# How might climate change impact Scotch Whisky production in the next 50-100 years?

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## Key Findings

- Future climate change projections indicate that Scotland will experience **hotter and drier summers** and **warmer and wetter winters** over the next 50-100 years. **Extreme weather events** are likely to increase in frequency and intensity across all seasons.

- As defined by law, Scotch Whisky distillation and maturation must occur in Scotland using only three raw materials: **cereals, water, and yeast**.

- There are currently **133 operating Scotch Whisky distilleries** in Scotland categorised into **five regions** of distinct geography and climate. The impacts of climate change on the industry are therefore likely to be experienced in diverse ways and to different extents.

- **Spring barley** is expected to benefit from elevated atmospheric $CO_2$ levels and rising temperatures, producing improved yields during favourable climatic conditions. However, an increase in the frequency and magnitude of **drought and heat stress** will impact harvest quality and quantity and result in **year-to-year yield fluctuations**.

- Although UK **winter wheat** agriculture is expected to remain viable over the next 50-100 years, an increased occurrence and intensity of **heatwaves, droughts, and heavy rainfall events** will create challenges for maintaining stability in annual crop yields.

- Climate change policies, land use management, market signals, and global factors must be considered when determining the **future availability and cost** of cereal crops.

- **Drought** frequency, intensity, and duration in Scotland is expected to increase throughout the 21st century leading to a **reduced and intermittent water supply** in some areas. Limits to water abstraction may decrease or halt production in distilleries as they are heavily reliant on a continuous water supply throughout production.

- The various stages of Scotch Whisky production, including malting, fermentation, distillation, and maturation, have been developed to suit the temperate maritime climate of Scotland. **Warmer air and water temperatures** will lead to inefficient cooling in traditional distilleries and create challenges for conserving the **character, consistency, and quality** of Scotch Whisky.

- An increase in the frequency and magnitude of **flooding and extreme weather events**, in addition to **rising sea levels and coastal erosion** will create additional pressures on the facilities and logistics of Scotch Whisky production.

# Contents

# 1. Climate Change in Scotland

Scotland is defined by a temperate maritime climate owing to its northern situation and the influence of dominant south-westerly Atlantic winds (McClatchey, 2014). A water abundant nation, total rainfall is often greater compared to the rest of the UK with rainfall distribution following the same characteristic east-west wet-dry gradient (Visser-Quinn et al., 2021). On average Scotland receives around 1000 mm of rainfall annually with over 1600 mm falling in western regions and eastern areas receiving approximately 700-800 mm (SEPA, 2021).

Historically, the extremes in rainfall and temperature found in continental climates have rarely occurred in Scotland (Werritty & Sugden, 2012). However, the typically mild climate has already experienced significant changes over the last few decades, trends that are projected to strengthen with climate change over the next 50-100 years (Figure 1). For example, Scotland's warmest 10 years on record have all occurred within the last 25 years and, over the last decade, temperatures have risen 0.69˚C above the 1961-1990 average. Rainfall has also increased with the last decade 9% wetter than the 1961-1990 average and winter precipitation increased by 19%. Furthermore, sea levels have risen on average 1.4 mm/year around the UK since the beginning of the 20$^{th}$ century resulting in enhanced coastal flooding and erosion (Adaptation Scotland, 2021; Lowe et al., 2019).

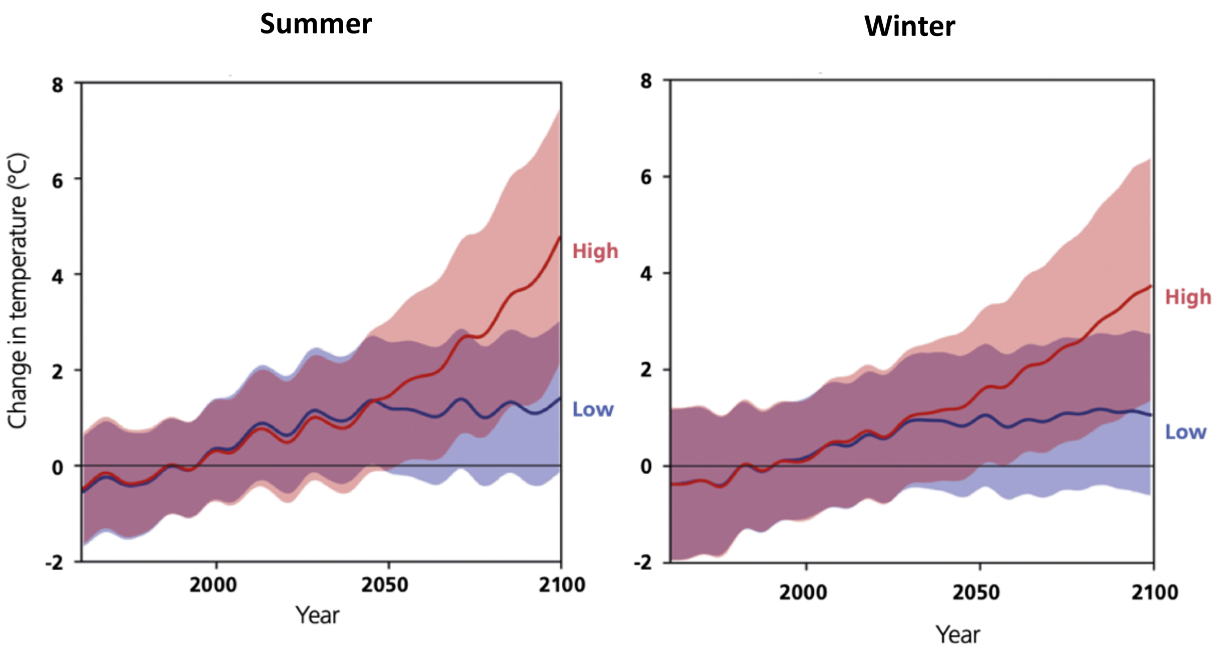


**Figure 1**
Projected changes in Scotland's summer and winter mean temperatures, relative to the 1981-2000 baseline, by 2100 under low (blue) and high (red) emissions scenarios (Adaptation Scotland, 2021).

By the 2050s, annual temperatures in Scotland are projected to become around 1.1˚C warmer, compared to the 1981-2000 baseline, and 1.1-2.0˚C warmer by the 2080s (UK Climate Risk, 2021). Warming is expected to be greatest during the summer months producing hotter and drier conditions with greater extremes. The probability of experiencing summers as hot as the UK 2018 summer heatwave has already increased by 12-25% and is projected to rise to 50% by 2050 (Adaptation Scotland, 2021; Lowe et al., 2019). Whilst a 7% decline in summer rainfall by the 2050s and 11-18% decrease by the 2080s will contribute to an overall drying trend during summer months, extreme rainfall events will become more frequent and intense (UK Climate Risk, 2021) (Figure 2). Future winters in Scotland are expected to become warmer and wetter. The total rainfall amount, number of wet days, and rainfall intensity are all expected to increase, particularly for western Scotland. By the 2050s, winters in Scotland could be 8-12% wetter than the 1981-2000 baseline with a 5-19% increase in precipitation by the 2080s (Adaptation Scotland, 2021; Lowe et al., 2019).

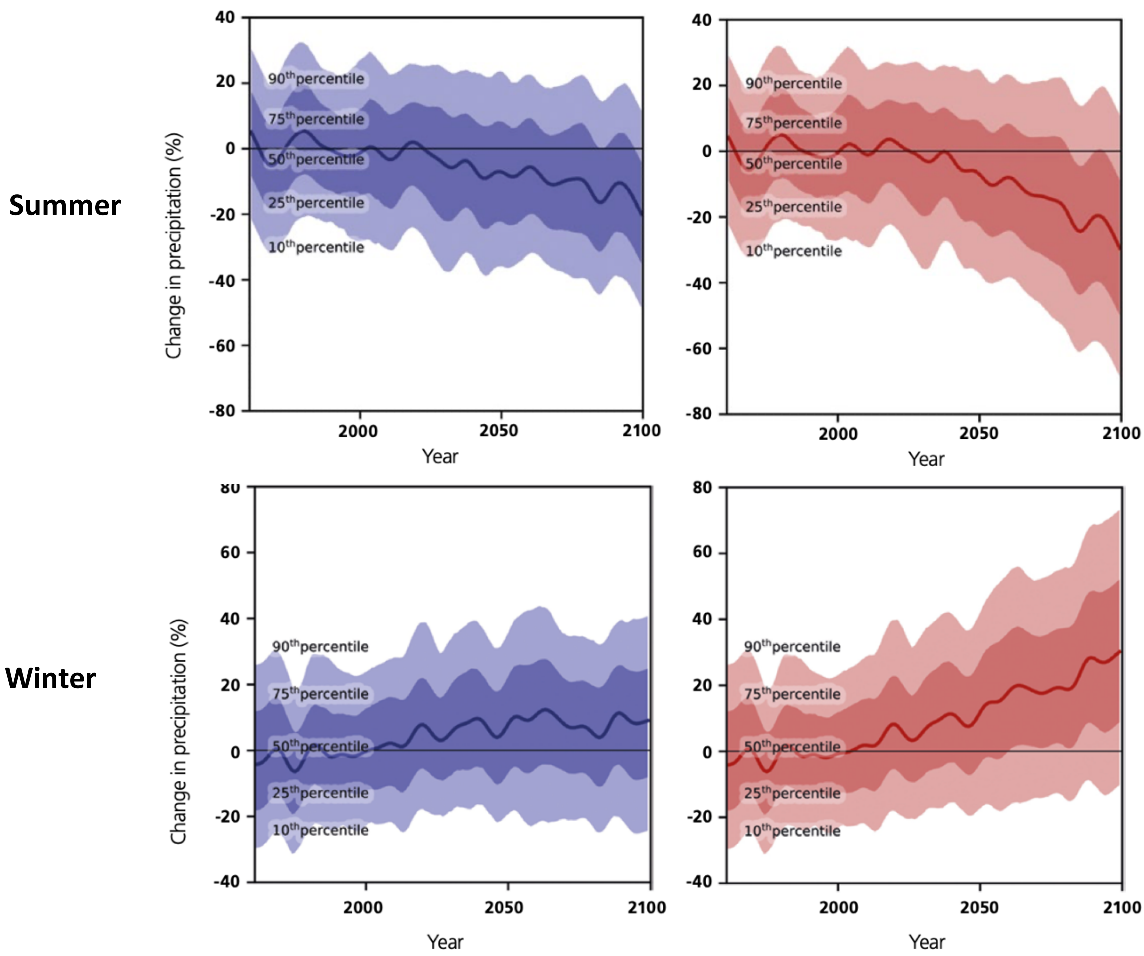


**Figure 2**
Projected changes in Scotland's summer and winter precipitation, relative to the 1981-2000 baseline, by 2100 under low (blue) and high (red) emissions scenarios (Adaptation Scotland, 2021).

## 2. The Scotch Whisky Industry

To be certified as Scotch Whisky under law, distillation and maturation must occur in Scotland using only three raw materials: cereals, water, and yeast (UK Government, 2009). The two major categories of Scotch Whisky, Malt Scotch Whisky and Grain Scotch Whisky, are distinct in the cereals used and the distillation processes. While Malt Scotch Whisky is distilled in a pot still using 100% malted barley, Grain Scotch Whisky incorporates other cereals (often wheat or maize) in addition to malted barley and is distilled in a patent still. Blended Scotch Whisky, a combination of malt and grain whiskies, accounts for the largest proportion of sales. Overall, the Scotch Whisky industry operates as the largest UK food and drink sector, contributing over £5 billion annually to the economy (The Scotch Whisky Association, 2020).

Scotland is home to currently 133 operating Scotch Whisky distilleries, the largest concentration of whisky production in the world (The Scotch Whisky Association, 2020). The character of the Malt Scotch Whisky produced is profoundly influenced by geographical location and thus categorised by the regions: Highland, Speyside, Islay, Campbeltown, and Lowland (Figure 3). The distinct geography and climate of different whisky production regions will play a fundamental role in the intensity and type of climate change impacts experienced (The Scotch Whisky Association, 2019).

**Figure 3**

Categorisation of Scotland's Malt Scotch Whisky distilleries according to geographical location: Highland, Speyside, Islay, Campbeltown, and Lowland.

# 3. Climate Change and the Raw Materials of Scotch Whisky

## *3.1. Cereals*

### *3.1.1. Barley*

Barley is a hardy crop suited to a cold temperate climate and forms the major constituent of Scotch Whisky. Over 85% of malting barley is grown domestically, accounting for 48% of the total arable land in 2019 and making it Scotland's most economically important crop (Rivington et al., 2018; The Scotch Whisky Association, 2020). Spring barley, usually sown from December until late April, is preferentially used in Scotch Whisky production over winter sown barley that does not fulfil malting requirements (Cammarano et al., 2019).

Climate change is expected to both benefit and pose risks to UK barley production with impacts varying spatially and temporally (Rivington et al., 2018). On the one hand, crops may positively respond to elevated atmospheric $CO_2$ levels through increased photosynthesis, water retention (due to reduced transpiration), and improved nitrogen use efficiency, a vital nutrient in plant growth (Claesson & Nycander, 2013; Clausen et al., 2011; DaMatta et al., 2010). In addition, warmer temperatures can encourage early maturity and help avoid the heat and water stresses of the summer months. Such responses have the potential to improve spring barley yields under future climate change and may provide the opportunity to grow barley in more marginal locations (Yawson et al., 2016, 2020).

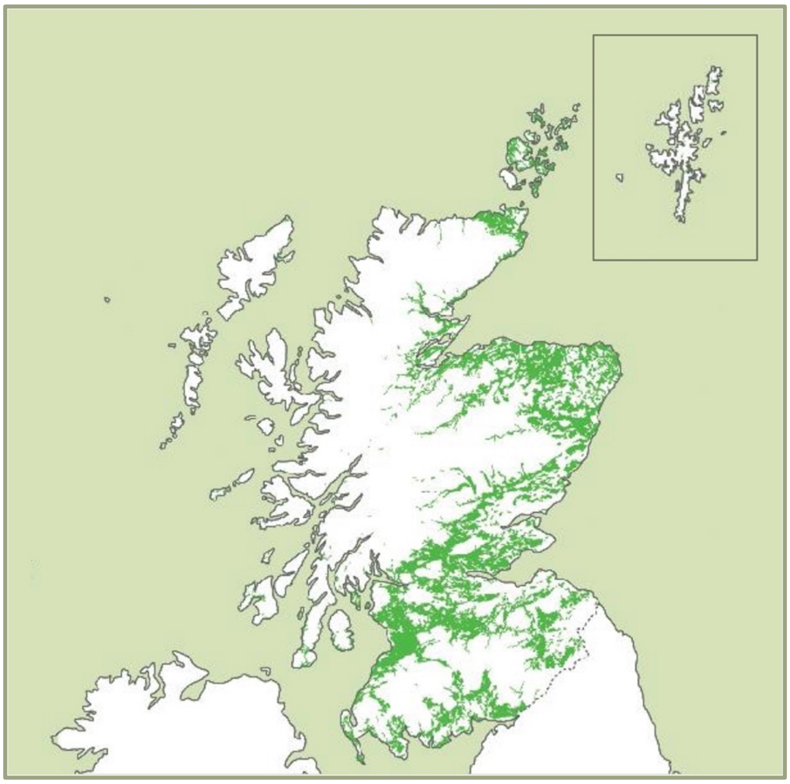

**Figure 4**

Distribution of land (green) in Scotland suitable for supporting mixed agriculture (primarily barley), accounting for around 20% of Scotland's land area (Birnie et al., 2010).

On the other hand, hastened crop development under higher temperatures can shorten the time window for biomass accumulation, reducing the amount of plant material converted to grains (Rivington et al., 2018). Elevated temperatures will also be accompanied by more frequent and severe heatwaves impacting crop yield and quality. Furthermore, water availability is vital to arable agriculture and soil moisture deficits can be detrimental to crop growth. The cultivation period of spring barley spans the months of April to August in which conditions are projected to become warmer and drier with increased temperature extremes (Lowe et al., 2019). In addition, most of the arable agriculture occurs in the drier east of Scotland where drought stress will be greatest (Figure 4). The high latitude of Scotland and hence lengthened summer days and high solar radiation could exacerbate drought stress (Cammarano et al., 2019).

Although barley is viewed as a relatively drought-tolerant crop, the negative consequences of drought stress have already been witnessed over the last decade, for example the UK summer 2018 heatwave resulted in a 7.9% decline in UK spring barley production (McGrane et al., 2018; The Scotch Whisky Association, 2020). The considerable yield reductions had repercussions on the value of UK malting barley, increasing the price per tonne to £179. In comparison, UK malting barley cost £145 per tonne in 2017 (Defra, 2020). As Scotch Whisky distilling requires around 800,000 tonnes of spring barley per year, a price increase of this magnitude would add costs of around £27 million for the industry (O'Connor, 2018).

It is widely considered that spring barley agriculture will remain viable in the UK over the next 50-100 years with potential mean yield gains. However, whether enhanced productivity in response to elevated atmospheric $CO_2$ concentrations and temperatures would be sufficient maintain stability in supply remains a fundamental question (Yawson et al., 2016, 2020). Ultimately, water availability may be a limiting factor and have the largest impact during sensitive growth stages and in soils susceptible to water deficits, such as high clay content and low organic matter soils. Similarly, climate extremes during vulnerable periods can severely impact harvest quality and quantity with heat stress during the flowering stage reducing spring barley yields by as much as 30-40%. Hence, future yields are likely to see both increases under favourable climatic conditions but also substantial reductions, a trend that will become enhanced towards the end of the century (Rivington et al., 2018).

#### *3.1.2. Wheat*

Growing favourably in a temperate climate, winter wheat constitutes the highest yielding UK crop and covers the greatest acreage of arable land (around 40%). Soft winter wheat, sown in late September to November and harvested the following year, is best suited for alcohol production (The Scotch Whisky Association, 2020). Since 1984, wheat has replaced maize as a major component in Grain Scotch Whisky and is now used as the primary cereal in six of the seven grain distilleries (Brown, 1990). An inherent part of the industry's philosophy favours local sourcing of cereals and thus over 70% of Scottish grown winter wheat is used by distilleries. As grain distilleries are predominately situated in southern and central Scotland, wheat grown in northern England is also commonly used (Bringhurst & Brosnan, 2014).

Wheat is a sensitive crop to adverse weather conditions and liable to substantial fluctuations in yields (Harkness et al., 2020). While heat stress during flowering can diminish grain quantity, similar conditions during the grain filling stage can impact the quality and size of wheat grains (Nasehzadeh & Ellis, 2017; Savill et al., 2018). Late frosts during ear emergence and flowering can also result in yield reductions (Al-Issawi et al., 2013). Water deficit is an additional stressor, particularly for the approximately 30% of UK wheat cultivated on soils predisposed to drought, and is predicted to intensify with future climate change (Weightman et al., 2005) (Figure 5). Drought episodes can halt growth and cause dieback during the stem elongation and grain filling stages, whilst limited water availability during reproductive maturity can diminish grain number (Ma et al., 2017). As winter wheat is sown in the autumn months, winter precipitation also plays an important role in determining the quality and quantity of harvest. Projected increases in rainfall could lead to the loss of topsoil and vital nutrients, waterlogged soils, and soil compaction (Berry et al., 2003).

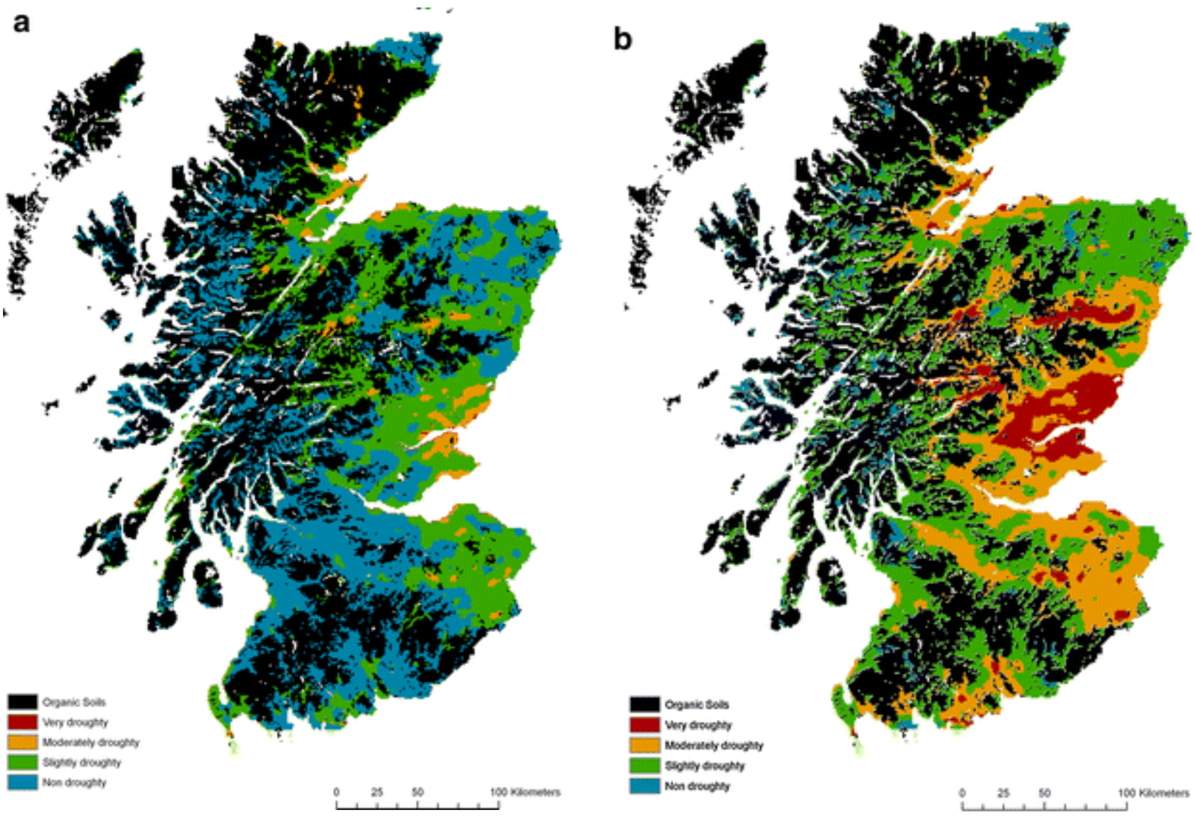


**Figure 5**
Drought risk for Scottish wheat production for the (a) 1981-2000 baseline and (b) projected by the 2050s (Brown et al., 2011).

In general, the UK's future climate is expected to remain suitable for growing winter wheat with potential improvements in conditions during sowing and harvesting (Harkness et al., 2020). However, maintaining consistent productivity alongside an increased frequency and severity of adverse weather events will present challenges. A heightened probability of extreme temperatures across east England by the 2050s may result in substantial yield variability (Arnell & Freeman, 2021). Furthermore, projected increases in winter and spring rainfall may produce issues of waterlogging, leaching, root anoxia, and lodging (stem collapse) (Harkness et al., 2020; UK Climate Risk, 2021).

#### *3.1.3. Other considerations*

Warmer conditions, lengthened growing seasons, and reduced frost incidence could promote the cultivation of less suitable regions and introduce new crops into the UK's agricultural landscape (McGrane et al., 2018). Once an integral ingredient in Grain Scotch Whisky, the importance of maize has declined substantially over the last few decades (Bringhurst & Brosnan, 2014). As a crop growing only marginally in parts of England, warmer temperatures could lead to a resurgence in the use of maize by distilleries (McGrane et al., 2018).

In addition to expanding the range of crops, warmer summers and milder winters are expected to increase the area of suitable habitats for invasive species, pests, and diseases (UK Climate Risk, 2021). Temperature is a fundamental determinant of disease development and pathogen survival. Reduced frost incidence is likely to make certain diseases, such as rusts and powdery mildews, more severe during winter and spring. However, warmer and drier summers may negatively impact pathogen populations growing on foliage and stems (West et al., 2015). A greater threat to crop production is posed by insect pest pressure through direct damage to plants and transmittal of pathogens. An increase in global temperatures by 2˚C may result in yield losses of 46% for wheat and 31% for maize across the world. Temperate regions, such as the UK, are likely to experience the greatest impacts as both the size of insect populations and their metabolic rate increases with warming (Deutsch et al., 2018).

The impact of climate change on soil nitrogen processes and availability for crops is more difficult to predict. The extent and timing of nitrogen availability will be fundamental in determining crop growth and grain quality. Complexities in the response of nitrogen in different soil types will lead to a large spatial variability in grain nitrogen uptake (Rivington et al., 2018).

Moreover, future agricultural production in the UK should not be considered in isolation from climate change policies, land use management, market signals, and global influences (Angus et al., 2009). Currently, over 50% of the UK's cultivated arable land area is dedicated to cereals, a figure likely to substantially decline in response to climate change mitigation measures involving biofuel and afforestation (Rowe et al., 2009). Tight regulations already exist for converting grassland to arable uses and such policies may become stricter, offsetting any yield gains (Yawson et al., 2020). Beyond domestic issues, potential changes in agricultural production and supply must be placed in a global context. For example, large quantities of UK feed barley are already exported to the Middle East where climate change impacts may be more severe and oil revenues can outcompete other users (Rivington et al., 2018).

### *3.2. Water*

The Scotch Whisky industry is reliant on a regular and sustainable source of freshwater for numerous stages in production including malting, mashing, distillation, removal of effluent, and dilution to bottling strength. To ensure a continuous supply of uncontaminated freshwater, each distillery relies on its own private water source in the form of a river, stream, loch, spring, or piped supply, which imparts unique flavour characteristics on the end-product. The industry's heavy reliance on this precious resource is reflected by the high concentration of distilleries in Speyside where water is abstracted from the River Spey (Bringhurst et al., 2014). In total, whisky distilleries use around 61 billion litres of water annually, the majority used in the cooling process. It is a water-intensive product in which a single litre of whisky requires 46.9 litres of water (McGrane et al., 2018).

The characteristic climate of Scotland with high annual rainfall totals and a general wealth of water resources has historically ensured Scotch Whisky distilleries a plentiful supply of clean, freshwater (Gosling, 2014). However, this image of Scotland masks the regional and temporal discrepancies in water storage and supply that climate change is predicted to exacerbate. Increased temperatures and changes in rainfall patterns that result in extreme low river flows and periods of drought will cause some areas to become increasingly water-scarce, impacting the environment and creating pressures on water supply (Blasco et al., 2015; Werritty & Sugden, 2012). Drought conditions are most likely to translate into water scarcity in parts of Scotland with small storage capacities, reliant on small lochs or direct river abstraction with limited groundwater contribution, such as the islands of Islay and Skye (Gosling, 2014). Furthermore, non-climatic pressures can intensify water shortages in areas of high demand and competition for different uses including public water supply, hydroelectricity generation, agriculture, and industry (Visser-Quinn et al., 2021). Future climate change may also contribute to water quality issues by introducing elevated quantities of nutrients and contaminants into waterbodies through increased surface runoff and soil leaching, as well as enhancing algal growth (UK Climate Risk, 2021).

Recent droughts have already demonstrated the detrimental impacts of water scarcity on the Scotch Whisky industry (Baird et al., 2021). In response to drought conditions during summer of 2018, five of Islay's ten distilleries and the Blair Atholl and Edradour distilleries in Perthshire were forced to halt production (McGrane et al., 2018). Furthermore, Glenfarclas in Speyside reported an entire month's loss of production, amounting to 300,000 litres of whisky (The Guardian, 2019). The event resulted from a reduction in spring and summer rainfall to 74-83% of the 1981-2010 average, translating into river flows 40% below the long-term average for the Tweed, Dee, Spey, and Deveron (Hannaford, 2015; Kendon et al., 2020). By the 2050s, Gosling et al. (2014) predict an increased frequency of summer droughts in which previously 1 in 40-year events may occur every 20 years. This is consolidated by research suggesting an increase in drought intensity and duration across Scotland by the 2080s, concentrated in the autumn season and focused in hotspots such as Speyside (Collet et al., 2018; Visser-Quinn et al., 2021).

A combination of factors including, the antecedent rainfall, type of water resource, water storage capacity, spatial distribution of rainfall, and demand from water users, will ultimately determine the availability of water to individual distilleries. A generalised picture of the drought vulnerability to Scotch Whisky producers can, however, be made at a regional scale. Speyside, situated in the drier eastern region of Scotland and home to numerous distilleries abstracting from the River Spey, has been identified as a future drought hotspot. In addition, a small water storage capacity in coincidence with a high concentration of distilleries, could threaten water shortages on the island of Islay (Baird et al., 2021).

## 4. How Climate Change May Impact the Production Process

The character, consistency, and quality of Scotch Whisky is a legacy of Scotland's mild and wet climate. Various stages in the production of this emblematic product have evolved under specific climate conditions that could alter under future climate change, requiring adaptation and investment (SWA & SWRI, 2011).

### 4.1. Malting

Malting involves soaking the cereal grain to initiate germination, followed by drying to breakdown grain protein walls for subsequent fermentation. Floor maltings have been historically used and are still retained by some distilleries often located in Islay and Orkney. During this process, temperatures must be kept below 70˚C to prevent the destruction of enzymes. However, distilleries reliant on floor maltings and without temperature control are vulnerable to high ambient air temperatures that result in overheating. Hot weather spells are also an issue for kilning, which relies on cold, dry air to quickly dry the malt. The additional moisture that warmer air carries results in kilning having to be extended and reduces the effectiveness of fermentation (Bringhurst & Brosnan, 2014).

## 4.2. Fermentation

Following mashing, the resultant wort must be cooled using water to create an optimum temperature that is maintained (usually a maximum of 33˚C) for yeast to convert sugars to alcohol during fermentation (Russell & Stewart, 2014). Hot summer days reduce the efficiency of cooling due to warmer ambient air and water temperatures, requiring additional water to prevent the fermentation from failing (UK Government, 2019). This can cause further problems during drought conditions, as experienced in 2018, resulting in distilleries reducing or halting production (McGrane et al., 2018; Rivington et al., 2018).

## 4.3. Distillation

The subsequent distillation stage is also impacted by warm air and water temperatures. High ambient temperatures can lead to high evaporative losses during distillation and inadequate cooling by condenser water can add an unwanted sulphur note to the spirit. To be collected at the desired temperature of around 20˚C, distillation is often run slower and less frequently during hot conditions, negatively impacting production schedules (Nicol, 2014). Under future climate change, a 1˚C rise in air temperature could result in water temperature increases of 0.4-0.7˚C in Scottish rivers during the summer. Rivers in north and north-west Scotland may demonstrate the greatest sensitivity to air temperature increases (UK Climate Risk, 2021).

## 4.4. Maturation

Traditionally, the mild climate of Scotland has promoted a gentle and gradual maturation of Scotch Whisky in oak barrels, contributing to its characteristic flavours. The ageing process involves the expansion and contraction of the whisky and oak in response to temperature and barometric pressure changes. Warm temperatures force the liquid into the oak, which extracts flavour and aroma compounds including tannins, vanillins, and wood sugars. As evidenced by whisky distilleries in hot climates, warm temperatures can accelerate maturation as the spirit interacts more aggressively with the oak and alters the whisky character. The porous nature of the wood means that as the whisky slowly matures a small amount evaporates through the wood into the atmosphere, referred to as the 'angel's share'. In warm and humid climates significant annual volume losses of whisky occur, strengthening the spirit. Although this issue can be counteracted by diluting the end-product and reducing the timeframe dedicated to maturation, the end-product can be substantially influenced by different climate conditions (UK Government, 2019).

## 4.5. Waste Removal

Significant volumes of wastewater are produced at several stages of Scotch Whisky production, amounting to 20 litres for every litre of spirit distilled. Whilst the mashing and fermentation processes can generate wastewaters containing caustic soda, significant levels of copper can result from the copper stills used during distillation (Murphy et al., 2009). Often effluent is treated to remove toxic volumes of contaminants before being discharged into the environment. However, as treated wastewater can only be released under consent into large and sufficiently fast-flowing waterbodies, drought conditions can restrict effluent discharge (SWA & SWRI, 2011).

Recent initiatives to improve waste removal and reduce environmental impacts have involved the use of wetlands to filter and cleanse wastewater. Wetlands remove excess and harmful pollutants by capturing, processing, and storing contaminants in soils and plant material, preventing release to the wider environment (Jack et al., 2014). However, wetlands are highly sensitive to temperature and hydrological changes, which can alter the biogeochemistry and functioning of the ecosystem (Baird et al., 2021). Elevated temperatures, altered rainfall patterns, and the increased occurrence of extreme events can transform the essential ecosystem services provided by wetlands into disservices. Instead of absorbing nutrients and contaminants, enhanced decomposition rates induced by increased temperatures and lowered water levels can release pollutants and destroy water purification services. Extreme drought can eventually lead to wetlands drying out entirely (Salimi et al., 2021)

## 4.6. Production Materials

The oak casks in which Scotch Whisky matures for a legal minimum of three years are commonly made from American white oak or European oak. Previously used in the production of bourbon, sherry, port, or even wines, second-hand casks are reused by Scotch Whisky distillers several times. The vast majority of oak casks are produced from American white oak grown throughout the eastern United States and southern Canada (Conner, 2014). Future climate stress is likely to be most pronounced in white oak populations farthest west and in central US, in response to higher summer temperatures and decreased summer precipitation. Eastern US populations are less likely to be adversely impacted and white oak may become more dominant in regions where competition with less drought and fire tolerant species, including American beech, red oak, and sugar maple, is reduced (Goldblum, 2010). A major threat to white oak populations is posed by pests and pathogens, which are predicted to increase under future climate change scenarios owing to milder winters and warmer summers (Rogers et al., 2017).

Traditionally Scotch Whisky production has involved the burning of peat to dry malted barley, imparting a smoky, peaty flavour to the product (UK Government, 2019). While many distilleries have since ceased the use of peat in the production process, the aromatic flavour has become characteristic to some distilleries, particularly those in Islay (Bringhurst & Brosnan, 2014). Covering more than 20% of the land area in Scotland, peatlands are a form of wetland in which waterlogged and cool conditions prevent full decomposition of plant material and create highly organic soils (Bruneau & Johnson, 2014). Maintaining the necessary cool, waterlogged environment required for peat formation will become increasingly challenging under warming conditions and drier summers (Ferretto et al., 2019).

# 5. Climate Stressors on Facilities and Logistics

## *5.1. Flooding*

The projected increases in the frequency and intensity of heavy rainfall events in Scotland threaten elevated risks of river and surface water flooding (Adaptation Scotland, 2021). Declines in snow cover expanse and depth in the Scottish Highlands and Cairngorms will exacerbate the issue, resulting in maximum peak flows earlier in the winter and higher peak flows in sensitive catchments (UK Climate Risk, 2021). The last four decades have already recorded increases in high river runoff by over 20%, amounting to an almost 45% increase during the winter (Hannaford, 2015). Projections for river flows under a high emissions scenario estimate an increase of over 50% by the 2080s (Kay et al., 2021).

A heightened flood risk would have implications for Scotch Whisky production in several ways, impacting agriculture, facilities including warehouses and distilleries, and logistics, such as supply and transportation (Schrieberg, 2017; SWA & SWRI, 2011). In recent years, extensive areas of agricultural land have experienced fluvial flooding, particularly along the major rivers of the Tay and Tweed. By the 2050s, the area of high-quality agricultural land at risk from fluvial flooding is estimated to increase by 26%, reaching 31% by the 2080s under a low emissions scenario. There are currently around 30,000 business and industry buildings under a medium likelihood flood risk and about 10,000 buildings face a high likelihood of flooding (UK Climate Risk, 2021).

## *5.2. Rising sea levels*

The dynamic response of coastlines to rising sea levels will create further challenges for coastal distilleries. Soft, erodible coastlines cover up to 19% of the Scottish coast and support between 30-50% of all coastal buildings and infrastructure (UK Climate Risk, 2021). Tidal gauges reveal that even small rises in sea level have resulted in more frequent flooding (Ball et al., 2008). Sea level rises of over 1 m along the Scottish coast by the end of this century will create significant risks of coastal erosion and flooding, especially for vulnerable low-lying islands (Adaptation Scotland, 2021).

### *5.3. Extreme weather events*

Alongside the flooding and erosion caused by rising sea levels, coastal distilleries also face more frequent and higher magnitude extreme weather events due to warmer sea temperatures. Delays and cancellations of ferry services may result and lead to shortages in raw materials and difficulties in shipping finished goods (Schrieberg, 2017; SWA and SWRI, 2011). Islay, a small island off Scotland's western coast, is already heavily impacted by numerous Atlantic storms, a situation that is likely to become more challenging for its ten Scotch Whisky distilleries (The Scotch Whisky Association, 2019b).

## 6. Conclusion

Scotland's climate is projected to experience substantial changes over the next 50-100 years, placing pressures on numerous elements of the Scotch Whisky industry from the sourcing and supply of raw ingredients and materials to the functioning of production and distribution processes (Harkness et al., 2020; Rivington et al., 2018; Yawson et al., 2016). While the overall impact of climate change on cereals, such as barley and wheat, is difficult to predict, significant annual and geographical variations in yield in response to extreme weather events is likely. One of the greatest challenges will be faced in maintaining a continuous freshwater supply, a resource that the Scotch Whisky industry is heavily reliant on throughout production. Drought conditions are mostly likely to translate into water shortages in areas with small storage capacities and where high competition for water sources exist (Gosling, 2014; Visser-Quinn et al., 2021). Climate extremes experienced over the last decade have already illustrated the industry's reliance on the relatively stable climate conditions under which Scotch Whisky has evolved, as well as the necessity to prepare for, adapt to, and mitigate future climate change impacts (SWA & SWRI, 2011).

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