Review of the Human Health and Environmental Impacts of Non-Methane Volatile Organic Compound Emissions from Malt Whisky Maturation in Scotland

Final Report

June 2023

Title	Review of the Human Health and Environmental Impacts of Non-Methane Volatile Organic Compound Emissions from Malt Whisky Maturation in Scotland: Final Report
Customer	Scottish Government
Recipient	Andrew Taylor
Report Reference	3051
Report Status	Final
Revisions	V1.1

Author(s)	Lotte Gleeson, Jennifer Kaczmarski, Mike Holland, Mark Gibbs, Bernard Hyde
Reviewed by	Mark Gibbs
Signature	
Date	30 June 2023

Company Details:	Aether Ltd Oxford Centre for Innovation New Road Oxford OX1 1BY UK Registered in England 6630896
Contact:	enquiries@aether-uk.com +44(0)1865 261466 www.aether-uk.com

Contents

Abbreviations

AAQD	Ambient Air Quality Directive
ACGIH	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
AQEG	Air Quality Expert Group
AQG	Air Quality Guideline
AQP	Air quality pollutant
AQSO	Air Quality Strategic Objective
AURN	Automatic Urban and Rural Network
BAT	Best Available Techniques
BEIS	Department for Business, Energy and Industrial Strategy
BRE	Building Research Establishment
b.w.	Body weight
CH_4	Methane
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO_2	Carbon dioxide
COMAH	Control of Major Accident Hazards
COMEAP	Committee on the Medical Effects of Air Pollutants
Defra	Department for Environment, Food and Rural Affairs
DHSC	Department of Health and Social Care
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EC	European Commission
ECHA	European Chemicals Association
EMEP	European Monitoring and Evaluation Programme
ERPG	Emergency Response Planning Guidelines
EU	European Union
FDA	Food and Drug Administration
GHG	Greenhouse gas
GWP	Global warming potential
HRAPIE	Health Response to Air Pollutants in Europe
HSE	Health and Safety Executive
IED	Industrial Emissions Directive
IARC	International Agency for Research on Cancer

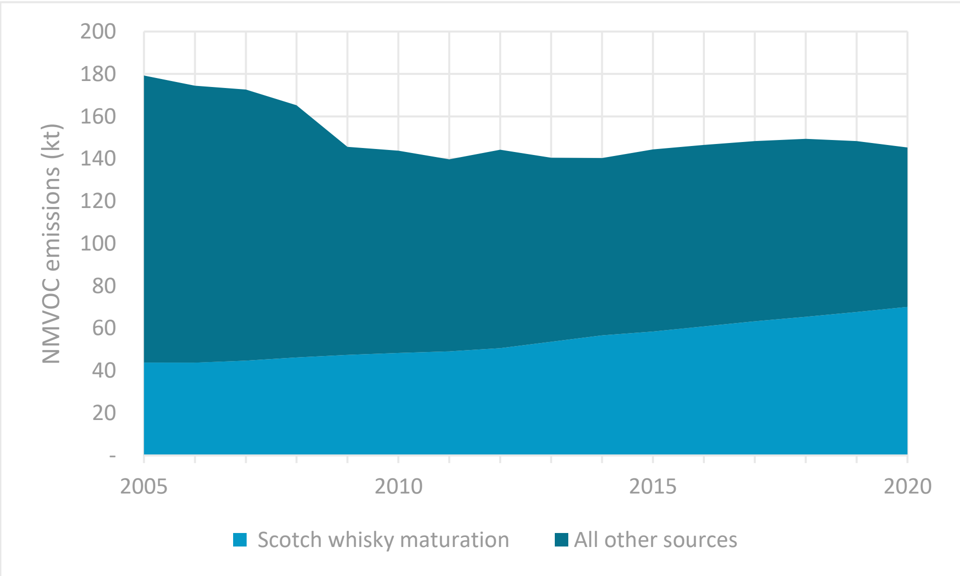
IPCC	Intergovernmental Panel on Climate Change
IRIS	Integrated Risk Information System
MATIN	Maturation Innovation
N_2O	Nitrous oxide
NAAQS	National Ambient Air Quality Standards (US)
NACE	Nomenclature of Economic Activities
NAEI	National Atmospheric Emissions Inventory
NECD	National Emissions Ceiling Directive
NHS	National Health Service
NMVOC	Non-methane volatile organic compounds
NO	Nitrogen oxide
NOx	Nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
PHE	Public Health England
PM	Particulate matter
POCP	Photochemical ozone creation potential
RF	Radiative forcing
SEPA	Scottish Environment Protection Agency
SIA	Secondary inorganic aerosols
SOA	Secondary organic aerosols
SPRI	Scottish Pollutant Release Inventory
STEL	Short term exposure limit
STP	Standard temperature and pressure
SWA	Scotch Whisky Association
SWRI	Scotch Whisky Research Institute
TLV	Threshold limit value
UK-PRTR	UK Pollutant Release and Transfer Register
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
WHO	World Health Organisation

1 Introduction

The Scotch whisky industry is of significant worth to Scotland, both culturally and economically. In 2022, Scotch whisky was responsible for 77% of Scotland's food and drink exports and employs over 11,000 people directly (Scotch Whisky Association, 2023). The industry has grown significantly in recent years, and this is predicted to continue. In 2022, a total of 22 million casks lie in Scotch whisky maturation warehouses in Scotland (Scotch Whisky Association, 2023a). Exports of Scotch whisky to meet the demand of the global market were worth £6.2 billion in 2022 (Scotch Whisky Association, 2023a). This is an increase of £3.8 billion since 2003, requiring increased production of Scotch whisky to meet the demand (SWA, 2023b).

During different parts of the process of whisky production non-methane volatile organic compounds (NMVOCs) are produced and released into the atmosphere, most significantly from malt whisky maturation as the product is stored and aged in oak casks (a key part of whisky making). NMVOC emissions from malt whisky maturation increased by 60% between 2005 and 2020, reflecting the expansion of the industry over this period. Figure 1 represents the proportion of all Scotland's NMVOC emissions from Scotch whisky maturation in the fifteen years to 2020 and reflects the increase in Scotch whisky production over this time. Total NMVOC emissions from Scotch whisky maturation were over 70,000 tonnes in 2020 (Garland et al., 2022), a figure that represents around half of all NMVOC emissions from anthropogenic sources in Scotland.

Figure 1 Proportion of all Scottish NMVOC emissions that originate from Scotch whisky maturation, 2005-2020



Although there is good evidence on the general human health and environmental impacts of NMVOCs, relatively little is known about the impacts of this specific source and whether the recent increases in emissions from malt whisky maturation are sufficient to generate any significant health or environmental impacts.

Aether was commissioned by the Scottish Government to review the potential human health and environmental impacts of NMVOC emissions from malt whisky maturation, as well as to understand the geographic distribution of the multiple small point sources that make up this sector in Scotland.

Additionally, this review assesses NMVOC emissions from Scotch whisky maturation in the context of NMVOC emissions from other sources, and the potential for mitigation measures to control these emissions.

Key whisky industry and regulatory bodies within Scotland were engaged with in order to provide them with the context of this project and to gain their insights.

The Scotch Whisky Association (SWA) and Scotch Whisky Research Institute (SWRI) were aware of the study and were able to provide us with relevant information on whisky maturation which has been included within this report. These bodies would be an important route if further engagement with the whisky industry on any potential regulatory and policy development is required.

The Scottish Environment Protection Agency (SEPA) advised on links between this study and the Clean Air for Scotland 2: Towards a Better Place for Everyone Strategy. They provided their Scotch Whisky Sector Plan which outlines how they work with and regulate the whisky industry.

1.1 Report Structure

This report seeks to understand the likely human health and environmental impacts related to the NMVOC emissions associated with Scotch whisky maturation, and any mitigation measures which may be available. Section 2 provides details on the general properties of NMVOCs which may impact the effects the emissions may have on human health and the environment. The pollutant category NMVOC includes many different compounds. Therefore, Section 2.2 also contains information on the specific NMVOC emissions from Scotch whisky and their properties.

In Section 3 we consider the geographical distribution of Scotch whisky facilities and their associated NMVOC emissions. This includes a discussion of the data included within industrial emissions reporting streams and the data included in the National Atmospheric Emissions Inventory (NAEI). Sections 4 and 5 explore the pollutant pathways and their associated human health and environmental impacts. An assessment of the significance of the risk for each pathway is made.

Following the exploration of potential impacts, the potential for NMOVC emissions mitigation from Scotch whisky facilities is discussed in Section 6. Conclusions and any recommendations based upon the research outlined in previous sections are included in Section 7.

2 Properties of NMVOC emissions specific to Scotch whisky production

2.1 Properties of NMVOCs

NMVOCs are a group of organic chemicals which cover a wide range of compounds. They essentially include all volatile organic compounds (VOCs) apart from methane, which is excluded from this grouping due to its lack of toxicity and low reactivity compared to other VOCs. NMVOCs are characterised by their low boiling point and their high vapour pressure at room temperature. NMVOCs are highly volatile, existing as a gas at room temperature and pressure.

As well as their high volatility, NMVOCs are also characterised by their relative ease of reaction with other compounds. They are involved in the photochemical production of ozone and secondary organic aerosols in the atmosphere. The category of NMVOCs includes between 10,000 and 100,000 different species (Goldstein & Galbally, 2007) and the reactivity of each NMVOC differs. Consequently, some species have a greater propensity to react to form other compounds than others.

The Air Quality Directive 2008/50/EC (European Parliament and Council, 2008) includes the following definition of VOCs:

> *"'Volatile organic compounds' (VOC) shall mean organic compounds from anthropogenic and biogenic sources, other than methane, that are capable of producing photochemical oxidants by reactions with nitrogen oxides in the presence of sunlight".*

This is broader than the definition provided by the European Monitoring and Evaluation Programme (EMEP)/ European Environment Agency (EEA) guidelines for the reporting of emissions inventories by countries (EEA, 2019):

> *"NMVOCs compromise all organic compounds except methane which at 293.15 K show a vapour pressure of at least 0.01 kPa (i.e. 10 Pa) or which show a comparable volatility under the given application conditions."*

Due to their ease of reactivity, NMVOCs can be involved in reactions with other pollutants in the atmosphere to produce 'secondary' pollutants. These include the formation of ozone, through the reaction between NMVOCs and nitrogen oxides (NOx), catalysed by sunlight.

In addition, NMVOCs can influence the formation of secondary organic aerosols (SOAs) and secondary inorganic aerosols (SIAs), particularly ammonium nitrate and ammonium sulphate. This is either by reactions involving NMVOCs directly, or by reactions involving secondary pollutants, particularly ozone, formed through other reactions involving NMVOCs. Both SIAs and SOAs are considered to be particulate matter which is typically categorised as PM_{10} or $PM_{2.5}$ where the aerodynamic diameter is less than 10 µm or 2.5 µm, respectively. SIAs and SOAs can belong to both of these fractions of particulate matter.

2.2 Properties of NMVOC emissions from whisky production

Over 90% of NMVOC emissions from whisky making occur during the maturation stage. This occurs by first the saturation of the wooden barrel and then evaporation through the wood into the atmosphere. Surface area of the barrel, temperature, and humidity can all affect the rate of emission of NMVOCs during the maturation process (Conner, 2014). Emissions also occur during fermentation and when the whisky is drained and pumped from the barrels, but these are minor compared to the maturation stage.

Greater than 99% of all NMVOCs produced in whisky production is ethanol (Passant et al., 1993). Other volatile compounds are produced, such as acetaldehyde, ethyl acetate, glycerol, for example, but only in trace quantities. Ethanol, like other NMVOCs, helps to form ground-level ozone and particulate matter in the presence of sunlight.

Across the UK, ethanol is now the largest NMVOC emitted by mass at approximately 16.8% of total UK VOC emissions which is partly due to the recent growth of the whisky industry (AQEG, 2020). However, ethanol is currently not monitored by the Defra Automated Hydrocarbon Network, operated throughout the UK, nor in other countries.

At the start of the maturation process, approximately 50% of the cask will contain ethanol. A typical cask will lose around 2% of its ethanol content each year (Conner and Forrester, 2017). Therefore, if whisky is matured in a typical 190 litre barrel for 6 years before being bottled, it will lose 14 litres of ethanol. More premium products with a longer maturation time will lose a greater amount.

In Kentucky, USA, the rate of evaporation of ethanol in whisky production is nearly twice that measured in Scotland (Conner and Forrester, 2017). This may not be purely due to climatic factors, but also due to warehouse design and layout, and the impact this may have on internal conditions within the warehouse. For example, stacking maturation barrels more densely may restrict airflow between barrels, maintaining more constant temperatures of the barrel surface and liquid.

3 Spatial distribution of NMVOC emissions from Scotch whisky maturation

3.1 Industrial emissions reporting streams

The UK Pollutant Release and Transfer Register (UK-PRTR) is an inventory of pollution from industrial sites. The 2003 Kiev Protocol on PRTRs, under the United Nations Economic Commission for Europe (UNECE) Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, requires that parties to the agreement make information on the pollution from these sources publicly available. The Air Quality (Miscellaneous Amendment and Revocation of Retained Direct EU Legislation) (EU Exit) Regulations 2018 (UK Statutory Instruments, 2018) amends the adoption of Regulation (EC) No 166/2006 (European Parliament and Council, 2006) of the European Parliament and of the Council concerning the establishment of a European Pollutant Release and Transfer Register (EC, 2010) to reflect that the UK has no obligation to report data under the E-PRTR to the European Commission, and instead 'appropriate authorities' (representing the focal points for England, Scotland, Wales and Northern Ireland) shall report the same data to the UK authority (the Department for Environment, Food and Rural Affairs).

Reporting to the UK-PRTR by facility operators is mandatory, but only if the facility undertakes an activity listed in Annex 1 of the UK-PRTR legislation (European Parliament and Council, 2006). UK-PRTR main activity 8(b)(ii) covers "*Treatment and processing intended for the production of food and beverage products from vegetable raw materials*". All facilities undertaking this activity must report if they are emitting more than 100 tonnes of NMVOC emissions per year *and* if the production at the facility exceeds a certain activity threshold. For activity 8(b)(ii), reporting is only mandatory when the "*finished product production capacity*" is 300 tonnes per day (average value on a quarterly basis). Due to the inherent long-term nature of Scotch whisky storage for maturation, a bonded warehouse or similar facility is highly unlikely to ever meet this activity threshold of daily production. Therefore, Scotch whisky facilities are not required to report NMVOC emissions to the UK-PRTR if only maturation activities occur onsite.

In Scotland, a pollutant release and transfer register is compiled by SEPA – the Scottish Pollutant Release Inventory (SPRI). This contains publicly available data on officially reported releases from SEPA-regulated industrial facilities. Facilities must report to the SPRI if they undertake the same activities which are listed in UK-PRTR regulation. Indeed, a subset of facilities included in the SPRI are then reported to the UK-PRTR. However, for most pollutants the emissions reporting threshold is not as high for reporting to the SPRI as it is to the UK-PRTR. Facilities emitting more than 10,000 kg of NMVOCs must report to the SPRI, but only if their finished product production capacity exceeds 300 tonnes per day. The SPRI states that the thresholds are set such that "*at a UK level (reflecting EU levels) and are designed to capture 95% of the UK's total emitted pollutants for the particular substance*". Based upon data in the NAEI, in 2020 NMVOC emissions associated with Scotch whisky production accounted for 11.5% of the UK's total NMVOC emissions from all sources. The NAEI is discussed further in Section 3.2.

In the UK-PRTR, a search can be performed by NACE code, which identifies the type of economic activity taking place at the facility. There are three facilities included within the UK-PRTR with NACE code 11.01 'Distilling, rectifying and blending of spirits' in

Scotland. There are no NACE codes which include the storage or maturation of spirits. These three facilities, which are shown in Figure 2, exceed the activity threshold and emission threshold for reporting to the UK-PRTR. As the NACE code does not specify the type of spirit being produced, the nature of the spirit being produced in these facilities was confirmed with industry experts. The facilities shown below are all large grain distilleries, mainly engaging in the production of gin. These facilities are Cameronbridge Distillery in Fife, Girvan Distillery in South Ayrshire, and Wheatfield Road Grain Mill in Edinburgh. Although reported NMVOC emissions may come from both combustion and industrial process activities at the site, they will mostly be as a result of the industrial processes.

Figure 2 Location of the UK-PRTR facilities with economic activity code 11.01 (shown by red stars)

The Industrial Emissions Directive (IED) was written into UK law in 2011. As part of this directive, facilities undertaking certain activities must use Best Available Techniques (BAT) to reduce their pollution emissions. The details of the BAT applied are included in permits issued by competent authorities to the facilities covered by the IED, which also detail the emission limit values applied to the facility. IED activity 6.4 (b)(ii) is "*Treatment and processing, other than exclusively packaging, of the following raw materials,* *whether previously processed or unprocessed, intended for the production of food or feed from only vegetable raw materials with a finished product production capacity greater than 300 tonnes per day or 600 tonnes per day where the installation operates for a period of no more than 90 consecutive days in any year".* As with reporting to the UK-PRTR, a Scotch whisky maturation facility would not meet the activity threshold that would require for regulation under the IED.

In addition to the individual permits that industrial facilities may be subjected to, at the planning stage facilities may be required to produce an Environmental Impact Assessment (EIA) if requested to by the local authority (Scottish Statutory Instruments, 2017). In this, both the air quality impacts and climate change impacts should be assessed if they cannot be screened out as being negligible. If the impacts of the development are deemed to be significant through the EIA process, the facility may still be built if the development is considered to still be beneficial to the local community. The Town and Country Planning Regulations (Scottish Statutory Instruments, 2017) list the types of developments which must be subjected to an EIA, which do not include Scotch whisky storage sites. Therefore, it is not mandatory for EIAs to be produced when applications for new bonded warehouses are made to the council. Instead, the requirement for an EIA would be at the local council's discretion. When EIAs have been produced for new Scotch whisky warehouses, the air quality and climate change impacts are usually deemed to be negligible. However, these assessments do not state a clear methodology for reaching these conclusions.

Another industrial reporting stream is set by the Control of Major Accident Hazards (COMAH) Regulations. These regulations have been established to ensure that businesses take all necessary measures to prevent major accidents if they are dealing with potentially dangerous substances. The high ethanol content in the Scotch whisky maturation barrels makes the maturing liquid highly flammable, and therefore regulated by the COMAH Regulations. All whisky facilities holding a quantity of flammable liquid above 5,000 tonnes must report under COMAH, which equates roughly to all maturation facilities with two or more typically sized bonded warehouses.

As COMAH Regulations concern the quantity of flammable liquid, a distinction will not be made in the database as to whether a listed facility is used for maturation or for bottled storage before export or delivery to other locations in the UK. The bottles in these storage facilities may also include other types of alcohol e.g. gin, wine or beer.

The COMAH database contains information on the procedures in place to reduce the likelihood of a major accident, as opposed to the emissions associated with a given facility. Therefore, the COMAH database has been consulted during this project to review and confirm the locations of Scotch whisky facilities that have already been identified via other reporting mechanisms.

3.2 Data included in the National Atmospheric Emissions Inventory (NAEI)

Data used to inform the Scotch whisky production emissions reported in the NAEI have been obtained from Ricardo, the lead organisation responsible for compiling the NAEI. The data includes the following information about each facility:

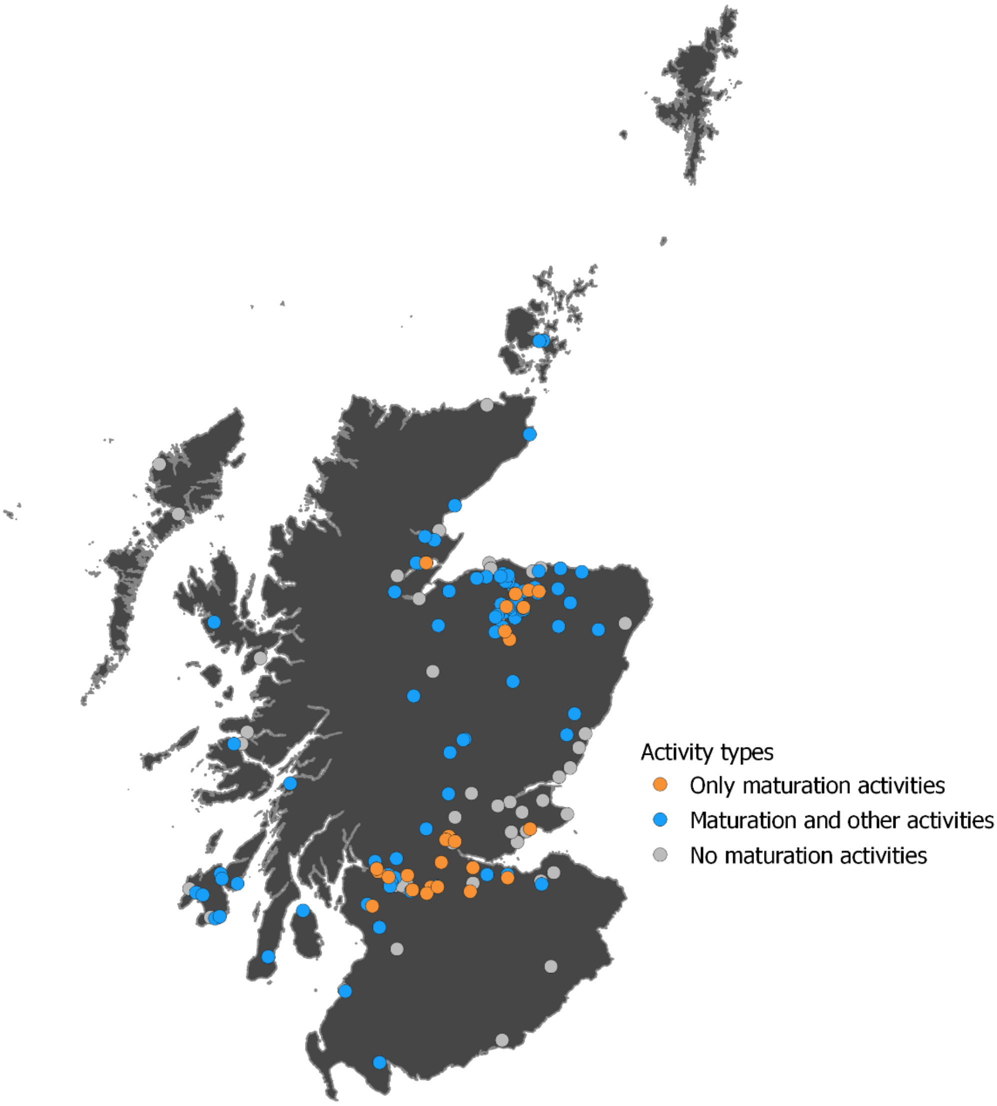
- Facility name;
- Facility operator;
- Coordinates of facility location; and

- NMVOC emissions per facility per activity for years 2018, 2019 and 2020.

The activities for which emissions are distributed between are casking, distillation, fermentation, spent grain drying, malting and Scotch whisky maturation. The total emissions for the Scotch whisky industry are derived from figures for the total quantity of whisky in annual statistical reports published by the SWA. However, the SWA has not provided production statistics in recent years and therefore data has been extrapolated by inventory compilers (Ingledew et al., 2023). These total industry emissions are then distributed between each site based on its size relative to the size of the entire sector. However, the relative size of each site is derived from surveys of the industry carried out in the 1990s, mostly from COMAH reporting. In the absence of other subsequent data collection, the production capacity of each facility is assumed to have stayed static since the surveys were collected. Given the rise in Scotch whisky production in recent decades (AQEG, 2020), this is likely to result in inaccuracies in the geographical distribution of emissions as there are no established data flows that inform the Ricardo team of recently built Scotch whisky facilities. This is especially true as the greatest uncertainty is estimated to occur in the emissions from maturation, as new Scotch whisky storage facilities are not easily identified by the Ricardo team. Given that the majority of emissions from Scotch whisky production occur during the maturation process, the uncertainty in the geographical distribution of emissions associated with maturation will have a larger impact on the uncertainty of the emissions distribution from the sector as a whole.

Most sites will not have all activities related to Scotch whisky production occurring on site. Some sites may only have one activity occurring there. For example, out of the 124 sites identified as having Scotch whisky storage on site for the purposes of maturation, 37 of them are sites where only maturation takes place and no other activity. Figure 3 displays all of the Scotch whisky facilities included in the NAEI dataset, colour coded by the types of activities occurring at each site. Of the facilities, 27 of them are only used for Scotch whisky maturation and have no other activities occurring onsite.

Figure 3 Scotch whisky facilities by activity type



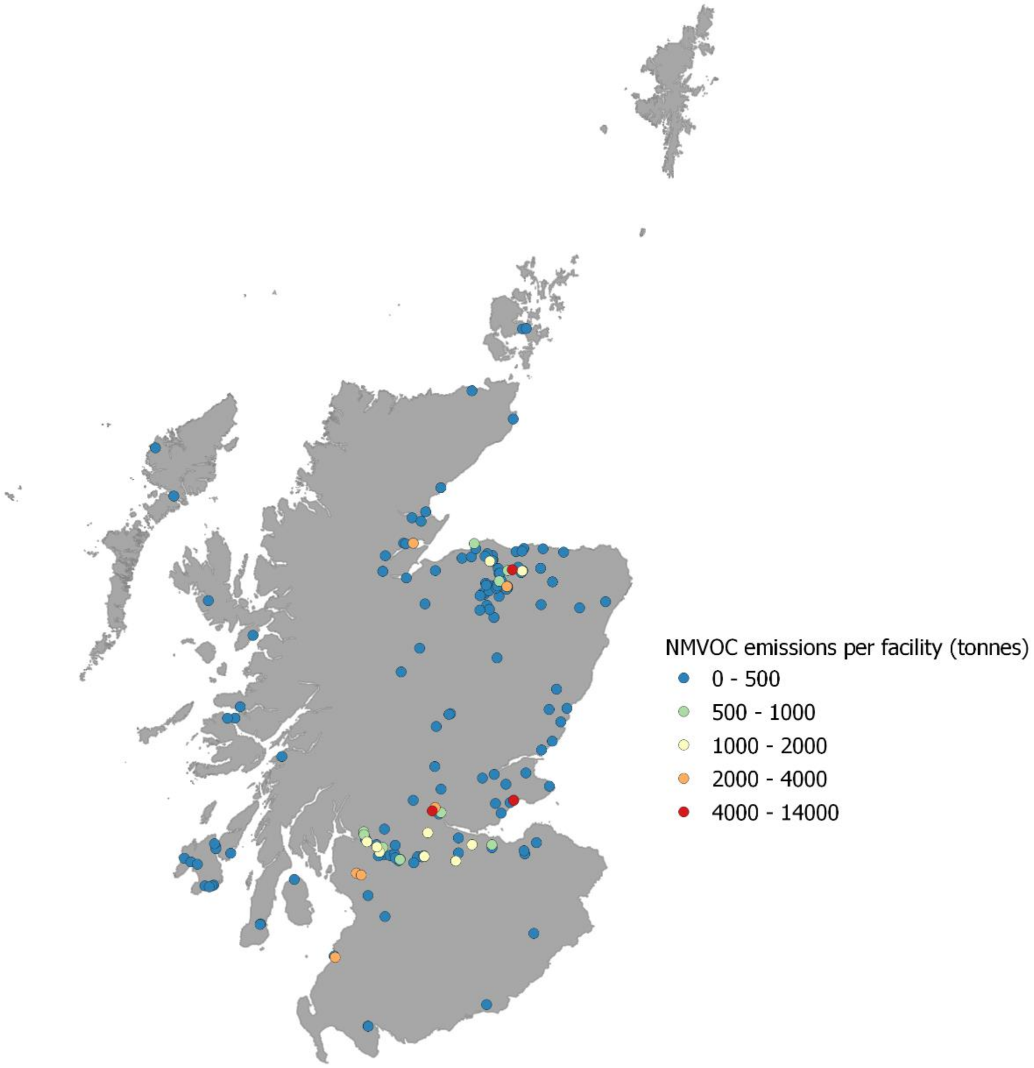
The distribution of NMVOC emissions from the sector between activities is displayed in Table 1 below. The emissions per activity have changed little between 2018 and 2020 for all activities except for Scotch whisky maturation, where emissions are estimated to have increased by 7.1%.

Table 1 NMVOC emissions per activity in 2018, 2019 and 2020. The distribution of the total NMVOC emissions from the sector per sector is given in brackets as a percentage.

Activity	2018 NMVOC emissions (tonnes)	2019 NMVOC emissions (tonnes)	2020 NMVOC emissions (tonnes)
Spirit manufacture - casking	223 (0.3%)	223 (0.3%)	223 (0.3%)
Spirit manufacture - distillation	448 (0.6%)	477 (0.6%)	477 (0.6%)
Spirit manufacture - fermentation	955 (1.3%)	954 (1.2%)	954 (1.2%)
Spirit manufacture - Scotch whisky maturation	67,652 (90.2%)	70,001 (90.5%)	72,438 (90.8%)
Spirit manufacture - spent grain drying	1,039 (1.4%)	1,038 (1.3%)	1,038 (1.3%)
Malting - all	4,614 (6.2%)	4,614 (6.0%)	4,614 (5.8%)
Total	**74,931**	**77,307**	**79,744**

NMVOC emissions from Scotch whisky are not evenly geographically distributed across Scotland. Figure 4 below displays the locations of the Scotch whisky production facilities. There are clusters of sites occurring in Speyside and around Glasgow. Many of the sites are located in rural areas with small local populations. However, there are some sites located within or close to cities and towns within Scotland.

Figure 4 Location of Scotch whisky production sites. Annual NMVOC emissions per site are shown.



The three facilities undertaking the economic activity 'Distilling, rectifying and blending of spirits' which are reported in the UK-PRTR all appear in the NAEI data as Scotch whisky production point sources.

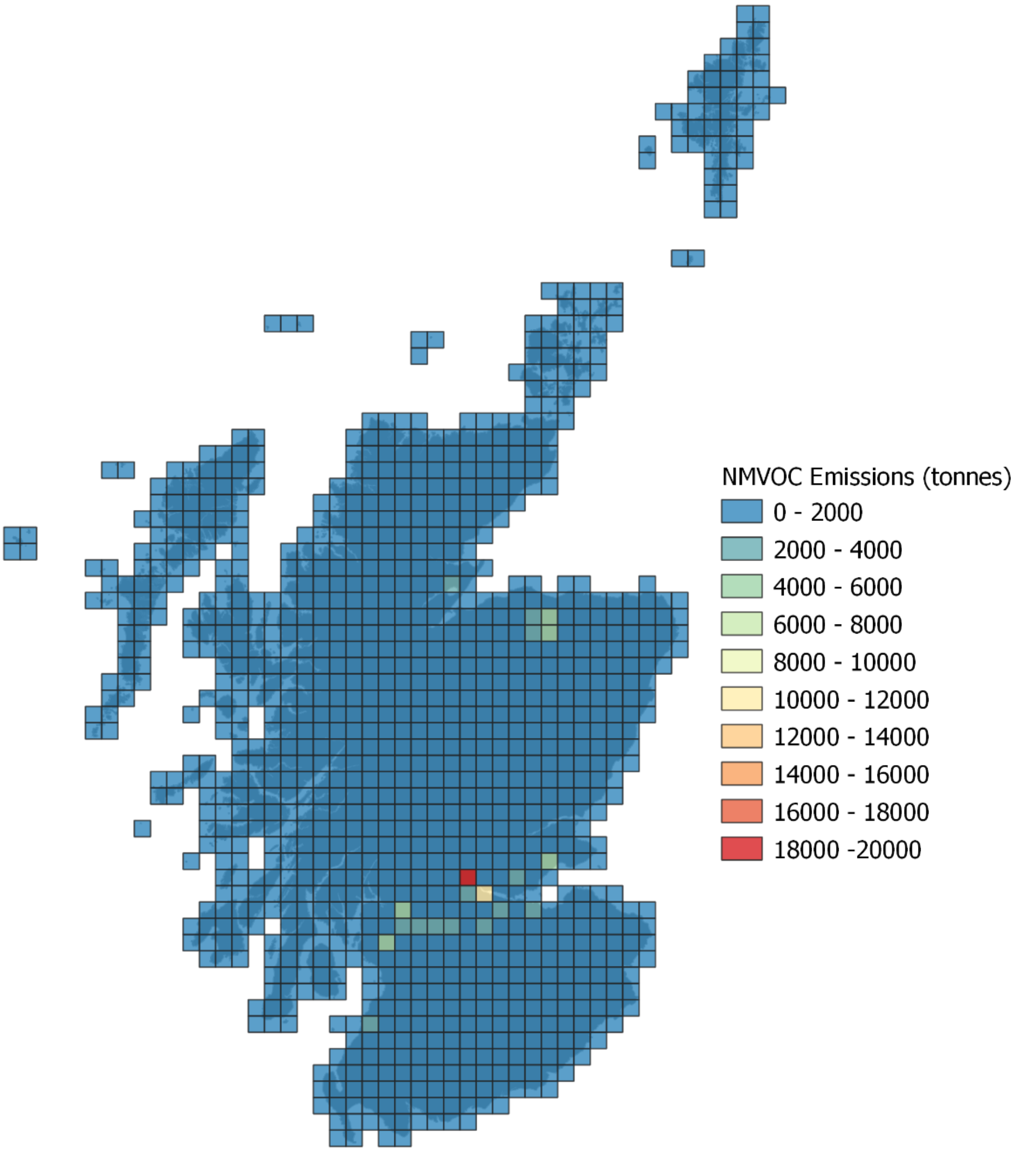
Table 2 displays the NMVOC emissions for 2020 for each site, both in the UK-PRTR (which includes emissions from the production of all spirits, see Section 3.1) and in the NAEI as associated with Scotch whisky. Though there is uncertainty in the per site NMVOC emissions in the NAEI as discussed above, this demonstrates that these facilities are mostly participating in the production of other spirits. As a result, the facilities meet the activity threshold for UK-PRTR reporting.

Table 2 NMVOC emissions for 2020 as reported in the UK-PRTR and as included within the NAEI point source data, per facility reporting to the UK-PRTR

Site name	Activities on site	NMVOC emissions reported to the UK-PRTR (tonnes)	NMVOC emissions in NAEI associated with Scotch whisky (tonnes)
North British Distillery	Spent grain drying, fermentation, distillation, casking, Scotch whisky maturation	6,550	26
Cameronbridge	Spent grain drying, fermentation, distillation, casking	5,930	405
The Girvan Distillery	Spent grain drying, fermentation, distillation, casking, Scotch whisky maturation	6,570	3,506

The NAEI also provides data for the total NMVOC emissions from all sources within each 1 km by 1 km grid square covering the UK. This data has been aggregated up to a 10 km by 10 km grid covering Scotland. The purpose of the aggregation is to provide a deeper understanding of the local impact of the clustering of multiple Scotch whisky facilities, as many are located within a few kilometres of each other. Additionally, the scale of some of the larger facilities means that the facility is sometimes the only entity within a 1 km by 1 km grid square. The total NMVOC emissions from all sources per 10 km by 10 km grid square is displayed in Figure 5. Most of Scotland is covered by grid cells where the total emissions within that cell totals less than 2,000 tonnes of NMVOC. Indeed, the median total NMVOC emissions per grid cell is 47.0 tonnes. Where there are clusters of Scotch whisky facilities in Speyside, near Stirling, near Glasgow and in central Fife, the total NMVOC emissions for that grid cell is greater. This is particularly true for the 10 km by 10 km grid cell covering land to the east of Stirling which contains four sites (the red grid cell in Figure 5). The total emissions from all anthropogenic sources in this grid cell sum to 18,268 tonnes of NMVOC.

Figure 5 Total NMVOC emissions from all sources per 10 km by 10 km grid square



Note: All rights reserved Defra, License number 100022861 (2022) and BEIS License number 100037028 (2022)

There are only two 10 km by 10 km grid cells in Figure 5 for which total NMVOC emissions are above 2000 tonnes and which do not contain Scotch whisky facilities. One of these cells is the grid cell with the second highest total NMVOC emissions from all sources. This cell contains the industrial hub of Grangemouth, to the southeast of Stirling, where a cluster of petroleum product and chemical industry point sources of NMVOCs are located. The other grid cell contains a large chemical industry facility located in west Fife.

Figure 6 displays the total NMVOC emissions from all Scotch whisky facilities that are located within the 10 km by 10 km grid cells used to produce the data shown above. From this figure, the areas with clustering of Scotch whisky facilities can be identified.

Figure 6 Total NMVOC emissions from Scotch whisky facilities per 10 km by 10 km grid cell

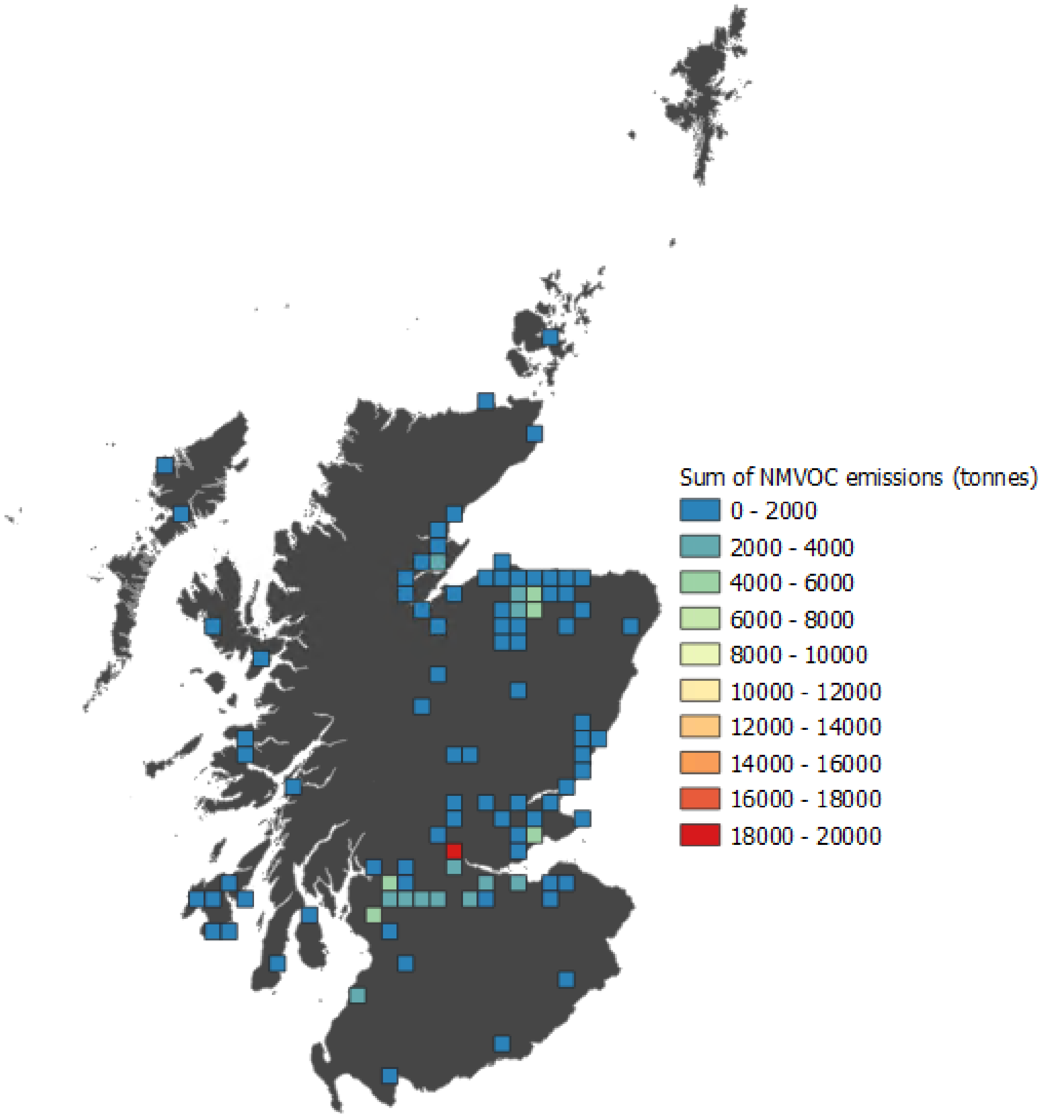
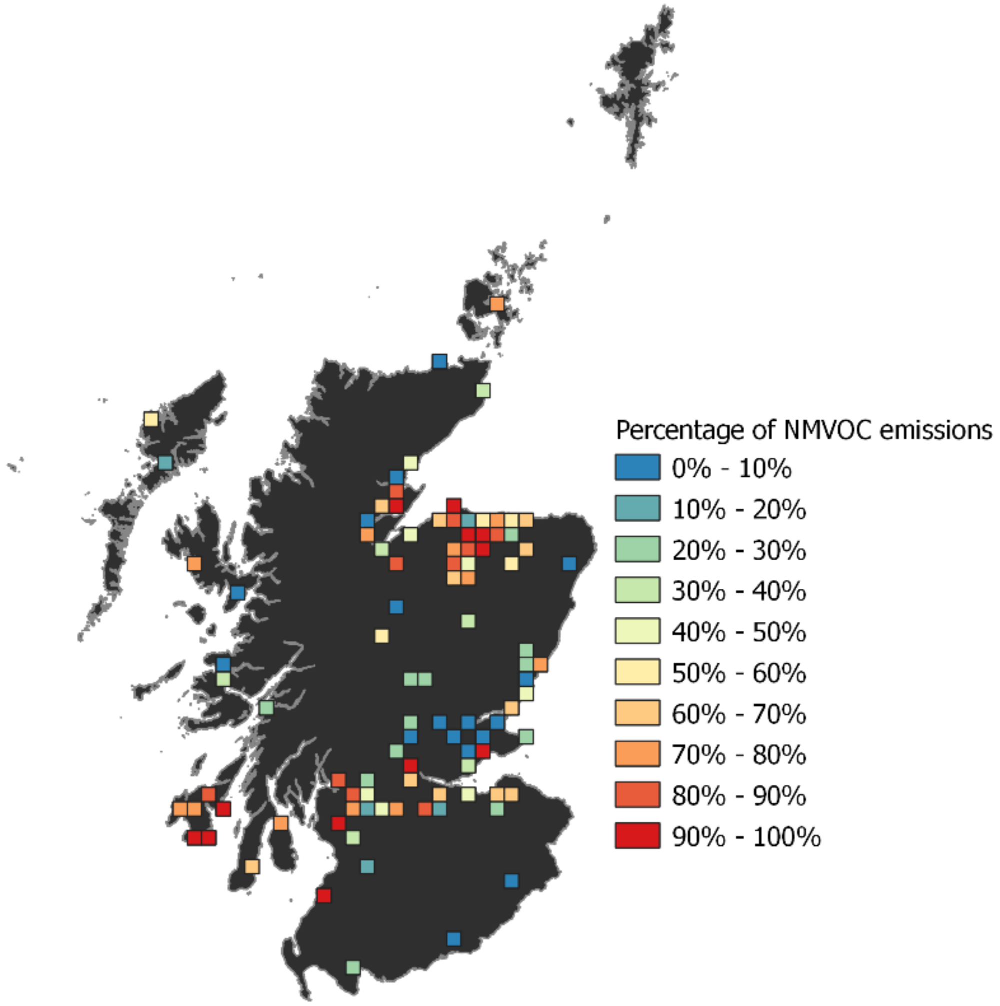


Figure 7 displays how the NMVOC emissions from Scotch whisky production sites contribute to the geographical distribution of total NMVOC emissions. For every 10 km by 10 km grid cell, the NMVOC emissions from every Scotch whisky site located within that grid cell were summed together to give the total NMVOC emissions for the Scotch whisky sector for that grid cell. The total for the sector was then divided by the total NMVOC emissions from all sources in the corresponding 10 km by 10 km grid cell. This provided the spatial distribution of the proportion of the total NMVOC emissions which can be attributed to the Scotch whisky sector.

Figure 7 Proportion of the total NMVOC emissions per 10 km by 10 km grid cell that can be attributed to the Scotch whisky sector



Note: All rights reserved Defra, License number 100022861 (2022) and BEIS License number 100037028 (2022)

At least one Scotch whisky site can be found in 97 of the 1,121 10 km by 10 km grid cells covering all of Scotland, and 39 cells contained at least two sites. Two grid cells, both in Speyside, each contained nine sites involved in the production of Scotch whisky. The Scotch whisky sector was responsible for over 90% of the total NMVOC emissions emitted in twelve of the grid cells (displayed in red on the map in Figure 7). Most of these are located in rural areas where it is not likely that there will be other significant NMVOC sources. However, some are located in more urban environments, where NMVOC emissions are likely to also result from other commercial or domestic activities. The 10 km by 10 km grid cell located to the east of Stirling, and indeed containing the east of the city, is one of these grid cells – 95 % of the NMVOC emissions from sources within this grid cell can be attributed to the Scotch whisky sector. This is also true for the grid cell containing the towns of Methil, Leven and Buckhaven in central Fife, where the proportion of total NMVOC emissions that are due to the Scotch whisky sector is 93%.

It is worth noting that the data provided in the NAEI only provides the total emissions per 1 km by 1 km grid cell, and not the concentrations that residents will be exposed to. The purpose of the NAEI is to provide emissions for international inventory compliance reporting rather than exposure. To determine exposure concentrations, dispersion modelling of ethanol would need to be carried out based upon the spatial distribution of the emissions provided in the NAEI. No such modelling has been published, and therefore there is an inherent uncertainty as to the extent of emission exposure from Scotch whisky. Modelling the dispersion of NMVOCs is complex, as each compound within this category will have a different pattern of dispersion due to compound weight and its propensity to take part in other atmospheric reactions.

The sites vary significantly in their size and therefore also in their estimated NMVOC emissions. Across the 182 sites included in the NAEI, the estimated NMVOC emission per site was 438.2 tonnes per annum on average in 2020. However, the median value was 91.1 tonnes per annum, demonstrating that the average value is skewed by several sites with significantly greater emissions than most sites. The Scotch whisky maturation site emitting the greatest amount of NMVOCs in 2020 was the Blackgrange/Cambus Bonds site located just outside of Stirling in Clackmannanshire at 13,050 tonnes – which is over 8,000 tonnes more than the next largest emitting site, Malcolmburn Warehouse in Moray, Speyside.

Based upon emission rates (emissions per annum), the likely concentrations that nearby sensitive receptors will be exposed to can be estimated using calculations in DEFRA's Industrial Emissions Screening Tool (DEFRA, 2017). As ethanol is not a pollutant with a set air quality objective, it is not included in this tool. Therefore, to gain insight into the approximate concentrations in the vicinity of Scotch whisky facilities, calculations for 1,3-butadiene have been used instead. Both 1,3-butadiene and ethanol are NMVOCs with a similar number of atoms per molecule. However, dispersion rates and patterns are determined by many factors such as reactivity and energy absorption rates. In this case, the -OH part of the ethanol molecule plays an important part in atmospheric chemical reaction, particularly exhibiting diurnal variations (Grosjean, 1997). Direct comparisons between the molecules should be treated with caution. As a result, there is uncertainty in the concentration estimates, and they are used here only to provide an approximate order of magnitude. The model also treats the emissions as originating from a point source out of a stack. This produces further uncertainty, as ethanol emissions from maturation are not emitted as a point source from a stack, but instead emitted through all façades of a bonded warehouse. Emissions are vented close to ground level and have no additional buoyancy that is associated with hot pollutant plumes from combustion processes. A release height of 3 m was used for these calculations. Concentrations have been estimated at a distance of 100 m from the source, as it represents a typical distance a property or other sensitive receptor may be located from an urban Scotch whisky facility.

Using the median emission rate of 91.1 tonnes per annum for a typical Scotch whisky facility, a concentration of 200 $\mu g/m^3$ was estimated at a distance of 100 m from the source. For the average emission rate of 438 tonnes per annum, the concentration was 800 $\mu g/m^3$ at the same distance. If we consider the facility assumed to be emitting the greatest quantity of ethanol per year (13,050 tonnes), the concentrations at 100 m are estimated to be 23,000 $\mu g/m^3$. These figures can be taken through to estimate dose under exposure scenarios, as discussed in Section 4.1 below. These calculations only provide an order of magnitude estimate of the ethanol concentrations that members of the public are likely to be exposed to close to Scotch whisky maturation sites. They should therefore be treated with caution.

4 Human health impacts

4.1 Direct inhalation of ethanol

Impacts of some individual species of NMVOC such as benzene (PHE, 2019) and formaldehyde (PHE, 2017) have been identified previously at concentrations close to typical ambient levels for public exposure. However, less research has been conducted into the harm from human exposure to typical ambient concentrations of ethanol or other likely evaporative emissions from the storage of whisky. The majority of studies performed on the impacts of ethanol do not concern the inhalation of ethanol but rather the consumption of it. It should be possible to estimate the quantity of alcohol inhaled annually by people living close to the bonded warehouses if ambient concentration data were available. Unfortunately, monitoring of ambient concentrations of ethanol does not occur. The International Agency for Research on Cancer (IARC, undated) states, however, that:

> *"There is no safe level of alcohol consumption for cancer risk, and all types of alcoholic beverages, including beer, wine, and spirits, are linked to cancer risk, regardless of their quality and price. The risk of developing cancer increases substantially when more alcohol is consumed."*

The NHS (2022) provides information for the public on the impacts of different levels of alcohol consumption. The following points are pertinent here:

- If you drink less than 14 units a week, this is considered low-risk drinking. It's called ‘low risk’ rather than ‘safe’ because there's no safe drinking level.
- The type of illnesses you can develop after 10 to 20 years of regularly drinking more than 14 units a week include: mouth cancer, throat cancer and breast cancer, stroke, heart disease, liver disease, brain damage, damage to the nervous system. Additionally, multiple studies conclude that alcohol consumption can make your mental health worse with strong links between alcohol misuse and self-harming, including suicide.
- The effects of alcohol on your health will depend on how much you drink. The less you drink, the lower the health risks.

That there is no safe drinking level indicates that any exposure has potential for harm, even amongst those that do not drink at all.

When alcohol vapour is inhaled, it is thought to bypass initial metabolism and instead be rapidly transmitted to the brain via the arterial blood (MacLean et al., 2017). A literature review of the impacts of inhalation found that results were inconclusive due to a lack of studies in this area (MacLean et al., 2017). It may be possible that inhalation of alcohol vapour increases the propensity for alcohol addiction to develop, as shown in trials on mice (McCool et al., 2015). It is unclear if a similar effect may be seen in humans, particularly in vulnerable populations who are already at an elevated risk of developing substance addictions.

Some studies have also examined the impacts associated with inhalation of alcohol vapours produced from the use of alcohol-based hand sanitisers (Mahmood et al., 2020; Han et al., 2022). The US Food and Drug Administration (FDA) warned that the vapours from alcohol-based hand sanitisers can cause symptoms such as headache, nausea and dizziness (FDA, 2022). However, it is worth noting that such products may not purely contain ethanol, but instead are likely to produce vapours that contain a variety of alcohols. Most commercially available hand sanitisers contain 70% ethanol and isopropanol (Bessonneau and Thomas, 2012). It is therefore unclear whether any conclusions drawn from these studies will also apply to inhalation of ambient ethanol from Scotch whisky production.

Public Health England list the possible side effects of acute exposure to ethanol vapours (PHE, 2015). These include irritation of the throat and difficulty breathing at 9,400,000 µg/m^3, and lacrimation and coughing at 30,000,000 µg/m^3. At higher concentrations, central nervous system depression may occur. Emergency response planning guideline (ERPG) values have also been provided in the US, which are designed to anticipate health effects to airborne chemical concentrations (AIHA, 2014). The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing other mild transient adverse health effects is listed as 3,456,000 µg/m^3. The concentration below which it is believed nearly all individuals could be exposed to for up to 1 hour without experiencing irreversible or serious health effects is 6,336,000 µg/m^3. These are short term exposure limits, and therefore it is still unclear what the effects may be due to long term ambient exposure for those living in the vicinity of Scotch whisky facilities. Due to the typical accumulation of exposure effects, long-term exposure limits are generally set at significantly lower concentrations than short term limits. For ethanol, this may not be as relevant as for other pollutants, as ethanol does not accumulate in the body (OECD, 2004), and therefore the greatest risk is likely to be from short term exposure to high concentrations.

The American Conference of Governmental Industrial Hygienists (ACGIH) is cited by the Indiana State Department of Health (2019) as concluding that airborne ethanol has chronic non-cancer health effects at concentrations of 2,200 µg/m^3 or higher. ACGIH (undated) refers to a higher level for effects (though possibly for cancer, specifically), giving a Threshold Limit Value – Short Term Exposure Limit (TLV-STEL) of 1,880 mg/m^3 (1,000 ppm), citing ethanol as a confirmed animal carcinogen.

The above exposure risk concentrations are summarised below in Table 3.

Table 3 Summary of the ethanol exposure risk concentrations and their associated human health risks

Study/Organisation	Ethanol concentration	Human health risk	Groups affected
PHE	9,400,000 µg/m^3	Irritation of throat and difficulty breathing	All
PHE	30,000,000 µg/m^3	Lacrimation and coughing	All
ERPG	3,456,000 µg/m^3	Mild transient adverse health effects	All
ERPG	6,336,000 µg/m^3	Irreversible or serious health effect	All
ACGIH	2,200 µg/m^3	Chronic non-cancer health effects	All

In the UK, the Health and Safety Executive (HSE) sets essentially the same workplace exposure limit of 1880 mg/m^3 (1,880,000 µg/m^3), though describes it as a long-term limit (8-hr reference period, versus 15 minutes for short term) (HSE, 2020).

Due to the lack of monitoring of ethanol concentrations, it is not possible to compare these exposure limits to the concentrations individuals may be exposed to. However, likely order-of-magnitude estimates for the ethanol concentration close to bonded warehouses were produced in Section 3.2. Concentrations 100 m from a Scotch whisky facility emitting the median or mean estimated emissions (200 µg/m^3 and 800 µg/m^3, respectively) do not exceed the thresholds stated above. However, the estimated concentrations from the largest emitting bonded warehouse (23,000 µg/m^3) does exceed the exposure threshold provided by the ACGIH for chronic non-cancer health effects. Note, however, that occupational limits tend to be many times higher than those established for exposure of the public. For example, limits for members of the public set under clean air regulations are all significantly lower than workplace exposure limits to pollutants where both such limits exist. The ambient air regulations in the UK, or any other country so far as we are aware, do not address ethanol concentrations specifically.

Rumgay et al. (2021), in a study conducted at the International Agency for Research on Cancer (IARC), provide analysis of cancer risks related to increments in consumption of alcohol of 10 g/day from <10 g/day to >150 g/day as part of the Global Burden of Disease initiative[1]. This study attempted to quantify the impact and the scale of the problem of excess drinking in different parts of the world. However, deriving response functions is complicated, for example because of potential confounding factors such as the relationships between consumption with diet, tobacco use, exercise and social interaction. Rumgay et al. (2021) note that they did not consider the synergistic effect between alcohol and tobacco, or, in the case of liver cancers, alcohol and hepatitis. Regarding cognitive function, a meta-analysis by Brennan et al. (2020) reported that results were inconclusive, noting:

> *"major limitations in the design and reporting of included studies made it impossible to discern if the effects of 'lower' levels of alcohol intake are due to bias. Further review of the evidence is unlikely to resolve this issue without meta-analysis of individual patient data from cohort studies that address biases in the selection of participants and classification of alcohol consumption."*

Converting atmospheric concentration to an estimate of alcohol consumption, and adopting the position that there is no safe level of alcohol consumption, we could generate an estimate of increased cancer incidence following the approach used for the Global Burden of Disease initiative by Rumgay, et al. (2021). Their paper refers to the 'Cancers Attributable to Alcohol Tool'[2] which may facilitate analysis. Quantification may be possible for some other effects such as stroke, but, bearing in mind the findings of Brennan et al. (2022), likely not all.

Quantification could either describe a change in risk (e.g. from X cases/100,000 people/year to Y cases/100,000 people/year), or the additional number of cancers if the

[1] The Global Burden of Disease initiative aims to provide a picture of mortality and disability from a various of risk factors. https://www.healthdata.org/gbd/2019
[2] https://gco.iarc.fr/causes/alcohol/home

affected population is known, though this number is likely to be very small indeed given the results of Rumgay et al. (2021).

Information on the website of the European Chemicals Agency (ECHA, 2022) states that ethanol: can cause damage to organs, is toxic if swallowed, may cause cancer, is toxic in contact with skin, is toxic if inhaled, causes serious eye damage, and causes skin irritation. However, this information is based on all exposure pathways, including ingestion. Inhalation, even in areas where ethanol concentrations are comparatively high, does not seem likely to be a major pathway.

The following assumptions have been used to quantify the amount of ethanol inhaled:

- Exposure assumes the concentrations at 100 m from a bonded warehouse as presented above in Section 3.2 (200 µg/m^3 for a median facility, 800 µg/m^3 for a mean facility and 23,000 µg/m^3 for the largest facility in Scotland).
- It is assumed that 100 m is a reasonable distance for the modelling work. If the exposed population is closer the points of release then they will be more highly exposed, by a factor of 4, for example, if located around 50 m from the site of release. If the exposed population is further away than 100 m, they would naturally be less exposed.
- Breathing rate for a resting adult is taken as 11 m^3 per day (Papathanasiou, 2017).
- A hypothetical case is taken of an elite male athlete who trains hard for 4 hours per day without moving from the area, during which inhalation increases to 240 litres per minute (Papathanasiou, 2017). In total (accounting also for periods when at rest) the athlete would inhale about 67 m^3 per day, 6 times more than the resting individual. This is a worst-case example designed to assess a feasible (even if highly unlikely) upper bound for exposure.
- Individuals remain exposed to the same high levels of ethanol throughout the day.
- An average adult weighs 80 kg.
- All ethanol inhaled is absorbed into the blood stream.
- 1 unit of alcohol is equal to 10 ml, or 8 g (Department of Health 2008).

Table 4 Quantification of potential inhalation rates experienced outside bonded warehouses of different sizes

Concentration, ug/m^3	200	800	23,000
Adult at rest			
Grams inhaled/day	0.0022	0.0088	0.25
mg/kg body weight	0.028	0.11	3.2
Units of alcohol per day	0.00028	0.0011	0.032
Units/week	0.0019	0.0077	0.22
% of 14 units per week	0.014%	0.055%	1.5%
Elite male athlete training hard for 4 hours per day			
Grams inhaled/day	0.013	0.053	1.5
mg/kg body weight	0.17	0.67	19
Units of alcohol per day	0.0017	0.0067	0.19
Units/week	0.012	0.047	1.34
% of 14 units per week	0.083%	0.33%	9.6%

Gorgus et al. (2016) considered exposure to ethanol for children from food not labelled as containing alcohol. They report that:

> *"orange, apple and grape juice contain substantial amounts of ethanol (up to 0.77 g/L). Furthermore, certain packed bakery products such as burger rolls or sweet milk rolls contained more than 1.2 g ethanol/100 g. We designed a scenario for average ethanol exposure by a 6-year-old child… An average daily exposure of 10.3 mg ethanol/kg body weight (b.w.) was estimated. If a high (acute) consumption level was assumed for one of the "categories," exposure rose to 12.5–23.3 mg/kg b.w.."*

Against this background level of exposure from food intake, the estimates above for the median and mean sized warehouses (<1 mg/kg b.w.) appear insignificant. The estimates around the largest plant are of a similar order of magnitude (accepting that our calculations are made for adults, though of course normalised against body weight).

Gürler et al. (2022) note that:

> *"Most foods produce higher methanol concentrations than the maximum allowable dose level (23 mg). Especially fruit juices lead to the critical level of ethanol for children (6 mg/kg body weight). Based on the results, adult daily intake of selected food groups does not bear ethanol that exceeds the legal limit of BAC [blood alcohol content] or the limit not allowed from a religious perspective and does not lead to acute alcohol toxicity. But these low levels of ethanol and methanol consumed via non-alcoholic foods for life can raise the vulnerability to chronic health problems (cancer, liver cirrhosis, Alzheimer's disease, autism, ocular toxicity and alterations in foetal development) and may lead to positive ethanol metabolite results (e.g., ethyl glucuronide) when a low cut-off level is used."*

Gürler et al. (2022) thus raises two further issues that may need further investigation:

- The science behind the 'critical level of ethanol for children' of 6 mg/kg b.w.;
- Links between low levels of alcohol exposure and chronic disease.

NHS guidance (2022) is not to drink more than 14 units of alcohol per week. Intake via inhalation is estimated to be less than 1% of this for the cases where exposure is to concentrations of 800 µg/m^3 or less. However, in the highest concentration zone, inhalation accounts for 2% and 10% of the weekly maximum for the resting adult and elite male athlete, respectively.

Exposure to emissions of ethanol from whisky production appears in most situations likely to lead to only a small increase in exposure to ethanol. No evidence has been identified to indicate that this could cause acute effects on the population. However, the analysis presented here should be seen in the context of:

1. Exposure to these emissions is additive to other exposures. Even amongst those who do not consumer alcohol deliberately there is exposure from food and drink such as bread and orange juice.

2. There are indications that low level exposure increases vulnerability to a range of chronic diseases.

3. Exposure of the public to emissions from whisky production is not voluntary.

4. Exposure would affect all age groups.

There are limited studies on the direct inhalation of ethanol particularly beyond the fenceline of maturation and production facilities, however given there is no safe drinking level of alcohol then an element of risk remains. While it is likely that the **impact on human health beyond the fenceline of Scotch whisky production facilities as a result of direct inhalation of ethanol is likely to be minor, monitoring of the actual ethanol concentrations close to the larger bonded warehouses is recommended.**

4.2 *Baudoinia compniacensis*

Baudoinia compniacensis is a sac fungus which thrives in habitats with a high concentration of airborne ethanol, such as outside or near distilleries, bonded warehouses or commercial bakeries. In appearance, the fungus forms black crusts on the façades of buildings where conditions are favourable and it uses ethanol for carbon nutrition as a source of calories. *Baudoinia compniacensis* is also known for its ability to withstand high temperatures with warm environments even increasing spore germination. As a result, the fungus is able to form colonies on the outside of buildings involved in whisky production as well as in the vicinity of those buildings if ethanol concentrations are high enough to sustain this.

A review of literature relating to the ethanol concentrations to sustain the growth of *Baudoinia compniacensis* has produced inconclusive results. A 2021 study determined that typical atmospheric ethanol concentrations of 5,000 to 10,000 µg/m^3 optimised growth (Craig et al., 2023), however there are some indications that higher concentrations of approximately 15% may begin to restrict growth (Ewaze et al., 2008). Therefore, if fungal growth is visible on neighbouring properties it is likely that the ethanol concentrations at these locations is within the 5,000 to 10,000 µg/m^3 range. Numerous climatic factors also have an impact on the growth of the fungus. The conditions in Scotland, especially in the west of the country, create ideal conditions for fungal growth. This is due to the combination of cool summers, mild winters and frequent rainfall (Craig et al., 2023).

There are three possible routes for exposure for the public:

- Touching *Baudoinia compniacensis* on the outside of buildings.
- Inhaling spores or other allergens produced by the fungus on the outside of buildings.
- Exposure to the fungus inside houses or other buildings around the bonded warehouses. This would require concentrations of ethanol inside the buildings concerned to be high enough to stimulate fungal growth, and other environmental conditions (damp) to provide a suitable habitat for the fungus. This route seems unlikely given information on the ecology of the species (Scott, 2016).

Research conducted by the Indiana State Department of Health Environmental Public Health Division did not find any reports of health risks from short or long-term exposure to *Baudoinia compniacensis* (Indiana State Department of Health, 2019).

Further investigation into the ethanol concentrations with which *Baudoinia compniacensis* grows is recommended. Ethanol concentrations close to Scotch whisky facilities will be greater either close to the larger facilities that emit the greatest quantities of ethanol, or in locations where air flow is reduced, for example in urban areas. In such areas, *Baudoinia compniacensis* growth is anticipated to be the most extensive. In addition, **a watching brief should be maintained for any future studies that demonstrate if there are any human health impacts of *Baudoinia compniacensis***.

4.3 Ozone formation

Photochemical reactions between NMVOCs (including ethanol) and NOx can form ground-level ozone. Therefore, NOx concentrations must also be considered when trying to understand the extent of ozone formation from NMVOCs. The reaction pathways between NOx and NMVOCs to produce ozone are complex, but in general ozone formation will be limited by whichever pollutant appears in the lowest concentrations in the atmosphere.

From an air quality legislation perspective, interest in NMVOCs has mainly focused on their contribution to ozone formation. Health impacts of ozone have been extensively reviewed by the UK Committee on the Medical Effects of Air Pollutants (COMEAP)[3] which is sponsored by Department of Health and Social Care but has a remit to advise government departments generally.

Ethanol has an intermediate photochemical ozone potential (POCP) of 46 g/mole (Altenstedt & Pleijel, 1998), a measure of an NMVOC's propensity to form ozone. This means that there are many NMVOCs that more readily form ozone than ethanol, but also many with a lower ability to form ozone.

[3] https://www.gov.uk/government/groups/committee-on-the-medical-effects-of-air-pollutants-comeap, meetings of which are attended by representatives from the devolved administrations, including SEPA.

Defra has also produced a damage cost tool (Birchby et al., 2019) that provides an estimate of cost per tonne of VOC emitted. The current estimate is £172/tonne of VOC (Defra, 2023) covering the following effects of exposure to ozone linked to VOC releases:

- Mortality
- Respiratory hospital admissions
- Cardiovascular hospital admissions
- Productivity
- Damage to materials (rubber goods)
- Damage to ecosystems (crops, forests, etc.)
- Damage to livestock production

The damage cost per tonne has been revised up to £172 in the latest update published in early 2023 from the previous value of £115/tonne of VOC. This revision is related to updating ecosystem valuations for ozone impacts on livestock production.

Toxicology studies reviewed by the US EPA (2013) report also on effects on the central nervous system including alterations in neurotransmitters, motor activity, short and long-term memory, sleep patterns, and histological signs of neurodegeneration.

Defra's modelling to quantify damage costs of pollutant releases covers the emissions themselves and their subsequent air transportation and chemistry, alongside the likely exposure and its impacts and resulting costs. It is convenient to use damage costs as an indicator for the likely significance of the impacts associated with the release of NMVOCs, rather than developing original modelling of the emission impacts. The use of the damage costs leads to some additional uncertainty in assessment but avoids the need to develop emission scenarios and run complex pollutant chemistry/dispersion models, which generate their own uncertainties. Modelling of this type would need to account for emissions of VOCs and NOx from all sources, including transboundary inputs at a European scale. This could be carried out in the UK, for example by the UK Centre for Ecology and Hydrology using the EMEP4UK model but would require significant additional input, beyond the scope of the present work.

The current estimate of £172/tonne (2022 price) represents an average across all VOC emissions, with each VOC species having a variable potency for generating ozone, i.e. the species' photochemical ozone creation potential (POCP). Further analysis could be undertaken to weight the £172/tonne estimate specifically to ethanol, drawing on information regarding the POCP and emission figures for VOCs more widely. Applying this damage cost to the emissions quantified above gives the following results.

Table 5 Total emissions and estimated damage costs (£M/year) associated with NMVOC emissions from the whisky industry in Scotland, based on Defra's damage costs. (2022 prices).

	2018	2019	2020
Emissions (t)	74,931	77,307	79,744
Damage cost (£M)	13	13	14

Premature deaths in the UK attributable to exposure to ozone were estimated to be 880 in 2019 (EEA, 2021b). The same study calculated the estimated years of life lost for the same year, which was 15 years of life per 100,000 inhabitants. The study covered most European countries, and it ranked the UK as having the third lowest relative impacts on health from ozone exposure in Europe. The two countries with the lowest relative impacts on health were Iceland and Ireland, reflecting both their northerly latitudes and prevailing wind directions that lead to reduce transboundary input compared to other European countries. Ozone production at low altitudes requires sunlight, and countries with the greatest relative health impacts were all in the Mediterranean region. Ground-level ozone concentrations are seasonal and highly episodic, with concentrations varying significantly month to month and year to year. The latest version of this work (EEA, 2022) does not contain information on the UK and instead only considers EU-27 countries.

Through the WHO, the Health Response to Air Pollutants in Europe (HRAPIE) study produced recommendations for changes to the concentration-response functions for the cost-benefit analysis of pollutants, including ozone (WHO Regional Office for Europe, 2013). The study estimated relative risks of exposure, defined as the comparison between the risk of a health event when pollutant exposure is occurring and the risk of a health event where pollutant exposure is not occurring. A relative risk of greater than one therefore indicates that pollutant exposure is increasing the likelihood of a health event. The relative risk of mortality for all natural causes and for all ages posed by short-term exposure to ozone was 1.0029 for a daily maximum 8-hour mean concentration of more than 70 µg/m^3, at STP EU[4]. In that study, this finding applied to all age groups. There was also evidence that this relative risk also applied to concentrations above a lower value of 10 ppb. For exposure to a concentration of more than 70 µg/m^3, at STP EU, as a daily maximum 8-hour mean, the relative risk of hospital admission due to cardiovascular disease was 1.0089 and admission due to respiratory diseases was 1.0044 for the age group of more than 65 years. Again, there was also evidence that these relative risk ratios also applied to concentrations of more than 20 µg/m^3, at STP EU.

In 2015, the US EPA lowered the National Ambient Air Quality Standards (NAAQS) for ozone from 75 ppb (147.8 µg/m^3 at STP US[5]) to 70 ppb (137.9 µg/m^3 at STP US), based on the annual fourth-highest daily maximum 8-hour concentration averaged over 3 years. As part of the study that informed this decision, a causal relationship was determined between respiratory effects and short-term exposure to ozone (US EPA, 2013). In addition, the study concluded that there is likely to be a causal relationship between cardiovascular effects and short-term exposure, and that there is evidence suggestive of a causal relationship between short-term exposure and central nervous system effects. The reasons for reducing the NAAQS included evidence of decreases in pulmonary function to exposures of 120-140 µg/m^3 at STP US in young, healthy adults, and evidence of increased blood coagulation at concentrations of more than 140 µg/m^3 at STP US.

Table 6 Ozone Targets and Exposure Limits

Target	Area applied to	Concentration (µg/m^3)	Measured as
New National Ambient Air Quality Standards	US	137.9	The annual fourth-highest daily maximum 8-hour concentration averaged over 3 years

[4] Conversions from ppb to µg/m^3 use the Standard Conditions for Temperature and Pressure (STP) for the EU, assuming temperature at 293K.
[5] For the US limits, conversions from ppb to µg/m^3 use STP for the US, assuming temperature at 298K.

(NAAQS), as of 2015			
Previous NAAQS	US	147.8	The annual fourth-highest daily maximum 8-hour concentration averaged over 3 years
Air Quality Strategic Objective (AQSO)	UK	100	Target set as fewer than 10 exceedances in a year of a mean concentration greater than the target within an 8-hour period
World Health Organisation	Global	100	The mean concentration within an 8-hour period

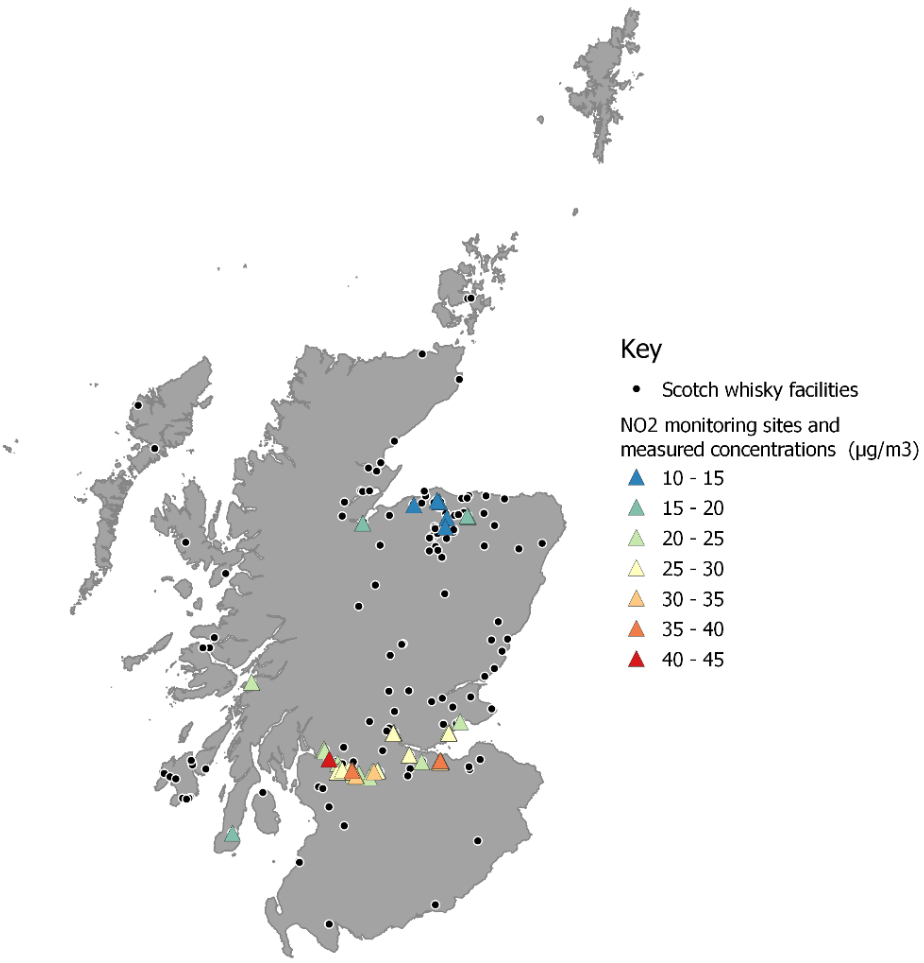
4.3.1 Scottish monitoring network data

Alongside the ozone monitoring network, monitoring relating to nitrogen dioxide (NO_2) concentrations can also be considered to gain an understanding of the drivers for the formation of ozone in Scotland. There is some monitoring of NMVOCs, but not those related to the whisky industry. Any monitoring of ethanol concentrations associated with Scotch whisky production that takes place will be informal, and likely only monitoring concentrations within the warehouse for compliance with health and safety standards for the exposure of workers.

NO_2 concentrations are monitored extensively throughout Scotland at over 100 sites. The majority of these monitoring sites are passive monitoring with diffusion tubes which are cheap and easy to analyse, though have a higher uncertainty than the main pollution monitoring stations. As a result, a bias adjustment factor is frequently applied, derived from the discrepancy in measured concentrations measured by co-located diffusion tubes and an automatic monitor. Both automatic and passive monitors are operated by the local authority, and details of their locations and the measured concentrations at each monitoring site can be obtained from the air quality annual status reports produced by each local authority.

Due to the extensive usage of diffusion tubes by local authorities, the likely NO_2 concentrations close to facilities where Scotch whisky maturation takes place can be estimated. For example, one of the facilities emitting the largest amount of NMVOC in Leven is located approximately 400 m from a diffusion tube on the side of a nearby A road. There, the concentrations measured in 2019 were 23 $\mu g/m^3$ but due to the fall-off in NO_2 concentrations with distance from a source, the concentrations at the facility are likely to be much lower than this. Figure 8 shows all NO_2 monitoring sites in Scotland within 1 km of a Scotch whisky facility and the concentrations measured at these sites in 2019. Though the latest data available corresponds to 2021, the year 2019 was chosen as it represents a year unaffected by traffic reductions due to restrictions imposed as a result of the COVID-19 pandemic. In 2019, only one of these monitoring sites recorded annual mean concentrations greater than 40 $\mu g/m^3$. This site is located just over 100 m from one of the bonded warehouses at the Dumbuck Maturation Site facility, which emitted 1,830 tonnes of NMVOCs in 2019.

Figure 8 All NO_2 monitoring sites within 1 km of a Scotch whisky facility. Measured NO_2 concentrations at each site correspond to the year 2019

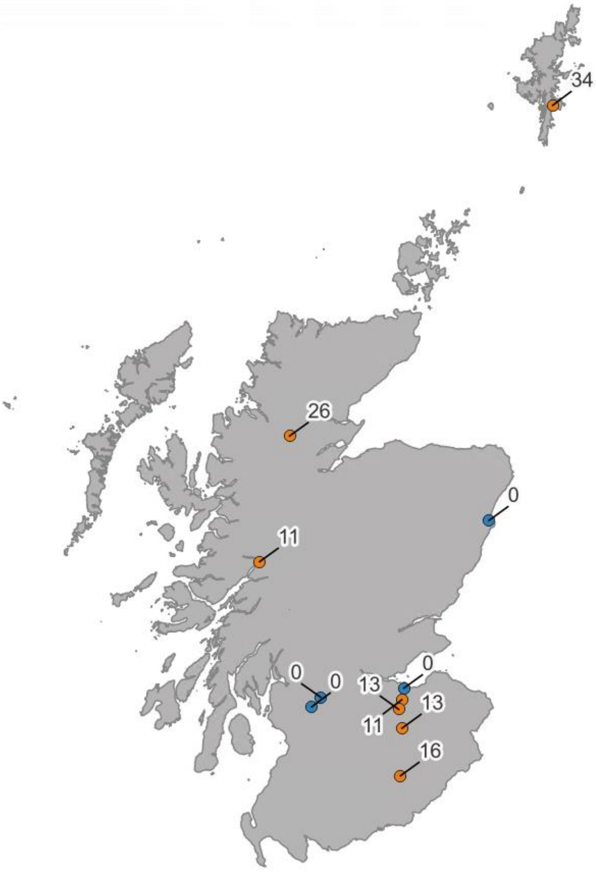


The trend of reducing NOx emissions from road transport has resulted in ozone production now being mostly NOx limited in the UK (AQEG, 2021). As a result, increases in NOx concentrations will have a greater impact on ozone concentrations than increases in NMVOC concentrations. NOx emissions from road transport are anticipated to decline further in future years, which is likely to further limit the production of ozone.

Across Scotland, there are 11 air quality monitoring sites which measure exceedances of the Air Quality Strategy Objective (AQSO) for ozone. These monitoring sites are shown in Figure 9 below with the latest year of monitoring data available. The AQSO is set by the Air Quality Standards Regulations 2010 and applies to the whole of the UK. For ozone, the AQSO is considered to be exceeded if there are 10 or more exceedances in a year of a mean concentration of 100 µg/m^3 within an 8-hour period. This is similar to the World Health Organisation (WHO) Air Quality Guideline (AQG) for short term ozone exposure which is set at a concentration of 100 µg/m^3 within an 8-hour period (WHO, 2021).

In 2018, almost all of the monitoring sites in Scotland recorded exceedances of the AQSO for ozone. This was even true for monitoring sites which rarely record even a single incident in other years where the mean concentration within an 8-hour period was more than 100 µg/m^3. AQEG (2021) notes that 2018 was a year with meteorologically driven inter-annual variability in surface ozone concentrations and, as a result, ozone concentrations in 2018 were the highest recorded in the UK for multiple years (AQEG, 2021). This suggests that exceedances of the ozone AQSO are driven by meteorological conditions rather than local emission sources.

Figure 9 Distribution of Scottish ozone monitors showing the number of incidents in 2019 where a mean ozone concentration was recorded of more than 100 µg/m^3 in an 8-hour period. Monitoring sites recording exceedances of the ozone AQSO (i.e. 10 incidents above 100 µg/m^3) are shown in orange.



In addition, there is variation in the ozone concentrations recorded at urban and rural locations. Ozone monitors in rural locations record a greater number of incidences of the mean concentration exceeding 100 µg/m^3 within an 8-hour period than urban locations. Therefore, it can be concluded that ozone concentrations are generally higher in rural areas than within towns and cities. This is due to the complex nature of the interactions between ozone and nitrogen oxides. Ground-level ozone reacts with nitric acid (NO) to produce NO_2 and oxygen, and therefore reducing the concentrations of ozone. NO is emitted from road transport and so NO concentrations are typically higher in urban areas. This means that NO is more readily available to react with ozone to produce other gases. Those living in rural areas are therefore at a greater risk of being exposed to elevated concentrations of ozone.

It is worth noting that emissions from the road transport sector are anticipated to continue to decrease. This is due to the continued efficiency improvements of engines and emissions control equipment, and a move to electric vehicles. In the future, it is expected that the availability of NO molecules to take part in reactions with ozone in urban areas will therefore decrease. Over recent years, AQEG report (2021) concludes that it is likely that little change has occurred in ozone concentrations in rural areas. In urban areas, ozone concentrations have slightly increased.

Overall, however, 45% of UK surface-level ozone was derived from precursor emissions outside of the UK (AQEG, 2021). Therefore, precursor emissions, such as NMVOC emissions, produced from sources within the UK will only be responsible for just over half of the UK surface ozone monitored within the UK. However, it is unclear if this is true throughout the UK or if local emissions sources, such as Scotch whisky facilities, may change this ratio locally.

By comparing the measured number of exposure limit exceedances to the concentration levels at which health impacts are predicted, it is likely that the observed presence of ozone in Scotland causes health impacts. Monitoring sites in Scotland repeatedly measure 8-hour mean concentrations exceeding 100 µg/m^3, despite evidence that health risks occur at concentrations exceeding 20 µg/m^3. However, secondary formation of ozone is NOx limited in the UK, and therefore additional emissions of NMVOC are unlikely to greatly increase ozone concentrations. Related to this, ozone formation is highly dependent upon meteorological conditions, which are likely to have a greater impact on ozone concentrations than the emissions from the Scotch whisky industry. That being said, Scotch whisky production contributes significantly to the total NMVOC emissions in Scotland which may form ozone. Therefore, while **the impact on human health of Scotch whisky production as a result of ozone formation is likely to be low further studies are recommended to fully verify this impact.**

4.4 Secondary aerosol formation

Secondary aerosols are produced from interactions between VOCs and other molecules in the atmosphere. When VOCs are oxidised they produce secondary organic aerosols (SOAs) which may then form tertiary aerosols through further reactions. First-generation products are mostly hydroxyl, carbonyl, hydroxycarbonyl, hydroperoxide and peroxynitrate (Hallquist et al., 2009). Small oxygenated compounds, such as ethanol, have a low propensity to form SOAs (McFiggans et al., 2015). VOCs may also form secondary inorganic aerosols (SIA) through other reactions. The categories of both SIAs and SOAs encompass a large variety of different pollutants with different properties and therefore with varying impacts on human health.

There are no studies concerning the specific make-up of the SOAs produced from the Scotch whisky production process. This is partly due to SOAs in general not being traditionally targeted in emissions studies (AQEG, 2020). Some research has been conducted covering the SOAs formed from ethanol emissions from the evaporation of biofuels (Suarez-Bertoa et al., 2015). However, typical biofuels are usually blended with gasoline and therefore the conclusions made in these studies cannot be applied to the emissions from the Scotch Whisky industry.

In addition to SOAs, NMVOC emissions from Scotch whisky may also form secondary inorganic aerosols (SIAs). SIAs consist of a mixture of components such as sulphates, nitrates, black carbon and mineral dust and are part of the particulate matter (PM) in the atmosphere. Smaller particles in the $PM_{2.5}$ fraction can be carried over long distances by wind before settling elsewhere. Consequently, the secondary formation of $PM_{2.5}$ as a result of the Scotch whisky industry will not have a purely localised impact.

Given the complexity of the formation pathways and the wide variety of aerosols which could be formed, assessing the human health impacts of SIAs and SOAs produced from Scotch whisky emissions will be difficult. It is still unclear what aerosols would be produced from ethanol emissions and the quantities of these aerosols produced.

If further research was conducted to fill the gaps in understanding the quantity and types of SIAs and SOAs that could be produced, then some progress may be able to be made to determine the likely human health impacts. Secondary aerosols are treated as $PM_{2.5}$ in the Defra damage cost assessment, and they are not distinguished according to their chemical species. The same assumption is widely applied, for example in work for the US EPA and the European Commission (EC). Defra's analysis of $PM_{2.5}$ covering both primary particles and secondary aerosols (Birchby et al., 2019; Defra, 2023) includes the following impacts:

- Mortality
- Respiratory and cardiovascular hospital admissions
- Coronary heart disease
- Stroke
- Diabetes
- Lung cancer
- New incidence of asthma in children
- Productivity
- Building soiling

These effects are quantified for primary particles and secondary particles formed in the atmosphere following release of NH_3, NOx and SO_2. SIA impacts are not included in Defra's damage costs for VOCs. They are, however, included in damage cost work for the European Environment Agency (EEA, 2014; Schucht et al., 2021a, 2021b) and this may provide a mechanism for data to be factored into an assessment of the damage costs associated with NMVOC emissions from Scotch whisky maturation. Such an assessment is, however, beyond the scope of this project.

As discussed in Section 4.3, NMVOC reacts with NO_2 to form ozone. NO_2 may then consume the ozone produced in this reaction, forming nitrates. Studies have found that secondary nitrates can be observed tens of hundreds of kilometres downwind from the source of the NO_2 (Allen, 2019). It is therefore likely to be difficult to determine the quantity of nitrates produced from Scotch whisky production emissions. Research into the health impacts of exposure to nitrates is not extensive. Some studies have suggested links between exposure and propensity for individuals to develop cardiovascular issues or respiratory issues (Kim et al., 2012; Son et al., 2012). In addition to nitrates, evaporated ethanol may also be converted into acetaldehyde which is a well-known carcinogen (IARC, 2012). As a result, people in the vicinity of maturation sites could be exposed to concentrations of acetaldehyde above the expected background concentrations. Advice from the UK government and the World health Organisation is to treat nitrates as of equal harmfulness as other particles.

No studies could be found regarding the creation of secondary aerosols from ethanol production. Given the complexity of the formation pathways and the wide variety of aerosols which could be formed, determining the associated impacts on human health were not possible at this time. Although the health impact is likely to **be minor or even negligible, judgement cannot be made as to the likely severity of the human health**

impacts from aerosol formation once the ethanol is emitted into the atmosphere without dedicated modelling.

5 Environmental impacts

5.1 Ozone formation

Increased concentrations of ozone can be damaging to ecosystems as well as to agricultural crops. Some vegetation may be more sensitive to ozone than others, with effects of excessive ozone exposure including visible leaf injury, increased die-back and reduction in growth and seed production (Global Challenge Network on Tropospheric Ozone, undated; Mills, 2011b). Vegetation damage can impact the entire ecosystem due to interspecies dependence, reducing biodiversity in areas of increased ozone concentration. Cropland damaged due to exposure to ground-level ozone may lead to reduced yields and reduced quality of product, with economic implications for the agricultural sector.

The EU Ambient Air Quality Directive (AAQD; European Parliament and Council, 2008) sets an accumulated ozone exposure threshold value over the averaging period of May to July. This threshold value is based on the sum of hourly ozone values that exceed 80 $\mu g/m^3$, and is set at 18,000 $\mu g/m^3$.hour. The AAQD also sets a long-term objective to reduce the exposure of vegetation to low-level ozone to 6,000 $\mu g/m^3$.hour or less. For forests, the critical ozone exposure level is set by the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) at 5,000 $\mu g/m^3$.hour (Mills et al., 2017). Although not a regulatory level, this exposure level instead acts as a guide for understanding when critical damage may be occurring due to ozone. Due to reduced light exposure to catalyse atmospheric reactions that produce ozone, much of the forested areas in northern Europe did not exceed the critical level in 2019 (EEA, 2021a). It is worth noting that ground-level ozone concentrations are highly dependent on sunlight exposure and therefore vary year upon year. Some studies, however, have still found evidence of the effects of ozone on vegetation in Northern Europe (Mills et al., 2011a).

Monitoring of ozone concentrations occurs throughout the UK, either through Defra's Automatic Urban and Rural Network (AURN) or by local authorities themselves, as well as across Europe with results compiled and presented by the EEA through the European Air Quality Index. As outlined in Section 4.3, ozone concentrations are typically higher in rural locations than in urban locations. The monitoring and reporting of the measurements taken is focused on assuring that the human health ozone objectives are met, rather than the AAQD for vegetation. In 2021, only one region of the UK, the South West, exceeded the ozone long-term objective for vegetation (Defra, 2022). However, in 2018, a high ozone year, the ozone long-term objective was exceeded at two of the Scottish regions – Highland and Scottish Borders (Defra, 2019). It can therefore be determined that, depending on climatic conditions, ozone has some impact on vegetation in Scotland though the significance of the impact is unclear.

Secondary formation of ozone is NOx limited in the UK, and therefore additional emissions of NMVOC are unlikely to greatly increase ozone concentrations. Additionally, ozone formation is highly dependent upon meteorological conditions, which are likely to have a greater impact on ozone concentrations than the emissions from the Scotch whisky industry. That being said, Scotch whisky production contributes significantly to the total NMVOC emissions in Scotland which may form ozone. Therefore, **the impact of Scotch whisky production on the environment as a result of ozone formation is likely to be low.**

5.2 Secondary aerosol formation

Formation of both secondary organic aerosols (SOAs) and secondary inorganic aerosols (SIAs) is discussed in Section 4.4.

The presence of SOAs can change atmospheric chemistry and interact with sulphuric acid, but it is unclear how the SOAs produced by Scotch whisky emissions may contribute to this. There is some evidence that SOAs can produce radiative forcing and therefore contribute to climate change (Shrivastava et al., 2017). SIAs can scatter and absorb solar radiation so contributing to climate change, as well as by modifying the properties of clouds (Verheggen, 2010).

As discussed in Section 4.4, the extent to which emissions from the Scotch whisky industry contribute to secondary aerosols in the atmosphere is unclear. **Further research is necessary to determine this contribution, and the potential environmental impacts they may cause. However, the environmental impact is assumed to be negligible for both SIAs and SOAs.**

5.3 Climate impact

Climate change can affect human health in two main ways: first, by changing the severity or frequency of health problems that are already affected by climate or weather factors; and second, by creating unprecedented or unanticipated health problems or health threats in places where they have not previously occurred (US Global Change Research Programme, 2016).

In addition, many air pollutants contribute to global warming by absorbing energy in the atmosphere and therefore slowing the rate at which energy escapes to space. Some air pollutants have the ability to absorb more energy and hold onto it for longer and therefore they have a greater impact on global warming. The measure of this is a pollutant's global warming potential (GWP).

Little research has been produced as to the GWP of ethanol in particular, however Collins (2002) has conducted research into the indirect GWPs of 10 NMVOCs. None of these are ethanol, but the study does include NMVOCs with similar chemical compositions such as ethane and methanol. This study was the first of its kind but did identify that pulses of short-lived organic compounds can induce perturbations in the tropospheric distributions of methane and ozone that are long-lived and decay on a 10- to 15-year timescale.

Ethanol and acetaldehyde (a secondary pollutant formed from reactions with ethanol) may be involved in reactions causing their complete degradation to CO_2 and H_2O (Australian Government, 2022). In addition, ethanol can act as a precursor, leading to the formation of photochemical smog. Ethanol may also form methane. This occurs because ethanol is a good nutrient and energy source for microbes who feed upon it. In the absence of oxygen, this can lead to the formation of methane (Australian Government, 2022) thus contributing to global warming.

It is worth noting that the production of CO_2 from the evaporation of ethanol will likely be climate neutral. Any CO_2 formed through atmospheric reactions with ethanol will be vegetative CO_2 returning to the atmosphere without degradation of the land that it originated on. There will therefore only be an additional climatic impact if either ethanol on release has a higher GWP than CO_2 or if ethanol degrades into other molecules with a higher GWP than CO_2. Many of the secondary pollutants resulting from NMVOC emissions are also greenhouse gases. Tropospheric ozone has a negative effect on plant growth/biomass, which might increase radiative forcing (US National Climate Assessment, 2014). Radiative forcing (RF) quantifies the change in energy fluxes where positive RF leads to surface warming and negative RF leads to surface cooling (IPCC, 2013). Secondary pollutants such as PM are also produced due to the emission of NMVOCs into the atmosphere. PM includes various different pollutants with a wide range of properties – some have a warming effect on the climate whereas others have an atmospheric cooling effect (US EPA, 2022b). The extent of PM derived as a result of whisky maturation is unknown and would require further investigation to determine the climate impact.

A review of the climatic effect of ethanol, and the release of secondary pollutants from NMVOC emissions, indicates there will be a climate impact. It is expected that the extent of impact will be small but is worth noting their contribution. **Further research is necessary to determine the exact extent of this contribution, and the potential climatic impacts that NMVOC emissions from whisky maturation may cause.**

6 Potential for NMVOC emission mitigation from Scotch whisky maturation

Whisky maturation is a sensitive and complicated process where maturation in given environments produces a spirit unique to the location and barrel that it matures in. Maturation, as the name suggests, refers to a long period of time and any mitigation deemed for consideration would need to take the lifetime maturation of any spirit into account.

The reactions which improve the quality of the whisky in relation to a greater amount of time matured are not yet known (Conner, 2014). This is mainly due to the lack of easily observable activity in a laboratory over the time periods that high quality maturation requires. Attempts could be made to better understand the long-term reactions during the maturation process. This could then be used to provide evidence that a suggested mitigation technology will not negative impact quality. Given the length of the maturation period, trials of any mitigation technology would need to take place for at least three years to ensure that quality is not impacted.

The MATIN (Maturation Innovation) project carried out by the Scotch Whisky Research Institute in collaboration with the Building Research Establishment (BRE), involved the monitoring of 17 warehouses in Scotland (Conner and Forrester, 2017). The team were unable to relate the parameters they monitored inside the warehouse to the rate of loss of ethanol. Alongside the monitoring, the project involved the development of a building energy model for maturation warehouses, based upon the conditions inside two warehouses. The conditions were recorded using 36 loggers recording temperature and humidity in the warehouse. From the model created, the team determined that, in a controlled environment, more than 98% of the variation in losses was due to temperature. The greater the temperature, the greater the loss in ethanol per year. Measurements of ethanol loss were taken from various casks in two warehouses over a two-year period, one warehouse in North Scotland and the other in South Scotland. However, amounts of ethanol loss were found to have varied considerably between casks, even within the same warehouse where the warehouse temperature was constant. The rate of loss is unlikely to be random, and it will most likely be driven by physical processes with quantifiable parameters related to the environment the whisky is in and others relating to variation in barrels that is not easily defined. If these parameters are studied in detail, then mitigation measures can be developed to control the parameters and therefore reduce the evaporative loss of ethanol.

The MATIN study determined that reducing warehouse temperature reduced the evaporative loss but also has an impact on the speed of the maturation process. In particular, the study determined that reduced temperatures slowed the extraction of colour and reduced the colour of the whisky. Therefore, reducing warehouse temperatures may result in casks requiring longer maturation periods to reach the same level of quality. It is not clear from the study, however, if the reduction in temperature reduces the NMVOC emissions over the entire length of the maturation process when taking into account any additional time that may be required for maturation due to the slowing of the maturation process. It is possible that controlling other parameters not determined by this study driving the rate of ethanol loss may not reduce the length of the maturation process, and thus the quality of the product produced.

The Central Valley of California has challenging air quality issues. There, the San Joaquin Valley Unified Air Pollution Control District, in its Rule 4695 requires VOC emissions from brandy aging and wine aging operations above a certain size to be controlled (San Joaquin Valley Unified Air Pollution Control District, 2009a). The rule applies to brandy aging and wine aging operations that have the potential to emit at least 10 tons (9,072 kg) of VOCs per year. A storage warehouse should be sealed so that it qualifies as a permanent total enclosure (PTE) pursuant to US EPA Method 204, although exception is made for moving product in and out of the warehouse and for maintenance. Emissions should be captured by the PTE and vented to a control device such that the total control efficiency is 90%.

A number of control technologies and devices can be used. The brandy aging industry in the district has universally selected the use of a regenerative thermal oxidizer to burn off the VOC emissions due to its low annual maintenance costs (San Joaquin Valley Unified Air Pollution Control District, 2009b). However, other technological feasible approaches include catalytic thermal oxidation; adsorption vapour recovery; wet scrubbing (absorption); condensation, refrigeration and cryogenic systems; and biological oxidation (San Joaquin Valley Unified Air Pollution Control District, 2009b).

In the Final Draft Staff Report for Rule 4695, San Joaquin Valley Unified Air Pollution Control District staff noted that the nature of whiskey aging operations differs from wine and brandy aging, with ambient conditions, such as storage temperature and humidity, as well as seasonal variations, being important factors in the whiskey aging process (San Joaquin Valley Unified Air Pollution Control District, 2009b). Consequently, whiskey aging was not included in the scope of Rule 4695.

The key importance of ambient conditions in the warehouse on product quality was discussed in a US EPA study of the control of VOC emissions from whiskey warehousing (US EPA, 1978). The barrel environment is extremely critical in whisky maturation and varies considerably by distillery and warehouse. In line with tradition and experience, distillers may alter the barrel environment to produce a product with the distinctive characteristics of its brand; this may include moving barrels between different locations in a warehouse or altering the amount of natural ventilation.

A collection system to capture gaseous emissions in a warehouse, as required for brandy aging operations in the California Central Valley, could be expected to significantly disrupt ventilation and air flow patterns around barrels in warehouses and so adversely impact product quality. The only known full-scale test of a control system, where a warehouse was closed and emissions ducted to a carbon adsorption unit, was run between 1960 and 1968, but product quality was adversely affected, ultimately resulting in termination of the test (US EPA, 1978).

In principle, instead of operating continuously an extraction system could be designed to fully replicate natural conditions as these affect air flow around barrels. This might include intermittent changes to ambient temperature and humidity, as well as replicating the formation of stagnant layers and temperature variations in different parts of the warehouse. Another concern with altering ventilation patterns in a warehouse is that ethanol concentrations could be raised above safe levels.

Because of the crucial importance of the unique taste and smell characteristics of each whisky brand for marketability and consumer acceptance, any measure that could affect the maturation process would have to be considered very carefully. **Any future full-scale**

demonstration of potential mitigation measures will require a substantial investment in product and time to show that product quality is not discernibly affected over the full maturation process.

6.1 Voluntary testing of mitigation solutions

Given the importance of the relationship between maturation and the quality of spirit, it is inevitable that whisky industry stakeholders will be cautious towards any proposed mitigation processes. A proposed approach could involve establishing a voluntary testing group with the Scotch Whisky Association (SWA) and Scotch Whisky Research Institute (SWRI). This working group could identify potential distilleries or companies to trial maturation mitigation systems over prolonged periods of time. Engagement of stakeholders will be crucially important for deriving effective solutions.

7 Conclusions and recommendations

This report has demonstrated that based on the available evidence **the health and environmental impacts of NMVOC emissions from Scotch whisky maturation are likely to be minor**. However, further investigation and research is necessary to fully understand, assess and mitigate against those impacts.

As part of this assessment, the spatial distribution of NMVOC emissions was determined. Our analysis has found that the geographical spread of NMVOC emissions from the Scotch whisky industry is uncertain, due to the data informing the spatial distribution of emissions in the National Atmospheric Emissions Inventory (NAEI) stemming from surveys conducted in the 1990s. New bonded warehouses in particular have not been reported to the NAEI compilers. It is therefore recommended that updated information on the geographical distribution of Scotch whisky activity is provided to the NAEI compilers to enable an accurate picture of the distribution of NMVOC emissions from the sector to be established.

Existing regulatory emission databases were also considered to determine the spatial distribution of Scotch whisky NMVOC emissions. Scotch whisky facilities are not normally reported to regulatory databases such as the UK-PRTR or SPRI as maturation is not an activity covered by these reporting streams. Additionally, Scotch whisky facilities rarely meet reporting thresholds for industrial reporting streams, such as the activity threshold for daily production of spirits. Emissions from these facilities are therefore not included in such industrial emissions databases and were therefore not available to review for this project.

In addition to the spatial and monitoring limitations identified as part of this review, determining the likely human health and environmental impacts of emissions from Scotch whisky production has proven challenging due to a lack of high-quality data and a lack of prior research. There is limited published evidence on the health and environmental impacts of whisky maturation including little data on the impact of NMVOC emissions on ozone formation or their impact on climate. Although **the human health impact of ozone production from Scotch whisky NMVOC emissions is likely to be minor based upon the currently available evidence**, it is recommended that increased monitoring of ozone is performed, particularly in rural locations where ozone concentrations are typically elevated. Increased monitoring could then feed into ozone modelling and source apportionment to develop a greater understanding of the contribution of the Scotch whisky industry to elevated ozone concentrations in Scotland.

On a review of available research it is clear that further investigation into the magnitude of long-term exposure to NMVOC emissions from whisky maturation via inhalation is necessary to fully determine the significance of their impact on human health. Based on the currently available evidence the health risks from inhalation (compared to ingestion) of ethanol are limited. **Monitoring of ethanol concentrations at the fence-line of facilities would be useful to gauge a likely upper bound on the ethanol concentrations experienced at nearby sensitive receptors.**

In order for the Scottish Government to fully determine the geographical, environmental and health impacts of NMVOC emissions from whisky maturation, the following recommendations and next steps have been identified:

1. Cross check all whisky production, maturation and storage facilities in the NAEI, COMAH and other applicable datasets;

2. Investigate introducing monitoring of ethanol concentrations at the fence-line of the largest whisky production, maturation and storage facilities, which could be on a voluntary basis by operators or as a research exercise by SEPA;

3. Conduct further investigation into determining the ethanol concentrations which can support the growth of *Baudoinia compniacensis* and review any future research on whether there are any human health impacts of *Baudoinia compniacensis*;

4. Further research the impact of ozone formation on human health and the contribution from whisky maturation through increased monitoring of ozone concentrations (particularly in rural areas) and source apportionment studies;

5. Research the potential human health and environmental impacts from secondary aerosol formation resulting from ethanol emitted into the atmosphere from Scotch whisky facilities;

6. Review any future research on the relative GWP of ethanol in comparison to CO_2 to evaluate the potential climate impacts of NMVOC emissions from whisky maturation;

7. Increase monitoring of conditions within Scotch whisky production, maturation and storage facilities to better understand the parameters that impact the rate of ethanol evaporation during maturation; and

8. Before any potential mitigation measures are introduced, conduct large-scale and long-term trialling and testing to ensure product quality is not affected.

Consideration of the above recommendations will provide the Scottish Government with further understanding of the possible environmental and health impacts of NMVOC emissions from whisky maturation. It will also facilitate consideration of whether any mitigation measures are required and, if so, what would be a proportionate and effective level of implementation.

References

ACGIH, undated. Ethanol. [Online] Available at: https://www.acgih.org/ethanol/ [Accessed 26 October 2022].

American Industrial Hygiene Association (AIHA), 2014. Emergency Response Planning Guideline Values. [Online] Available at: https://www.aiha.org/get-involved/aiha-guideline-foundation/erpgs [Accessed 1 February 2023].

Allen, S., Ree, A., and Ayodeji, S., 2019. Secondary inorganic aerosols: impacts on the global climate system and human health. Biodiversity International Journal, 3(6), pp. 249-259.

Altenstedt, J., and Pleijel, K., 1998. POCP for individual VOC under European Conditions. Goteborg: IVL Swedish Environmental Research Institute.

AQEG, 2020. Non-methane Volatile Organic Compounds in the UK, prepared for Defra. [Online] Available at: https://uk-air.defra.gov.uk/library/reports.php?report_id=1003 [Accessed 31 January 2023].

AQEG, 2021. Ozone in the UK – Recent Trends and Future Projections, prepared for Defra. [Online] Available at: https://uk-air.defra.gov.uk/library/reports?report_id=1064 [Accessed 31 January 2023].

Australian Government, Department of Climate Change, Energy, the Environment and Water, 2022. Substance Fact Sheets: Ethanol (ethyl alcohol). [Online] Available at: https://www.dcceew.gov.au/environment/protection/npi/substances/fact-sheets/ethanol-ethyl-alcohol#:~:text=Ethanol%20will%20oxidise%20quickly%20(less,the%20formation%20of%20photochemical%20smog. [Accessed 19 January 2023].

Bessonneau, V., and Thomas, O., 2012. Assessment of Exposure to Alcohol Vapor from Alcohol-Based Hand Rubs. International Journal of Environmental Research and Public Health, 9(3), pp. 868-879.

Birchby, D., Stedman, J., Whiting, S., and Vedrenne, M., 2019. Air Quality damage cost update. [Online] Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1902271109_Damage_cost_update_2018_FINAL_Issue_2_publication.pdf [Accessed 26 October 2022].

Brennan, S.E., McDonald, S., Page, M.J., Reid, J., Ward, S., Forbes, A., and McKezie, J., 2020. Long-term effects of alcohol consumption on cognitive function: a systematic review and dose-response analysis of evidence published between 2007 and 2018. Syst Rev 9, 33.

Collins, W.J., Derwent, R.G., Johnson, C.E., and Stevenson, D.S., 2002. The Oxidation of Organic Compounds in the Troposphere and their Global Warming Potentials. Climatic Change, 52, pp. 453-479.

Conner, J., 2014. Chapter Eleven of 'Whisky: Technology, Production and Marketing. Elsevier Science, pp. 199-220.

Conner, J., and Forrester, A., 2017. Building for the Future: Innovative Warehouse Design for Efficient Maturation of Scotch Whisky. Brewer and Distiller International, May 2017 issue.

Craig, N., Pilcher, N., Forster, A.M., and Kennedy, C., 2023. Ethanol-driven building fungus colonisation: "Whisky Black" in urban build environments. International Journal of Building Pathology and Adaptation, 41(1), pp. 238-257.

Defra, 2017. Industrial Emissions Screening Tool v3.0. [Online] Available at: https://laqm.defra.gov.uk/air-quality/air-quality-assessment/industrial-emissions-screening/ [Accessed 9 February 2022].

Defra, 2019. Air Pollution in the UK 2018 – Compliance Assessment Summary. [Online] Available at: https://uk-air.defra.gov.uk/assets/documents/annualreport/air_pollution_uk_2018_issue_1.pdf [Accessed 30 October 2022].

Defra, 2022. Air Pollution in the UK 2021 – Compliance Assessment Summary. [Online] Available at: https://uk-air.defra.gov.uk/library/annualreport/ [Accessed 31 October 2022].

Defra, 2023. Air quality damage cost update 2023 – Final Report. [Online] Available at: https://uk-air.defra.gov.uk/library/reports?report_id=1103 [Accessed 1 February 2023].

Department of Health, 2008. Alcohol Units: A brief guide. [Online] Available at: https://lx.iriss.org.uk/sites/default/files/resources/Alcohol%20Units%20a%20brief%20guide.pdf [Accessed 15 February 2023].

ECHA, 2022. Substance Infocard: Ethanol. [Online] Available at: https://echa.europa.eu/substance-information/-/substanceinfo/100.000.526 [Accessed 26 October 2022].

EEA, 2014. Cost of Air Pollution from European Industrial Facilities 2008-2012 - an updated assessment. [Online] Available at: https://www.eea.europa.eu/publications/costs-of-air-pollution-2008-2012 [Accessed 26 October 2022].

EEA, 2019. EMEP/EEA air pollutant emission inventory guidebook 2019. Luxembourg, Publications Office of the European Union.

EEA, 2021a. Exposure of Europe's ecosystems to ozone. [Online] Available at: https://www.eea.europa.eu/ims/exposure-of-europes-ecosystems-to-ozone [Accessed 26 October 2022].

EEA, 2021b. Health impacts of air pollution in Europe, 2021. Briefing no. 19/2021. [Online] Available at: https://www.eea.europa.eu/publications/air-quality-in-europe-2021/health-impacts-of-air-pollution [Accessed 18 January 2023].

EEA, 2022. Health impacts of air pollution in Europe, 2022. Briefing no. 05/2022. [Online] Available at: https://www.eea.europa.eu/publications/air-quality-in-europe-2022/health-impacts-of-air-pollution [Accessed 23 January 2023].

European Parliament and Council, 2006. Regulation (EC) No 166/2006 of the European Parliament and the Council, Annex I. [Online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32006R0166 [Accessed 25 April 2023].

European Parliament and Council, 2008. Directive 2008/50/EU on ambient air quality and cleaner air for Europe, 2008. [Online] Available at: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050 [Accessed 25 April 2023].

European Parliament and Council, 2010. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32010L0075 [Accessed 25 April 2023].

Ewaze, J., Summerbell, R., and Scott, J., 2008. Ethanol physiology in the warehouse-staining fungus, *Baudoinia compniacensis*. Mycological Research, 112(11), pp. 1373-1380.

Garland, L., Jones, L., Richmond, B., Collins, A., Pearson, B., and Richardson, J., 2022. Devolved Administration Air Pollutants Inventory (2005-2020). [Online] Available at: https://naei.beis.gov.uk/reports/reports?report_id=1100 [Accessed 30 January 2023].

Global Challenge Network on Tropospheric Ozone, undated. Ecosystem effects of ozone. [Online] Available at: http://www.ozone-net.org.uk/sites/ozone-net.org.uk/files/documents/filedepot/4/GNC_OzoneFactSheets_EcosystemEffects.pdf [Accessed 26 October 2022].

Goldstein, A., and Galbally, I., 2007. Known and Unexplored Organic Constituents in the Earth's Atmosphere. Environmental Science & Technology, 41(5), pp. 1514-1521.

Gorgus, E. Hittinger, M., and Schrenk, D., 2016. Estimates of Ethanol Exposure in Children from Food not Labeled as Alcohol-Containing. Journal of Analytical Toxicology, 40(7), pp. 537-542.

Grosjean, D., 1997. Atmospheric chemistry of alcohols. Journal of the Brazilian Chemical Society, 8(5).

Gürler, M., Martz, W., Tastekin, B., Najafova, T., and Dettmeyer, R.B., 2022. Estimates of Non-Alcoholic Food-Derived Ethanol and Methanol Exposure in Humans. Journal of Analytical Toxicology, 46(2), pp. 200–211.

Hallquist, M., Wenger, J.C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., Dommen, J., Donahue, N.M., George, C., Goldstein, A.H., Hamilton, J.F., Herrmann, H., Hoffmann, T., Iinuma, Y., Jang, M., Jenkin, M.E., Jimenez, J.L., Kiendler-Scharr, A., Maenhaut, W., McFiggans, G., Mentel, Th.F., Monod, A., Prévôt, A.S.H., Seinfeld, J.H., Surratt, J.D., Szmigielski, R., and Wildt, J., 2009. The formation, properties and impact of secondary organic aerosol: current and emerging issues. Atmospheric Chemical Physics, 9, pp. 5155-5236.

Han, A., Buerger, A., Allen, H., Vincent, M., Thornton, S., Unice, K., Maier, A., and Quiñones-Rivera, A., 2022. Assessment of ethanol exposure from hand sanitizer use and potential for developmental toxicity in nursing infants. Journal of Applied Toxicology, 42(9), pp. 1424-1442.

HSE, 2020. EH40/2005 Workplace exposure limits: Containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations 2002 (as amended). [Online] Available at: https://www.hse.gov.uk/pubns/books/eh40.htm [Accessed 26 October 2022].

IARC, undated. Alcohol and cancer in the WHO European Region. [Online] Available at: https://www.iarc.who.int/infographics/alcohol-and-cancer-in-the-who-european-region/

IARC, 2012. Personal Habits and Indoor Combustions. Volume 100E: A Review of Human Carcinogens. IARC.

Indiana State Department of Health, 2019. *Baudoinia compniacensis* "Whiskey Fungus". [Online] Available at: https://www.in.gov/health/eph/files/Baudoinia-compniacensis-Fact-Sheet-Final-March-2019.pdf [Accessed 26 October 2022].

Ingledew, D., Churchill, S., Richmond, B., MacCarthy, J., Avis, K., Brown, P., Del Vento, S., Galatioto, F., Gorji, S., Karagianni, E., Kelsall, A., Misra, A., Murrells, T., Passant, N., Pearson, B., Richardson, J., Stewart, R., Thistlethwaite, G., Tsagatakis, I., Wakeling, D., Walker, C., Wiltshire, J., Wong, J., Yardley, R., Hobson, M., Gibbs, M., Dore, C., Thornton, A., Carswell, A., Misselbrook, T., Dragosits, U., and Tomlinson, S., 2023. UK Informative Inventory Report (1990 to 2021). [Online] Available at: https://www.ceip.at/status-of-reporting-and-review-results/2023-submission [Accessed 20 April 2023].

IPCC/TAEP, 2005. Safeguarding the Ozone Layer and the Global Climate System. Cambridge: Cambridge University Press.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kim, S.Y., Peel, J., Hannigan, M., Dutton, S., Sheppard, L., Clark, M., and Vedal, S., 2012. The temporal lag structure of short-term associations of fine particulate matter chemical constituents and cardiovascular and respiratory hospitalizations. Environmental Health Perspective, 120(80), pp. 1094-1099.

Kroll, J., and Seinfeld, J., 2008. Chemistry of secondary organic aerosol: Formation and evolution of low-volatility organics in the atmosphere. Atmospheric Environment, 42(16), pp. 3593-3624.

MacLean, R., Valentine, G., Jatlow, P., and Sofuoglu, M., 2017. Inhalation of Alcohol Vapor: Measurement and Implications. Alcoholism Clinical and Experimental Research, 41(2), pp. 238-250.

Mahmood, A., Eqan, M., Pervez, S., Alghamdi, H.A., Tabinda, A.B., Yasar, A., Brindhadevi, K., and Pugazhendhi, A., 2020. COVID-19 and frequent use of hand sanitizers; human health and environmental hazards by exposure pathways. Science of the Total Environment, 742, 140561.

McCool, B., and Chappell, A., 2015. Chronic intermittent ethanol inhalation increases ethanol self-administration in both C57BL/6J and DBA/2J mice. Alcohol, 49(2), pp. 111-120.

McFiggans, G., Alfarra, M., Allan, J., Coe, H., Hamilton, J., Harrison, R., Jenkin, M., Lewis, A., Moller, S., Topping, D., and Williams, P., 2015. A review of the state-of-the-science relating to secondary particulate matter of relevance to the composition of the UK atmosphere, project AQ0732: Full technical report to Defra. [Online] Available at: https://uk-air.defra.gov.uk/library/reports?report_id=874 [Accessed 25 April 2023].

Mills, G., Harmens, H., Hayes, F., Pleijel, H., Buker, P., and González-Fernández, I., 2017. Chapter 3: Mapping critical levels for vegetation. [Online] Available at: https://icpvegetation.ceh.ac.uk/biblio [Accessed 30 January 2023].

Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Büker, P., 2011a. Evidence of widespread effects of ozone on crops and (semi-) natural vegetation in Europe (1990–2006) in relation to AOT40- and flux-based risk maps. Global Change Biology, 17(1), pp. 592-613.

Mills, G., Pleijel, H., Braun, S., Büker, P., Bermejo, V., Calvo, E., Danielsson, H., Emberson, L., Fernández, I.G., Grünhage, L., Harmens, H., Hayes, F., Karlsson, P.-E., and Simpson, D., 2011b. New stomatal flux-based critical levels for ozone effects on vegetation. Atmospheric Environment, 45(28), pp. 5064-5068.

NHS, 2022. The risks of drinking too much. [Online] Available at: https://www.nhs.uk/live-well/alcohol-advice/the-risks-of-drinking-too-much/ [Accessed 31 October 2022].

OECD (Organisation for Economic Co-operation and Development), 2004. Screening Information Data Set (SIDS). Initial Assessment Report for SIAM 19: Ethanol. [Online] Available at: https://hpvchemicals.oecd.org/ui/handler.axd?id=87AE34EB-5241-44A3-87EB-37F8FF949D99 [Accessed 1 February 2023].

Papathanasiou, S., 2017. We Breathe 11,000 Litres of Air Daily. See The Air. [Online] Available at: https://seetheair.org/2017/01/31/we-breathe-11000-liters-of-air-daily/ [Accessed on 14 April 2023].

Passant, N., Richardson, S., Swannell, R., Gibson, N., Woodfield, M., van der Lugt, J., Wolsink, J., and Hesselink, P., 1993. Emissions of Volatile Organic Compounds (VOCs) From the Food and Drink Industries of the European Community. Atmospheric Environment, 27A(16), pp. 2555-2566.

PHE, 2015. Ethanol: Incident Management. [Online] Available at: https://www.gov.uk/government/publications/ethanol-properties-uses-and-incident-management [Accessed on 1 February 2023].

PHE, 2017. Formaldehyde: general information. [Online] Available at: https://www.gov.uk/government/publications/formaldehyde-properties-incident-management-and-toxicology/formaldehyde-general-information#:~:text=Inhalation%20of%20formaldehyde%20can%20lead,the%20early%20stages%20after%20ingestion [Accessed on 31 January 2023].

PHE, 2019. Benzene: general information. [Online] Available at: https://www.gov.uk/government/publications/benzene-general-information-incident-management-and-toxicology/benzene-general-information#:~:text=Ingestion%20of%20benzene%20may%20cause,if%20in%20contact%20with%20skin. [Accessed on 31 January 2023].

Rumgay, H., Shield, K., Charvat, H., Ferrari, P., Sornpaisan, B., Obot, I., Islami, F., Lemmens, V.E.P.P., Rehm, J., and Soerjomataram, I., 2021. Global burden of cancer in 2020 attributable to alcohol consumption: a population-based study. Lancet Oncol 2021; 22: 1071–1080.

Russell, L., Bahadur, R., and Ziemann, P., 2011. Identifying organic aerosol sources by comparing functional group composition in chamber and atmospheric particles. Environmental Sciences, 108(9), pp. 3516-3521.

San Joaquin Valley Unified Air Pollution Control District, 2009a. Rule 4695 Brandy Aging and Wine Aging Operations. [Online] Available at: https://www.valleyair.org/rules/currntrules/r4695.pdf [Accessed 7 February 2023].

San Joaquin Valley Unified Air Pollution Control District, 2009b. Final Draft Staff Report for New Draft Rule 4695 (Brandy Aging and Wine Aging). [Online] Available at: https://www.valleyair.org/Workshops/postings/2009/09-17-09/4695/4695%20Final%20Draft%20Staff%20Report.pdf [Accessed 24 April 2023].

Schucht, S., Real, E., Holland, M., Garland, L., Gibbs, M., Colette, A., Guerreiro, C., Brignon Jean-Marc., Rouil, L., and Marnane., I., 2021a. ETC/ATNI Report 18/2019: Development of a refined methodology for the EEA externalities assessment. [Online] Available at: https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-18-2019-development-of-a-refined-methodology-for-the-eea-externalities-assessment-1 [Accessed 26 October 2022].

Schucht, S., Real, E., Létinois, L., Colette, A., Holland, M., Spadaro, J., Opie, L., Brook, R., Garland, L., Gibbs, M., Calero, J., Zeiger, B., Rouïl, L., Brignon, J., and German, R., 2021b. ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017. [Online] Available at: https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-04-2020-costs-of-air-pollution-from-european-industrial-facilities-200820132017 [Accessed 26 October 2022].

Scotch Whisky Association, 2023a. Facts & Figures. [Online] Available at: https://www.scotch-whisky.org.uk/insights/facts-figures/ [Accessed 6 April 2023].

Scotch Whisky Association, 2023b. Scotch Whisky Exports Over £6bn for First Time. [Online] Available at: https://www.scotch-whisky.org.uk/newsroom/scotch-whisky-exports-2022/ [Accessed 21 April 2023].

Scott, J., 2016. The role of VOCs in microfungal colonization biology: Baudoinia compniacensis. [Online] Available at: https://web.archive.org/web/20161102033318/http:/individual.utoronto.ca/jscott/projects/baudoinia/baudoinia.html [Accessed 2022 October 2022].

Scottish Statutory Instruments, 2017. The Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017. SI 2017/102.

Shrivastava, M., Cappa, C., Fan, J., Goldstein, A., Guenther, Jimenez, J., Kuang, C., Laskin, A., Martin, S., Ng, N., Petaja, T., Pierce, J., Rasch, P., Roldin, P., Seinfeld, J., Shilling, J., Smith, J., Thornton, J., Volkamer, R., Wang, J., Worsnop, D., Zaveri, R., Zelenyuk, A., and Zhang, Q., 2017. Recent advances in understanding secondary organic aerosol: Implications for global climate forcing. Reviews of Geophysics, 55(2), pp. 509-559.

Srivastava, D., Vu, T., Tong, S., Shi, Z., and Harrison, R., 2022. Formation of secondary organic aerosols from anthropogenic precursors in laboratory studies. Climate and Atmospheric Science, 5(22).

Son, J.Y., Lee, J.T., Kim, K.H., Jung, K., and Bell, M., 2012. Characterization of fine particulate matter and associations between particulate chemical constituents and mortality in Seoul, Korea. Environmental Health Perspective, 120(6), pp. 872-878.

Suarez-Bertoa, R., Zardini, A., Platt, S., Hellebust, S., Pieber, S., Haddad, I., Temime-Roussel, B., Baltensperger, U., Marchand, N., Prévôt, A., and Astorga, C., 2015. Primary emissions and secondary organic aerosol formation from the exhaust of a flex-fuel (ethanol) vehicle. Atmospheric Environment, 117, pp. 200-211.

UK Statutory Instruments, 2018. The Air Quality (Miscellaneous Amendment and Revocation of Retained Direct EU Legislation) (EU Exit) Regulations 2018. No. 1407, Regulation 2. [Online] Available at: https://www.legislation.gov.uk/uksi/2018/1407/regulation/2/made [Accessed 24 April 2023].

US EPA, 1978. Cost and Engineering Study - Control of Volatile Organic Emissions From Whiskey Warehousing. [Online] Available at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100BFY7.txt [Accessed 25 April 2023].

US EPA, 2013. Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report, Feb 2013). [Online] Available at: https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=247492 [Accessed 18 January 2023].

US EPA, 2019. Method 201 – Criteria for and Verification of a Permanent or Temporary Total Enclosure. [Online] Available at: https://www.epa.gov/sites/default/files/2019-06/documents/method_204_0.pdf [Accessed 24 April 2023].

US EPA, 2020. Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report, Apr 2020). [Online] Available at: https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=348522 [Accessed 18 January 2023].

US EPA, 2022a. Health Effects of Ozone in the General Population. [Online] Available at: https://www.epa.gov/ozone-pollution-and-your-patients-health/health-effects-ozone-general-population [Accessed 28 October 2022].

US EPA, 2022b. Air Quality and Climate Change Research. [Online] Available at: https://www.epa.gov/air-research/air-quality-and-climate-change-research [Accessed 31 October 2022].

US Global Change Research Programme, 2016. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. [Online] Available at: https://health2016.globalchange.gov [Accessed 9 February 2013].

US National Climate Assessment, 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. [Online] Available at: https://data.globalchange.gov/report/nca3 [Accessed 9 February 2013].

Verheggen, B., and Weijers, E., 2010. Climate change and the impact of aerosol: A Literature Review. Energy Research Centre of the Netherlands E-series, 9(95). Petten, Energy Research Centre of the Netherlands.WHO Regional Office for Europe, 2013. Health risks of air pollution in Europe - HRAPIE project: Recommendations for concentration-response functions for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide. [Online] Available at: https://apps.who.int/iris/handle/10665/153692 [Accessed 18 January 2023].

WHO, 2021. WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. [Online] Available at: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y [Accessed 21 April 2023].

Oxford Centre for Innovation

New Road

Oxford

OX1 1BY UK

+44(0)1865 261466

www.aether-uk.com