, 2000).

5. CONCLUSIONS

The variety of responses that can be expected between habitat types, and between specific sites within those types, highlights the importance of site-specific analyses in implementing water scarcity management plans. The results presented offer an overview of the likely changes to drought risk in the near future, but taking action to mitigate these threats necessitates exploration of the unique risks and dynamics of individual sites to ensure measures are tailored to the challenges.

To that end, further work is needed to apply these results, with a necessary focus on practical solutions and applications. For NatureScot in particular, this may mean targeting protected areas such as SSSIs, SACs and Ramsar sites as focus areas for restoration work and maintenance, planned with drought risk in mind. This would help ensure that resources are used most effectively, and can be targeted to areas in greatest need.

However, a site-based approach should also sit within the context of landscape scale ecology and land-use, incorporating impacts on hydrology at a catchment level. This is a key area for partnership working to facilitate mitigation work. There may also be opportunities to influence land management support schemes in connection with the exit from the European Union, to put clear emphasis on climate change risk management – including drought risk.

Overall, this study shows a clear increase in extreme drought risk is likely in the imminent future, with wide-ranging associated implications. The impacts of the drought over the summer of 2018 illustrate the potential damage water scarcity can do in Scotland, as well as the cross-seasonal nature of many drought events (Stevens *et al*., 2019). As the impacts will vary by area, these results can facilitate targeted water scarcity planning that could mitigate some of these effects, especially in highlighted hotspots, through proactive management approaches. It is imperative that NatureScot and others take advantage of this opportunity to focus its climate change planning, and include drought risk as a key potential threat to Scottish environment and ecosystems.

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