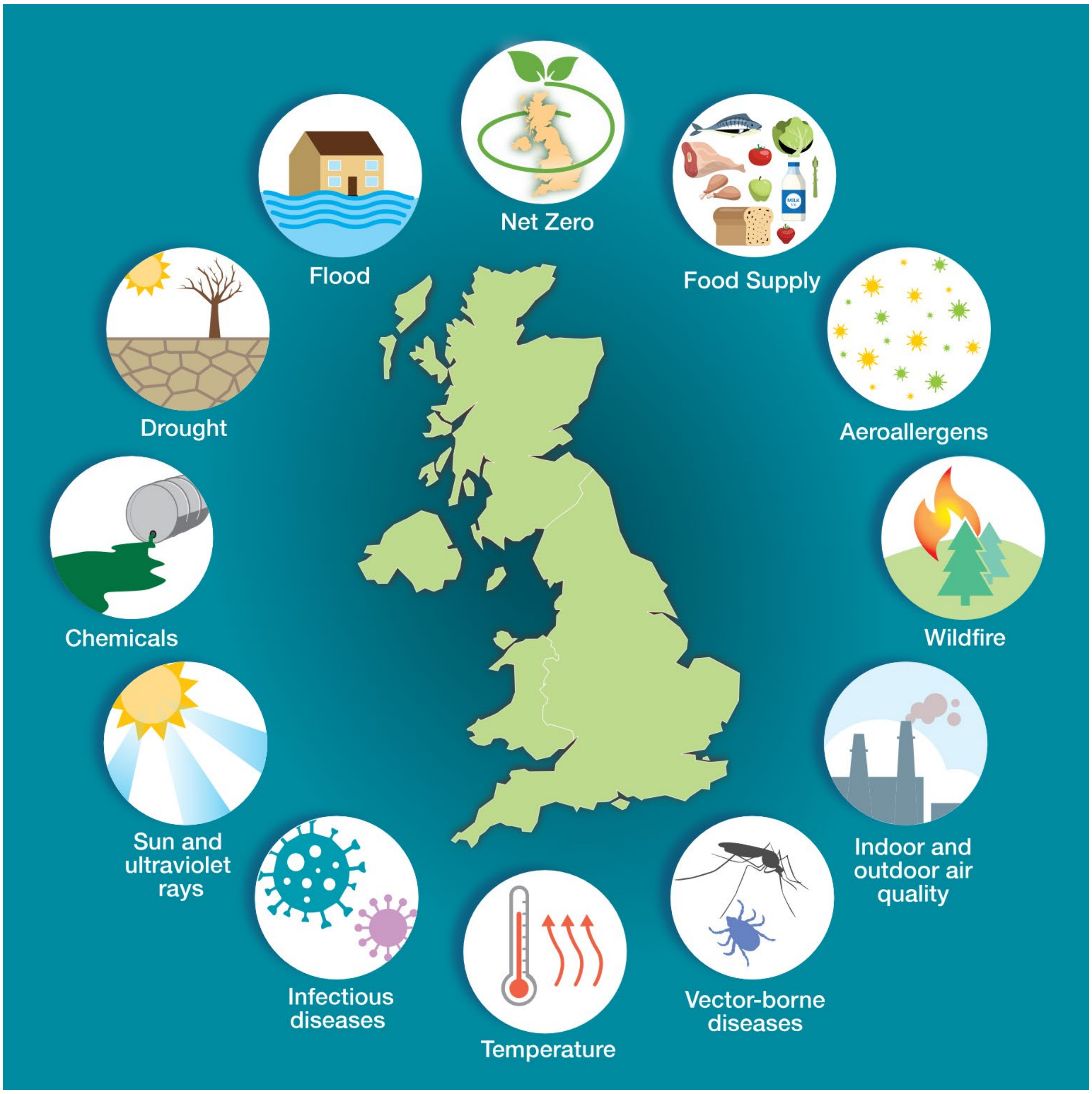
UK Health Security Agency

Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 12. Impact of climate change on human exposure to chemicals in the UK



Summary

People are exposed to chemicals every day from multiple sources. Exposure to chemicals in our environment can negatively impact health, ranging from acute events such as poisonings and asthma attacks to long term effects such as cancer and damage to the immune system. Climate change may affect the behaviour of chemicals in the environment and the amounts and types of chemicals used, stored and transported which could impact population exposures and health. Chapter 12 presents a review of evidence of how climate change may affect exposures of human to chemicals and the potential health impacts. This is the first time that a chapter on chemicals has been included in a Health Effects of Climate Change in the UK report. The chapter was led by scientists at the UK Health Security Agency (UKHSA). The authors identified a lack of empirical data; however, they conclude that it is almost certain that climate change will affect human exposure to chemicals.

Changes in temperature, precipitation, humidity, wind conditions, erosion and extreme events due to climate change will affect the fate and behaviour of chemicals in the environment (atmosphere, water, soil, sediment and biota). Climate change is likely to increase the release of chemicals, including contaminant discharge from polar ice and high-altitude glaciers (which act as sinks to harmful chemicals). There is also likely to be increased release of chemicals due to higher temperatures and reduced precipitation, which can volatilise persistent organic pollutants (POPs) and pesticides into the atmosphere and potentially increase air pollution.

There are several other mechanisms by which climate change may further increase exposure to chemicals, including increased use of agriculture-related chemicals such as pesticides and fertilizers to account for declines in crop productivity, longer crop growing seasons, introduction of new crops and increases in suitable agricultural land. Climate change may also benefit pest populations, with reduced overwintering mortality, increased population growth rate and introduction of new pest species. Individuals may be exposed to different pesticides, particularly for those living close to agricultural areas. Climate change may also increase the release of contaminants from land deposited waste driven by changes in soil and groundwater conditions, for example, and increased release of chemicals from industrial sites (such as fires, explosions, leakages and overflows) following extreme weather events.

Temperature changes may increase the volatilisation and atmospheric transport of some chemicals such as pesticides. After volatilisation, chemical compounds can be transported over wide areas at low concentrations in the air. Temperature increases in water can lower the pH and increase the solubility of ionic compounds (such as heavy metals), resulting in enhanced distribution and uptake of such pollutants. More frequent, severe and longer heatwaves are likely to increase the frequency and size of wildfires, which will release significant amounts of air pollutants into the atmosphere and potentially lead to elevated levels of pyrogenic by-products, such as polycyclic aromatic hydrocarbons (PAHs).

Precipitation (particularly excessive precipitation following drought, which leads to flooding) can cause runoff and contaminant leaching, as well as affecting soil and groundwater conditions, microbiological communities and their processes and thus impact on chemical transport and fate in the environment. Longer and drier summer periods in future may lead to very dry soils, decreasing the ability of soil to absorb water and causing increased runoff during heavy rainfall.

Changes in precipitation patterns may also alter the distribution of contaminants such as POPs and PAHs. Areas with decreased rainfall may experience increased volatilization and dust transport of contaminants, while regions with increased rainfall are likely to have greater surface deposition of airborne POPs and increased pesticide run-off. In addition, studies have found that more frequent and heavy storms result in increased chemicals in water bodies. Sea-level rise, increased winter precipitation and drier summers could also alter the risk level to contaminants in situ, such as those in landfills.

The chapter highlights 3 key insights for public health. First, measures should be taken to reduce exposure to harmful chemicals including pesticides. Second, the management of chemical stockpiles and landfills and the remediation of contaminated sites, should incorporate consideration of vulnerability to extreme weather events such as flooding. Finally, the potential implications of increased frequency and intensity of flooding and storms should be considered in relation to the risk of remobilization of chemicals such as POP into the environment from waste disposal sites, soils and sediments.

This chapter highlights several research gaps and priorities, including the need to:

- develop methods for assessing the potential direct effects of climate change on chemical toxicity, including identification of priority contaminants and risks to human health
- develop routine geographic, demographic, socio-economic and ecological analysis of the drivers of human vulnerability to chemical exposures and how they are affected by climate-induced shifts and other stressors that are altered by a warming climate
- develop standards and guidelines to limit emerging contaminant concentrations in soil and water.
- develop international collaborations, to facilitate collection of scientific data and provide experimental evidence of potential direct impacts of climate change on the fate of chemicals at specific sites (such as contaminated land) and their remediation methods.
- develop effective monitoring and evaluation of future uncertainties in relation to droughts and flood events, so adaptation strategies can be reviewed and adjusted to remain within an acceptable level of risk

UKHSA is working with national and international partners to improve the management of chemicals and associated wastes, reduce the release and impact of chemicals on the environment and reduce the burden of disease caused by exposure to chemicals. This includes undertaking research and development activities to understand the effects of climate on the risk to health from chemicals, providing evidence informed advice, including to low- and middle-income countries through overseas development assistance and contributing to national action plans and international efforts and commitments. UKHSA is conducting research on the health effects from exposure to chemical hazards as part of the NIHR Health Protection Research Unit in Environmental Change and Health due to climate change.

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1. Introduction

1.1 Summary of previous reports

Previous 'Health Effects of Climate Change in the UK (HECC)' reports (1 to 3) have not had a dedicated chapter on the impacts of climate change on human exposure to chemicals in the UK, although exposure to chemicals were considered in the context of indoor and outdoor air pollution and flooding. This chapter will focus on how climate change impacts chemical fate in the environment, followed by examples of sources of human exposure to chemicals arising from agricultural processes, industrial processes (such as large-scale production and storage of chemicals) and contaminated land. It will not focus on chemicals which are covered under indoor and outdoor air quality (including carbon monoxide, particulate matter (PM), nitrogen and sulphur dioxides, and volatile organic compounds such as formaldehyde, benzene and other aromatic hydrocarbons), flooding (such as chemical contamination and carbon monoxide poisoning from clean-up equipment) or natural fires (products of combustion and air pollution) as there are dedicated chapters on these topics in this report (see Chapters 3, 4 and 5).

1.2 State of the current science and chapter aims and objectives

In 2019, it was thought that pollution was responsible for approximately 9 million premature deaths globally, with air pollution causing the greatest burden at 6.7 million deaths, followed by water pollution at 1.4 million deaths and lead pollution at 900,000 premature deaths (4). Toxic occupational hazards (excluding workplace deaths due to safety hazards) closely followed at 870,00 deaths in 2019 (4). The global cost of health damages associated with air pollution exposure is estimated at US$8.1 trillion, which is equivalent to 6.1% of global gross domestic product (GDP) in 2019 (5). Furthermore, IQ losses in the European Union due to polybrominated diphenyl ethers (PBDEs) and organophosphate pesticides have been reported, resulting in economic productivity losses of US$12.6 billion and US$194 billion, respectively (6). These figures may continue to increase and be exacerbated by climate change (6).

Human exposure to chemicals released into the environment through natural and human activities can directly and indirectly affect human health (7). Toxic effects range from acute events such as poisonings and asthma attacks to chronic effects such as immunosuppression and cancer (8). Indirect effects include increased health risks associated with food and water supply as a result of chemical contamination, through to affecting other human diseases and changes in behaviour. Some of the key chemical contaminants or groups of chemical contaminants discussed in the chapter and the potential health impacts following long-term exposure are presented in Table 1.

Global climate change is causing major physical and ecological changes across the planet, with significant changes in both long-term weather characteristics and short-term weather extremes in different regions (see Chapter 1), increasing the risk of certain health threats in the future (7, 9). Exactly how the environment impacts on human health is often complicated, particularly at a global level where a myriad of factors are at play. However, there is increasing awareness of the importance of predicting the potential exposures and effects of chemicals in the changing environment. Weather and climate factors are known to affect the fate and behaviour of chemicals in the environment by altering physical, chemical and biological drivers of partitioning between the atmosphere, water, soil, sediment, and biota, through transformation and degradation (10). Climate change may therefore have important impacts on the dispersion and exposure risk to chemicals in the future. As a consequence, there is a growing need to identify and mitigate potential negative health effects, particularly in the most vulnerable populations (10). In addition, changes in climate are likely to affect the amounts and types of chemicals used, stored and transported for a range of scenarios.

Table 1. Summary of the key (groups of) chemical contaminants, and examples of their health impacts

Chemical (group)	**Abbreviation**	**Examples**	**Examples of health impacts following long-term exposure**
Heavy metal(loids)	-	Mercury (Hg) (and organic mercury - methylmercury), lead (Pb), arsenic (As), cadmium (Cd), chromium (VI) (Cr(VI))	Potential to disrupt many body organs including the nervous system, gastrointestinal system, cardiovascular system, kidneys, liver and lung; carcinogenic (As, Cr(VI)); heart disease and diabetes (Cd); cognitive impairment (Pb) (11 to 13)
Persistent organic pollutants	POPs	Polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and -biphenyls (PBBs), perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA), hexabromocyclododecanes (HBDC), polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), perfluoroalkyl and polyfluoroalkyl substances (PFASs), hexachlorocyclohexane (HCH), organochlorine pesticides (such as atrazine)	Cardiovascular disease, cancer, metabolic disorders, and effects on neurobehavioral, endocrine and reproductive systems, suppressed immune system function (14)
Organo-phosphate pesticides	OPPs	Chlorpyrifos	Potential effects on the central and nervous systems (15, 16)
Polycyclic aromatic hydrocarbons	PAHs	Benzo(a)pyrene, naphthalene	Carcinogenic (B(a)P), possible carcinogen (naphthalene) (11, 17)
Volatile organic compounds	VOCs	Formaldehyde, benzene, ethylbenzene, toluene, xylenes, Methyl tert-butyl ether (MTBE), trichlorethylene (TCE) and its breakdown product vinyl chloride (VC)	Adverse health effects and diseases, such as haematological effects (benzene); carcinogenic (including benzene, formaldehyde, TCE, VC);

Chemical (group)	Abbreviation	Examples	Examples of health impacts following long-term exposure
			neurological, liver and kidney damage, adverse effects on fertility in men (TCE) (13)
Semi-volatile organic compounds	SVOCs	Aldrin (agricultural chemicals)	Potentially carcinogenic, adverse effects on the central nervous system (18)

Future risks of chemical exposures could be very different to today, so it is important to consider the implications that a changing climate will have on human exposure to chemicals and assess the subsequent health impacts in the near- and long-term. The most susceptible populations to climate change-driven negative health impacts linked to interactions between contaminant exposures include older individuals (10), as well as low-income populations (19), infants (20) and the chronically ill (21). However, it is recognised that further studies are required to gain a better understanding of susceptibility amongst all populations.

Climate change impacts are likely to result in increased primary (direct) and secondary (indirect, including reaction of primary pollutants with other chemicals in environment) releases of hazardous chemicals, potentially increasing human exposure and subsequent harms to health. Primary releases include contaminant discharge from natural sinks such as polar ice and high altitude glaciers (which act as sinks to harmful chemicals). For example, perfluoroalkyl and polyfluoroalkyl substances are being released from melting glaciers from the Tibetan Plateau, contaminating downstream lakes and streams, with mercury being released from the thawing permafrost. One examples of secondary releases is increased temperatures leading to changes in pesticide behaviour. For every 10°C increase in temperature, the half-life of pesticides in soils is predicted to decrease by 60% (meaning that it takes the pesticide longer to be reduced by half in soil) (22). This could result in increased volatilisation (the conversion of a liquid chemical into a vapour, which escapes into the atmosphere), as the vapour pressure of most pesticides increases with temperature (22). As such, pesticides may be transported from areas with high concentrations to regions with lower concentrations, potentially exposing new populations to the harmful effects of the pesticides. Increased chemical volatilisation and degradation may also necessitate increased pesticide usage (10).

Primary mechanisms by which climate change is anticipated to influence contaminant releases, resulting in further exposure to chemicals, relates to the increased:

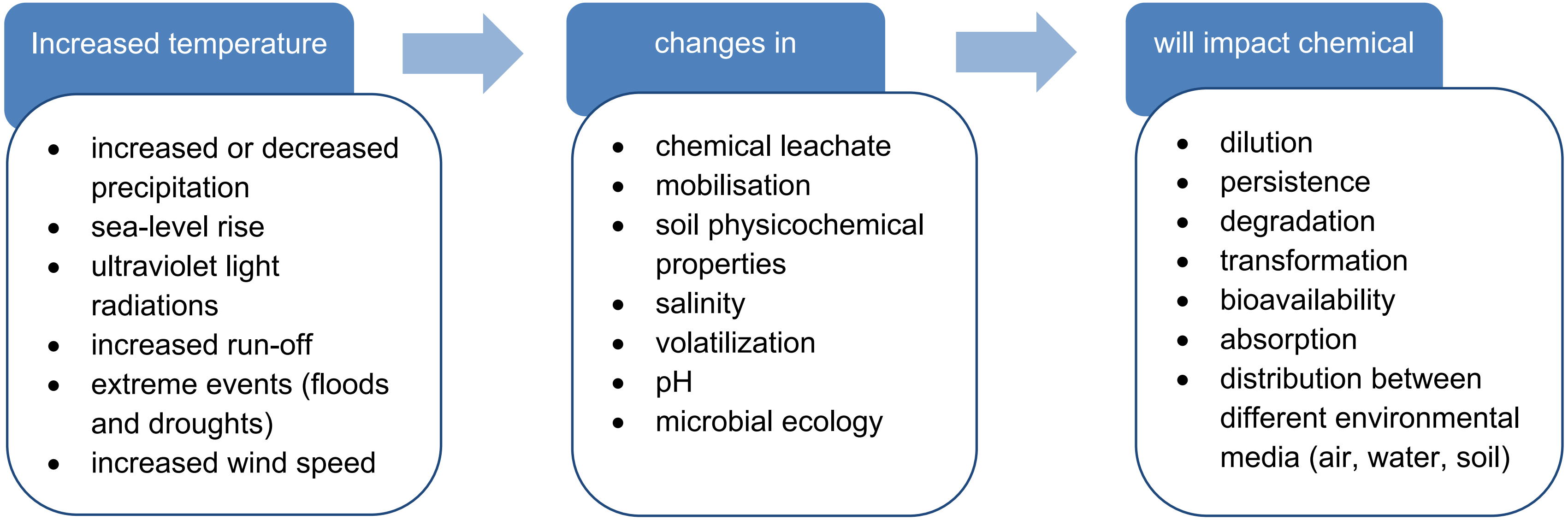
- use (amount, frequency and longer period of application) of agriculture-related chemicals, such as pesticides, fertilizers, veterinary pharmaceuticals and wastewater sludge, including the introduction of potential new chemicals
- contaminant releases from land deposited waste (contaminated land, contamination remediation sites, historical waste disposal sites, as well as current engineered waste disposal sites) through changes in soil and groundwater conditions, chemical reactions of contaminated soils and landfilled materials, and potential destabilisation and damage of past contamination containment
- release of chemicals from industrial sites (such as fires, explosions, inundated tanks, leakages and overflows) via more severe and frequent natural extreme events potentially disrupting and damaging infrastructure

In this chapter, we discuss how human health risks to chemicals might be altered through climate change, by exploring the current scientific evidence for health effects resulting from environmental exposure to chemicals arising from agriculture and industrial processes; the potential impacts of climate change on the inputs of chemicals into these industrial and agricultural systems; and the human exposure pathways resulting from these changes. This chapter makes recommendations for approaches to mitigate and minimise increases in adverse health risks, as well as highlighting knowledge gaps and future research priorities. Although this chapter has a UK-focus, the topics discussed and the conclusions reached may be relevant to other countries and sectors.

2. Climate change impacts on chemical fate and transport

There are numerous ways in which climate change is predicted to affect human exposures to chemicals (see Figure 1 for an overview). Global warming-driven changes in environmental conditions, such as increased temperatures, changes in precipitation, water levels, salinity and runoff, as well as changes in the frequency of floods and droughts, increased windspeed and erosion, affects transport of chemicals within the environment (7, 10). A changing climate will impact chemical fate, dilution, persistence, transformation and transport between the different environmental media (air, water, soil, sediment and biota). Such impacts could lead to changes in contaminants leaching (draining away from material by the action of percolating liquid, such as rainwater), volatilisation, soil physicochemical properties, chemical degradation process and microbial ecology (9, 24 to 26). Salinity changes due to irrigation, sea level rise or saltwater intrusion into coastal aquifers alters the bioavailability of contaminants and can increase the chemical toxicity of organic compounds. These compounds are less soluble and more bioavailable in saltwater, therefore increased concentrations of pollutants are more likely to be absorbed in aquatic organisms (10). Some pesticides (such as malathion) have a longer degradation half-life in seawater compared to freshwater, meaning that it takes this pesticide longer to be reduced by half in saline environments. This supports the concept of increased pesticide persistence due to salting out effects. Environmental degradation could therefore increase aquatic biota exposure to contaminants, and thus potentially increasing human dietary exposures and risks to health (10). In addition, seawater salinity is predicted to change regionally, potentially affecting the solubility of POPs in water, making them less soluble in more saline water and resulting in changes in partitioning from water to the atmosphere (14). Other factors which influence chemical fate in the environment include pH and ultraviolet (UV) light irradiation, particularly in water environments. These parameters can also affect the chemical toxicity of common pharmaceuticals. For example, a decrease in pH enhances the toxicity of acetaminophen, enrofloxacin and chlortetracycline while increased UV-B radiation increases the toxicity of sulfthiazole due to photomodification (27).

Figure 1. Flow diagram summarising how climate change may impact on chemical fate in the environment



Text version of Figure 1.

Climate change can lead to:

- increased temperature
- increased or decreased precipitation
- sea-level rise
- ultraviolet light radiations
- increased run-off
- extreme events (floods and droughts)
- increased wind speed

This can lead to changes in:

- chemical leachate
- mobilisation
- soil physicochemical properties
- salinity
- volatilization
- pH
- microbial ecology

Which will impact chemical:

- dilution
- persistence
- degradation
- transformation
- bioavailability
- absorption
- distribution between different environmental media (air, water, soil)

End of text version of Figure 1.

2.1 Temperature-related processes

Temperature is a key factor influencing chemical degradation rates, and therefore chemical persistence. Persistent chemicals can react further with other environmental contaminants, and regionally increase concentrations of some air pollutants, such as tropospheric ozone (10, 28). More details on outdoor and indoor air quality can be found in Chapters 4 and 5. Temperature changes may increase the volatilisation and atmospheric transport of some chemicals, such as pesticides, mainly driven by increased temperatures, direct exposure to sunlight and high soil moisture content (22, 29). After volatilisation, chemical compounds can disperse from high-concentration areas and be transported at low concentrations over wide areas in aerial inputs or wet deposition in rain (29). In water, temperature increases can lower the pH, which in turn increases the solubility of ionic compounds (such as heavy metals in water), enhancing the distribution of such pollutants and their uptake (9).

Distribution, release and degradation of POPs are highly dependent on environmental conditions. Therefore, a changing climate may affect POP contamination and exposure through altered sources, transport, pathway and degradation processes, having direct consequences for human exposure (14). Temperature in particular is likely to be the most important factor in the environmental fate of POPs in the context of climate change (14). Temperature rises may enhance both primary (intentionally produced) and secondary (unintentionally produced from environmental reservoirs) emissions of POPs by changing their mobilisation rate from materials and stockpiles, or by impacting use patterns (14, 26). Such changes in POP concentrations will result in increased exposure in humans as contact with POPs mainly occurs via environmental media (for example, polluted air) and the food chain (such as consuming contaminated fish) (14), with subsequent risks to health.

Increased temperature is also anticipated to affect releases from historically-contaminated environments and directly influence POP distribution through altering the chemical's half-life, partitioning between phases (for example, from soil and water to air), increased volatilisation, as well as indirect impact (such as on the hydroxyl radical formation process). The potential increased degradation of POPs is most likely to be relevant to historic POP reservoirs in soils, vegetation and seawater (14). The influence of higher temperatures on semi-volatile POPs is likely to be "the most important and stronger effect of climate change on the environmental recycling of POPs" (14). However, it is still unclear whether potential increased degradation associated with higher temperatures would outweigh the increased volatilisation, which would vary depending on the chemical properties (25). It also remains unclear how microorganisms responsible for biodegrading POPs will be impacted by climate change, and if POP metabolites and degradation products will be more toxic and persistent than the parent compound (such as hydroxylated polychlorinated biphenyls (PCBs)) (14, 30).

The distance that POPs can be transported via wind depends in part on the surface characteristics and the physicochemical properties of the compound, and also the substance to which it is sorbed or bound. Persistent chemicals with a lower vapour pressure will deposit in areas close to their emission source, while compounds with a higher vapour pressure are more easily transported further away from the source (31). Temperature rises will likely increase the vapour pressure characteristics of many chemicals, leading to a higher risk of environmental dispersion, and therefore exposure, to POPs (see temperature-related mobilisation below in this section), increasing health risks.

Higher temperatures can increase metabolic activity of many organisms, such as molluscs and crustaceans, which in turn will increase the potential for bioaccumulation and biomagnification of certain chemical contaminants. For instance, increased biodegradation activity may increase breakdown products which can be more toxic (such as methylmercury, which is toxic to the central and peripheral nervous systems), while warmer temperatures can accelerate the conversion of mercury to methylmercury (9) and also an increase in the uptake of methylmercury (7), potentially increasing health risks. Organomercury compounds, like methylmercury, are a particular environmental and public health concern due to their toxicity and formation through the methylation of inorganic mercury by micro-organisms in aqueous environments, accumulating in the aquatic food chain. However, the inverse can also occur, where temperature increases can actually lower organochlorine concentrations in fish, which may reduce risk of exposure via the food chain.

Whilst warmer temperatures favour biological degradation and transformation of compounds, reduced humidity has the opposite effect. Contaminants such as heavy metals that are transported via leachate have decreased movement in higher temperature and drier environments (32). Temperature changes in soil can affect metalloids behaviour within soil; increased temperature leads to higher content of soil organic matter (SOM – organic soil constituents which are important in soil pollutants absorption) therefore binding larger amounts of metals in the soil, leading to increased uptake by plants (9). Some of the more compelling evidence shows that warmer ambient temperatures alter toxicokinetic and energy metabolism pathways that in turn increase the toxicity of some metals, although the exact mechanisms are not fully understood (28). Temperature increases could also decrease water content in soil, while evapotranspiration increases water content. As a consequence, a higher resuspension of soil dust particles is envisaged, leading to the suspension and dispersion of any heavy metals present in the soil (33).

Melting sea ice, snow and soil have the potential to mobilise primary and secondary sources of POPs, such as PCBs, PBDEs, organochlorine pesticides and methylmercury, by influencing their portioning between soil, sediment, water and atmosphere, including air-surface exchange, wet-dry deposition and reaction rates (9, 26), and transporting to downstream locations. Secondary sources associated with the historic use and storage of chemicals are anticipated to represent major active stores and sources of pollutants (26). This could increase POP levels in water, soil, biota and food chains as they are becoming more bioavailable (10, 28, 34). It has been further estimated that climate variability may include annual variations of POP re-volatilisation that could undermine efforts undertaken globally to reduce environmental and human exposure to POPs (26).

More frequent and longer heatwaves in mid- and northern latitudes are likely to lead to more frequent and larger wildfires (see Chapter 10), releasing significant amounts of carbon dioxide, carbon monoxide and fine PM into the atmosphere, potentially leading to elevated levels of pyrogenic by-products, such as polycyclic aromatic hydrocarbons (PAHs) and dioxins or furans (28), exposing local and regional populations to these air pollutants. The resulting air pollution can lead to various health concerns, such as respiratory and cardiovascular problems (35). Several PAHs, including benzo(a)pyrene, have been classified as carcinogenic.

It is important to note that prediction models will have to be altered, as many physicochemical properties of chemicals, such as vapour pressure and solubility, are generally measured at between 20°C and 25°C and will need to be updated to reflect rising temperatures. These properties can affect diffusion and partition coefficients in air and water.

2.2 Precipitation, drought and wind speed-related processes

Droughts and precipitation impact on chemical transport and fate in the environment, by affecting soil and groundwater conditions, the microbiological communities and their processes, as well as runoff and leaching of contaminants. Precipitation is reported to be the key driving factor for agricultural runoff and soil erosion (29). A 5-fold increase in applied pesticide loss to runoff during intense precipitation has been reported (10). Predicted longer and drier summer periods in the UK may lead to very high soil moisture deficiencies, increasing soil hydrophobicity and resulting in increased runoff during heavier rainfall in summer (36). Furthermore, changes in precipitation patterns have the potential to change spatial and temporal distribution of contaminants, such as POPs and PAHs, wet deposition from atmosphere to surfaces (including water and soil) and their degradation products (26, 37).

Precipitation is important at the regional scale (14) with areas receiving more intense rainfall being subjected to elevated runoff of toxicants into water systems, particularly pesticides, fertilizers, petroleum products and other non-point chemicals from agricultural and urban land use (28). While regions subject to decreased rainfall may experience increased volatilization and dust transport of POPs and pesticides to the atmosphere, areas likely to experience increased precipitation will have lower air pollution levels, greater surface deposition of airborne POPs and increased pesticide run-off (10). Precipitation removes gases and aerosols with adsorbed chemical particles from the air, depositing them to surfaces and lost in runoff, exposing humans to these chemicals (10). Furthermore, changing precipitation will impact upon soil moisture and microbial soil communities which biodegrade POPs, thus impacting the fate of these chemicals in the environment (14). Heatwaves and droughts generally favour increased persistence (25), although a 'Contaminated Land: Applications in Real Environment bulletin (CL:AIRE)' concluded that higher temperatures favour biological degradation (32).

Wind speed plays a role in the global fate and transport of chemicals. Enhanced transport of POPs, (such as PCBs) between continents has been investigated in several studies that have shown that these chemicals are transported away from the source area within moving air (14, 26). Enhanced atmospheric transport of airborne particles and associated POPs may counteract increased POP deposition (14). Model projections indicate higher atmospheric POP concentrations in regions downwind of their primary sources; however, changes in the magnitude and direction of global wind patterns are difficult to assess (14). Thus, the 'Climate Change Risk Assessment (CCRA2) Synthesis Report' stated that wind speeds across the UK have shown a very slight decline across all regions except the South East UK where speeds have slightly increased; whilst these changes are consistent with climate change projections, many uncertainties remain (38).

In the longer term, the transportation of relatively water-soluble chemicals, such as hexachlorocyclohexane (HCHs), perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), is also affected by ocean currents (14). POP fate in the ocean is complex and dependant on many processes related to ocean currents, volatilisation and phase partitioning between air and sea water, degradation in sea water and deposition with suspended PM. Changes in radiation intensity and light conditions, which have an impact on photochemical degradation, may also influence POP transport patterns (26).

Cold temperatures can induce the deposition and accumulation of POPs in Arctic environmental media, resulting in the so-called cold-trapping effect of these compounds (31). The fate of POPs depends on meteorological conditions, and therefore climate change will modify their concentrations and trends in the Arctic, which ultimately affects the rest of the world (31). Melting of glacial ice may reintroduce POPs into the environment, and potentially bioaccumulate in the food chain through fish (34).

Studies investigating storm intensity and chemical concentrations in controlled waters have generally associated more frequent and heavy storms with chemical increases in water bodies (10). For example, the transport and fate of 5 pesticides (atrazine, carbaryl, diquat dibromide, imidacloprid, and fipronil) in water bodies in 2 parts of the USA were recorded under different storm intensities, and all 5 pesticide concentrations increased with increasing storm intensity (10). Following Hurricane Katarina, soil and sediment concentrations of several contaminants (including aldrin and other semi-volatile organic compounds (SVOCs) and metals) exceeded relevant USA human health soil screening levels, likely due to runoff from extreme rainfall events (10). Climate change can shift the risk and contamination pathways of heavy metals, as modelling showed that decreased soil water content combined with increased wind speed and temperature (evapotranspiration) exacerbated the resuspension (or re-emission) of lead and other heavy metals from water and soil particles into the air (33). This occurs more in areas with higher populations and can lead to increased heavy metal contamination and accumulation in the food chains (33). Storms can additionally affect surface water supply treatment, even where contamination is by a natural source, in this case peat. For example, heavy runoff into an upland reservoir in England, led to high levels of organic content in raw water (39).

Whilst it has been suggested that decreased biodegradation is associated with drier conditions (32), another study reports that intense precipitation may lead to water-logged soils, resulting in anaerobic ground conditions and longer chemical half-lives of compounds requiring aerobic conditions (40). A study undertaken for agricultural soils under anaerobic conditions recorded no degradation of ibuprofen, carbamazepine, diclofenac, hydrochlorothiazide and gemfibrozil over 30 days (40). Increased drought frequencies may also impact chemical fate and transport processes including increased formation of desiccation cracks in cohesive soils, resulting in increased water infiltration into soils, further impacting chemical transportation to groundwater and surface waters from sources such as agriculture (22, 25). Raised groundwater levels will directly impact on the contaminant mobility, and increased precipitation could accelerate the leaching process, for example, by leaching of basic cations and increasing soil acidity, further increasing solubility of heavy metals in water. As a result of this and other processes discussed above, the impact of climate change drivers on soil dynamics may increase chemical exposures to the population, thus adversely impacting public health.

In addition to temperature and moisture, soil properties such as organic matter, mineral fractions and microbial activities are reported as key processes controlling the toxicological aspects of chemicals in soil (9). Climate change could increase human exposure to soil contaminants due to processes involving soil organic carbon (SOC), surface run-off, redox state and microbial community (9). Climatic change may alter organic carbon cycling and SOC dynamics in soils, leading to changes in the bioavailability of contaminants that are bound to SOC; for example, the availability and mobility of heavy metals depend on their adsorption and desorption in soil which are strongly related to SOM (9). Fine particle size and related organic matter, especially organo-clay complexes in soil, respond to increased soil temperature and the release of bound heavy metals that may become available in soil. Climate change-related exacerbated soil erosion is predicted to cause near-surface clay loss in agricultural soils, affecting the chemical transport bound to clay fractions (9).

The literature review undertaken for this chapter highlighted that although there is evidence of climate change-induced negative impacts on the distribution and toxicity of contaminants, there is still insufficient information available to provide a full understanding of the interactions between climate change, hazardous chemical releases and resulting human exposure and health impacts. The UNEP report concludes that "there is a need for generation of further relevant information and data on the links between climate change and hazardous chemicals to be gathered through targeted studies in areas less comprehensively studied in the open literature. Examples of such areas include groundwater, freshwater systems, pesticide usage projections and desertification. A comprehensive needs assessment is required to identify specific research and development target areas" (14).

Table 2 describes the primary mechanisms by which climate change influences chemical transport and behaviour in the natural environment, resulting in potential increase in harmful human exposures to chemical pollutants. The information in this table is illustrated graphically in Figure 2.

Table 2. Summary of climate change impacts, the chemical contaminants involved and their health impacts
(The information in this table is illustrated graphically in Figure 2, below.)

Climate change impact	Climate change factors affecting impact	Potential contaminants	Potential key exposure pathway	Potential exposure (plus/minus)	References
Waste fires (fires in dumpsites and landfills for solid waste)	Increased temperature and drought, high winds	PM, PAHs, dioxins, dibenzofurans, formaldehyde, acrolein, inorganic acid gases (such as halogen acids – HC, HF, HBr and SO_x, NO_x)*	Air	[plus] Increased exposure to chemical air pollutants	(41)
Dispersal of particulates and gases by heavy wind. Deterioration of contaminated soil, waste site or contamination containment infrastructure	Related to increased temperature, heavy wind, drought, heavy rainfall, (sea) water level rise, repetitive tides	Variety of contaminants present in near surface soils (such as pesticides, fertilisers) and chemicals in solid wastes (such as plastics, mercury and lead)	Air, water, soil, food	[plus] Increased exposure to chemical air pollutants [plus] Increased exposure to contaminated water [plus] Increased exposure to contaminated soils through food	(9, 41)
Physical damage to an industrial waste site resulting in migration of contaminants	Extreme events	Variety of contaminants present in near surface soils and wastes, chemicals in storage or manufacturing plants	Air, water, soil	[plus] Increased exposure to contaminated water [plus] Increased exposure of freshwater and sea life (entry into food chain)	(41 to 43)
Flooding inundates waste, contaminated soils or agricultural soils resulting in mobilisation of chemicals or remobilisation of chemicals absorbed in soils into uncontaminated water and soils	Extreme event related, increased rainfall	POPs, pesticides, dioxins, heavy metal(loids), hydrocarbons, ammonium cyanides	Water, soil, food	[plus] Contamination of local water supplies, entry into the food chain	(9, 14, 41)
Volatilisation and dispersion of volatile chemicals from water and soil (including agricultural land), waste, buildings, furniture into air	Increased temperature, soil moisture and wind speed, direct exposure to sunlight	Methane, ammonia, nitrous oxides, sulphides, mercury, POPs, pesticides	Air	[plus] and [minus] Increasing outdoor exposure due to volatilisation Increased exposure to indoor POPs (such as PBDEs, HBCDs, PFOS**)	(9, 10, 14, 41, 44)
Increased solubility of contaminants more apt to be retained in water and migration of contaminants	Increased temperature, altered water pH (acidic conditions favour solubility)	POPs, heavy metals	Water, crops, food	[plus] Potentially decreased water quality	(9, 10)
Degradation (via microbial action, chemical reactions and sunlight)	Increased precipitation (and associated soil moisture), increased sunlight and temperature	Pesticides, POPs, mercury (and potentially other heavy metals)	Soil, water, air	[plus] Potential for more mobile, persistent and toxic compounds.	(7, 9, 10, 14, 44)

Climate change impact	Climate change factors affecting impact	Potential contaminants	Potential key exposure pathway	Potential exposure (plus/minus)	References
				[minus] Potential reduction of chemicals in the environment through enhanced degradation and reduced persistence	
Increased precipitation and associated enhanced leaching of unprotected waste, contaminants and pesticides in soil and surface runoff into uncontaminated water and soils. Decreased precipitation reduce chemical runoff but may increase persistence and increase the level of airborne particulates containing POPs	Increased or decreased precipitation (duration, seasonality, intensity) and associated potential water level rises, increased temperature	Pesticides, POPs, PM, heavy metal(loids), dioxins, hydrocarbons, cyanide, ammonium, sulphates	Water	[plus] and [minus] Downstream migration and potential impact on drinking water quality	(9, 10, 14, 41, 42, 44)
Rainfall collecting gases and aerosols, with adsorbed chemical particles, from the atmosphere and depositing them to surfaces, such as soil and water	Increased precipitation	POPs, PM, mercury	Soil, crops, water	[plus] Increased precipitation deposits contaminants into the soil and water surfaces	(9, 10)
Increased or decreased toxicant intake due to changes in diet (food supplied from different geographical areas) and changed ocean currents delivering contaminants	Increased temperature, changes in precipitation, wind and ocean currents	POPs	Food	[plus] and [minus] Changes in food supply structure	(14)

Notes

[plus] indicates increase in potential exposure.

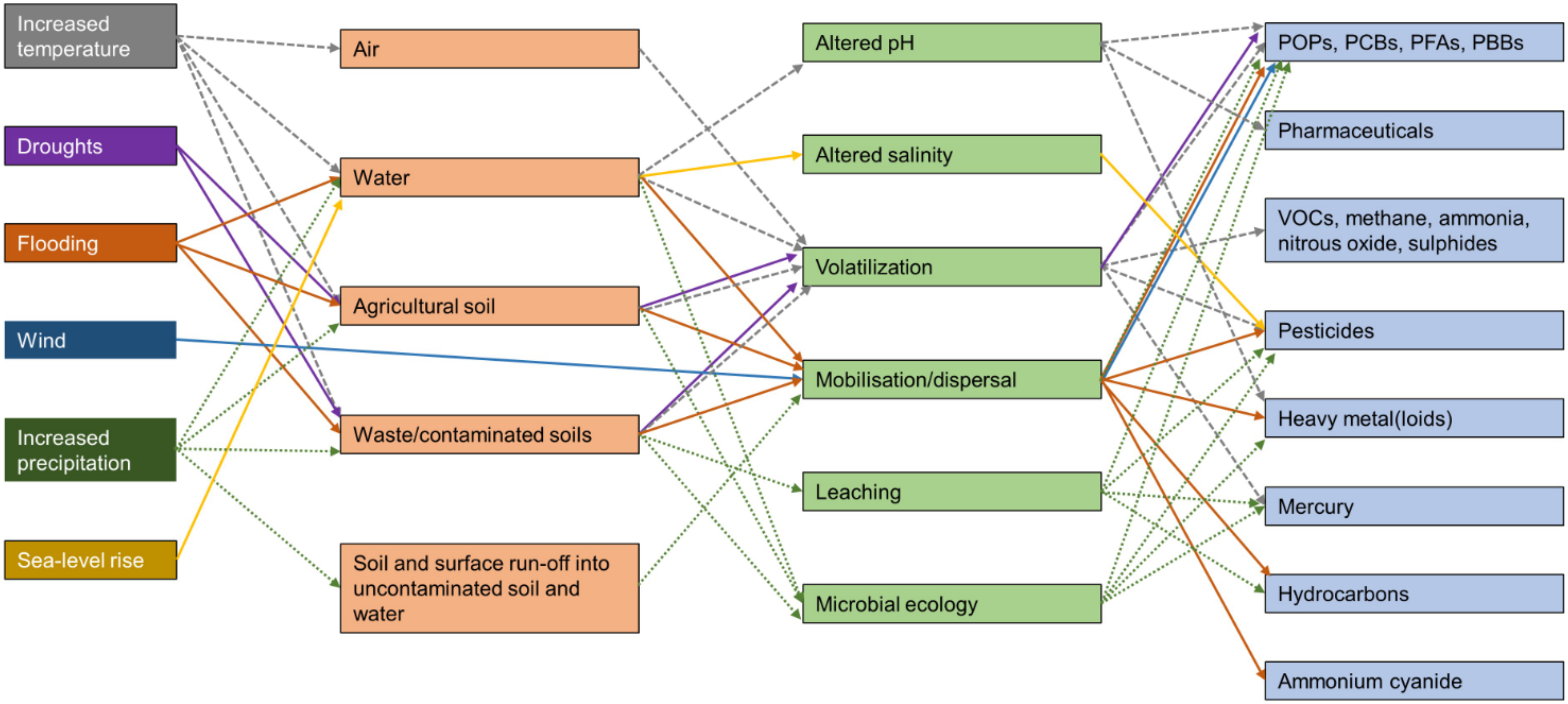
[minus] indicates decrease in potential exposure.

[plus] and [minus] indicate both increases and decreases in potential exposure.

* Hydrochloric, hydrofluoric, hydrobromic and other acids such as sulphuric and nitric acids.

**Persistent organic pollutants (POPs) such as: polybrominated diphenyl ethers (PBDEs), hexabromocyclododecanes (HBCDs) and perfluorooctane sulfonate (PFOS).

Figure 2. Factors impacting the exposure to chemical pollutants due to climate change
(This is a graphic version of Table 2.)



3. Climate change, agriculture-related chemicals and human exposure

3.1 Determinants of exposure

Several adverse health effects are known to be associated with exposure to agricultural chemicals (particularly through occupational exposure or poisoning). For example, Parkinson's disease has been linked with pesticide exposure and recurring exposure to low levels of organophosphates can increase risks of certain cancers (45). While the link to pesticide exposure is clear (46), it is difficult to comprehensively identify the determinants contributing to pesticide exposure in humans (45). In addition, resistance to a variety of pesticides is increasing, leading to pesticides being used more frequently or intensively for pest control (47).

Numerous agricultural chemicals, or mixtures of chemicals, such as pesticides, fertilisers, veterinary pharmaceuticals, treated municipal wastewater and feed additives, are emitted by agricultural systems. Chemicals from other non-agricultural sources such as personal care products, may enter the environment as a result of agricultural soil irrigation using treated municipal wastewater and application of sludge biosolids for soil amendment (25). Climate change is forecasted to change the types and quantities of the chemicals used, emitted and cycled in agricultural processes through changes in use patterns (25). With predicted changes in temperature and precipitation patterns, potentially more intensive, widespread and frequent use of pesticides will be required as a result of increased and changing pest, weed and disease generation, longer growing seasons, introduction of new crops and increases in suitable agricultural land area (10, 48). For example, warmer temperatures will result in longer growing seasons (38) and potentially increase agricultural activities and pesticide use. In future, southern England is estimated to become favourable for growing sunflowers, grapes, peaches (4) and grain maize (22), requiring the use of new pesticides, in addition to increases in the volume and selection of pesticides (10). In addition, climate change may reduce crop pest population generation times and over-wintering mortality, therefore increasing population growth rates and number of pest generations (10). Generally, most pest species favour warm and humid weather and in cropped ecosystems, pest outbreaks often coincide with changes in climatic conditions, such as early or late rains, drought, or increases in humidity, flooding and storms. These variations in climate, coupled with more frequent pest occurrence will affect the crop growth, yield and availability of certain crops, thereby threatening food security (48). However, these changes are likely to be specific to species and regions. Potential effects of climate change on agriculture include reductions in crop yields in warmer regions due to heat stress, damage to crops, soil erosion and inability to cultivate land due to heavy precipitation and other forms of extreme weather and land degradation due to extreme drought, increasing the reliance on, and use of, agricultural chemicals (49).

Climate change factors, changes in crop geographical distribution and productivity, as well as abundance of pests, fungi, weeds and diseases, all influence pesticide application (including potential increase in volume and variety of pesticides). In addition, pesticide application can also be altered by changes in soil conditions (such as SOM, the size and frequency of crack formation in soils) and by any changes in pesticide behaviour in the environment which can potentially accelerate volatilisation, runoff, leaching and degradation. Studies have shown that intense precipitation significantly impacts chemical fate and transport in agricultural systems, and the time between precipitation events may alter pesticide application methods, impacting the pesticide mobilisation once rainfall occurs (25). In addition, other factors potentially contributing to greater pesticide use include increased pesticide resistance (47) and changes in the timing of pest activity (25).

Volatilisation is a key factor in the environmental partitioning of pesticides, and increased temperatures caused by climate change may enhance this relative to soil and water (10). Moreover, a warming climate may have a significantly effect on accelerating pesticide degradation which takes place via 3 types of degradation: chemical reactions, microbial degradation and light (44). Some of these degradation products may be more harmful to health than their parent molecules, for example the main metabolite of the organophosphate insecticide chlorpyrifos (3, 5, 6-trichloro-2-pyridinol (TCP)), is much more mobile and toxic when compared to its parent chlorpyrifos. Both chlorpyrifos and its degradation products have been commonly detected in soils, sediments, and groundwater in many areas (44). Factors influencing pesticide microbial degradation and the rate and type of chemical degradation in soil include temperature, soil moisture and soil pH, whilst the degradation rate of pesticides by sunlight (photo-degradation) depends on the light intensity, exposure length, and chemical properties (44). Overall, given the likely increase in pesticide use due to chemical volatilisation, degradation and runoff, together with expanded cropping patterns and increased pest pressures, climate change-driven impacts in agriculture may lead to increased human exposure to pesticides (10, 44).

Climate change may reduce concentrations of pesticides applied to crops due to increased volatilisation and accelerated degradation, which are both significantly affected by elevated temperatures, sunlight exposure and a high moisture content, and pesticide use (such as increased spraying frequencies and volumes during the growing season) may be altered to overcome this (29). Changes in pesticide use may impact human exposure at the top of the food chain as the residue concentrations might double for some products, while others will disappear faster and cause a residue increase in crops (29). In addition, increased temperature and CO_2 levels promote plant growth, which in turn can decrease pesticide residue by diluting the absorbed pesticide concentration. In addition, roots can penetrate deeper soil layers, reducing the uptake of pesticides typically present in topsoil. However, root uptake may be accelerated due to decreasing SOM content and higher evaporation rates (29).

Herbicides are another important agricultural chemical which will also increase in use. Temperatures significantly alter weed communities, and increases in soil temperature are thought to induce a decline in the persistence of herbicides, leading to a decline in weed control by chemical means (50). Increased water temperatures can also increase the photodegradation rate of several phenyl-urea pesticides, whilst increased rainfall may contribute to increased leaching and runoff of pesticides through more frequent storms and flooding events. Longer, drier summers may lead to prolonged soil moisture deficits, which would make the soil more hydrophobic and increase runoff from summer rainfall (36). This would also lead to an increase in contamination of surface water bodies. In addition, greater atmospheric CO_2 concentration directly raises herbicide tolerance and efficacy in weeds (29, 51). As herbicides and pesticides become less effective, their use will increase either alone (frequency of application) or in combination with multiple chemicals, or agricultural workers may turn to more harmful pesticides. Hence, the overall use of pesticides and herbicides could increase under climate change (50).

The application of sludge and biosolids from wastewater treatment to agricultural fields is a common practise in the UK (52). Approximately 3 million to 4 million tonnes of biosolids are applied annually to agricultural land, representing approximately 75% of sewage sludge production (53). Sludges and biosolids originating from wastewater treatment plants potentially act as a source of heavy metals, POPs, pharmaceuticals, endocrine-disrupting chemicals, home and personal care products, microplastics (25), engineered nanomaterials, perfluoroalkyl acids (PFAAs) and hormones (54). Sewage sludges emit large amounts of hydrogen sulphide, ammonia and VOCs into the atmosphere, representing risks to human health and increasing CO_2 emissions, thus exacerbating the problem of climate change (55). The presence of types and concentrations of chemicals in wastewater sludge depends on the chemicals disposed down-the-drain from connected domestic and commercial properties (55). Also, pharmaceutical and personal care products are becoming very common in sewage sludge, as although effective wastewater treatment plants stop chemicals being discharged in the water course, these compounds are present in the sludge which could then be deposited on land. While such depositions are limited by legal requirements (52, 56), these contaminants could severely impact health (54). Furthermore, the technologies applied in wastewater treatment plants affect the presence of types and concentrations of chemicals in sludge. Some of the contaminants are biodegraded during wastewater treatment, whilst others remain unchanged in sewage sludge (55). Climate change could exacerbate the potential exposure to chemicals in sludge due to current practice via the route discussed above.

The quality of water used for crop irrigation is a key factor in determining the risk of crop contamination. The Food Standards Agency (FSA) reports that the 2 main irrigation water sources in England are surface water and groundwater (together account for about 95% of irrigation water use), with the remaining 5% mainly accounted for by mains water, recycled water and harvested water (57). Re-use of water from sewage treatment works for crop irrigation is not normally practiced in the UK (57). Therefore, the discharges of wastewater to surface waters, the primary source of irrigation water, are of relevance in terms of crop contamination. Surface waters are particularly vulnerable to contamination from raw sewage, treated sewage effluent and livestock manures from surface run-off and exceeded capacity of wastewater infrastructure during heavy rainfalls (57) which are predicted to become more frequent because of the changing climate. In addition, during the drier summer period, which is generally peak irrigation time, river flows may consist predominately of treated wastewater (57) due to anticipated drier summers leading to surface waters having less water and contaminants being less diluted (36).

There is significant evidence of the presence of emerging contamination of soils and surface waters, such as pharmaceuticals, personal care products and hormones linked to treated wastewater discharges (40). Concentrations of numerous pharmaceuticals in surface waters and influent and effluent water associated with sewage treatment plants in the UK have also reported increased levels of these emerging contaminants in the surface water exposed to treated wastewater (54). Accumulation of phthalate esters (often used as additives to improve the flexibility of polyvinyl chloride resins) in agricultural soils could lead to the contamination of food chains and vegetables and subsequent direct or indirect exposure to humans (54). However, the fate of these emerging contaminants in treated sewage is not clearly understood (54). There is also a need to better understand how irrigation and the use of biosolids affect crop uptake, bioaccumulation and entry into the food chain of these emerging contaminants (54), which could become more relevant as climate change puts additional pressure on the availability of water due to changing weather patterns (such as prolonged drought).

One of the greatest direct climate change-associated threats for the UK, is water shortage (38). Irrigation demands are likely to increase due to warmer and drier summers, putting pressure on water supplies; the availability of water for irrigation is expected to decline in the future due to potential restrictions on abstractions and anticipated reduced recharge due to climate changed impacts (57). The re-use of treated municipal wastewater is often suggested as a possible response to pressure on water resources (3). This could lead to the use of poorer quality water (including treated wastewater), increased risk of crop contamination (36) and increased emissions of chemicals into agricultural environments (57). One of the most important adverse impacts on the environment associated with wastewater use for agricultural irrigation is the increase in soil salinity, potentially decreasing productivity (58).

Use of wastewater for both irrigation and fertilisation is a long-established practice in agriculture, as it contains valuable micronutrients for crops and maximises water efficiency for a population. Indeed, it is estimated that around 10% of the world’s population depends on food grown with wastewater (59). However, there are obvious safety concerns using wastewater, and this is relevant to the UK as a large proportion of fruit and vegetables are imported (57) and may have been subject to wastewater irrigation in the country of origin. Changes in chemical use due to climate change may lead to localized increases of dissolved phosphorus and nitrate in drain flow and floodwaters, which in turn could lead to more overall exposure via waterways (60). The ‘Third Climate Change Risk Assessment (CCRA3)’ states that fertilisers, pesticides and other chemical concentrations may be increased following a long dry period, although the drought conditions themselves are not likely to raise fertilizer levels, but the peak concentration could potentially occur after the rains return when flow is restored (61).

The use of veterinary pharmaceuticals (such as antibiotics, steroidal substances, endo- and ecto-parasiticides) in livestock rearing results in the presence of metabolites and residues of these substances in agricultural environments, usually following livestock treatment and the spreading of manure onto the land. Climate change-driven changes, such as more frequent flooding, may increase disease incidence by spreading pathogens contained within manure and creating more favourable conditions for parasite and virus vectors, leading to increased use of veterinary pharmaceuticals (25).

3.2 Environmental and health impacts

Out of the 3 billion kilograms of pesticides reported to be used globally every year, only 1% are considered effective at controlling insect pests on target plants, leaving large amounts of remaining pesticides penetrating or reaching non-target plants and environmental media (44). This results in environmental pollution and potential adverse human health impacts as exposure to pesticides can cause a wide variety of adverse health conditions such as cancers, neurological diseases and adverse effects on fertility or pregnancy (45). Individual exposure to pesticides can result from a combination of several sources: direct or indirect occupational exposure; contact with people who work with pesticides; household pesticide use; dietary ingestion of contaminated food or water; and environmental exposure (51). These exposures can occur through dermal, oral and respiratory routes, leading to both chronic and acute health effects, particularly for those living close to agricultural areas. In these areas, agricultural drift would contribute to a substantially higher exposure, including transfer of sprayed pesticides into the atmosphere, deposits of pesticide which accumulate near the area of application and sustained aerial emission for days or even weeks after application via volatilisation of pesticides from plants and soil or wind erosion (45). In addition, contaminated surface waters could be a source of human exposure to organochlorine pesticides through volatilisation, although water companies test for a whole suite of pesticides so exposure via drinking water is unlikely. Proximity to areas which undergo pesticide application results in much higher levels detected inside people's homes (45).

Increased temperatures and humidity brought about by climate change may affect the way pesticides are absorbed into the body. For example, the dermal absorption of propoxur, a carbamate insecticide, increases proportionally with humidity, with higher temperatures accelerating pesticide absorption across human skin (51). Chemical exposures are reported to potentially affect homeostatic temperature regulation in humans (62). Organophosphate and carbamate insecticides are shown to produce a fever in humans; therefore, intoxication by these pesticides may indirectly affect human health under warmer climate conditions, potentially making it difficult for humans to maintain normal core temperatures, especially during times of thermal stress, such as heatwaves (10). For example, many chemicals and pesticides are endocrine-disrupting (63), and animal studies have shown that test animals exposed to endocrine-disrupting chemicals are unable to adapt to changing temperatures (64).

3.2.1 Food safety issues

The UK is currently lacking in specific policies to address the implications of climate change for food safety, including chemical contamination which may enter the food chain through many sources, such as increased runoff resulting from heavy rainfall events (61). The priority chemical contaminants for food safety standards are listed as natural toxins (mycotoxins and marine biotoxins), environmental and process contaminants (such as dioxins, PCBs) and pesticides (36). Risks to food safety and quality were included in CCRA2 which concluded that there was little evidence of unsafe food entering the UK, however, there is evidence of risk to food quality in the UK resulting from global climate change impact overseas. CCRA3 includes risks to UK food safety and security (H9); and UK food safety and quality from climate change impacts overseas (ID1) (65, 66). The report acknowledges that climate change may affect food quality in the UK by altering meat chemical constituents and chemical contamination of food from increased rainfall and runoff, causing food to become contaminated with pesticides and other chemicals (66). The report further recognises that there is currently very little evidence about climate risks and chemical contamination of food, and more action is needed for this risk.

Humans are exposed to chemicals primarily through ingestion of food, drinking water and dust, and to lesser extent through inhalation of ambient and indoor air and particulates (14). The food web is a significantly more important factor than other environmental factors, such as temperature and rainfall, for determining human exposure to chemicals as a result of changes driven by global warming (14). However, lack of sufficient research data on climate change effects on the food chain means that it is not currently possible to have reliable predictions of the extent of these impacts on human health (14).

It is likely that heavy metals entering the food chain will increase due to climate change, either through accumulation in fish as increases in the amount and intensity of precipitation would enhance run-off of heavy metals from soil into water systems, in addition to melting of permafrost which will further release heavy metals. Heavy metals are likely to be absorbed into crops, particularly rice, where uptake and accumulation of arsenic is an existing threat which could be compounded by increased soil temperatures (67, 68).

Under certain environmental conditions, such as temperature, humidity, and plant water stress, fungi (which grow on a variety of crops) can produce toxic substances called mycotoxins (69, 70). A slight increase in CO_2 levels impacts on the prevalence of mycotoxigenic fungi (67), for example, aflatoxins produced by *Aspergillus flavus,* or toxins produced by *Claviceps purpurea* ('ergot fungus'). These compounds have been reported to elicit a range of human health impacts, ranging from effects on growth, liver cancers, cirrhosis, gastrointestinal disease, neurotoxicity, severe dermal toxicity and death (7). Cereals such as maize, rice and wheat account for 56% of global human consumption and are also the most severely affected by pathogenic and mycotoxigenic fungi (67), and areas where fungal infestations are endemic are at particular risk, as these will likely increase with climate change. The UK food system can be disrupted by mycotoxins, as changing variability of temperature and rainfall may lead fungal species to be more prevalent and result in more rapid proliferation of infections across the UK (65). This increase usage and exposure to fungicides (71).

Prokaryotic microalgae such as cyanobacteria produce cyanotoxins, and eukaryotic dinoflagellates and diatoms produce marine algal toxins, all collectively known as phycotoxins. Phycotoxins are neurotoxic and threaten human health through contamination of freshwater reservoirs, lakes and drinking water. Phycotoxins can also bioaccumulate in various tissues of aquatic organisms such as bivalve molluscs and fish, which can enter the food chain (67). For example, consuming seafood contaminated with saxitoxin causes paralytic shellfish poisoning. Under certain environmental conditions, including increased temperature, light, ocean acidification, precipitation and wind, naturally-occurring microalgae can rapidly spread to large numbers, known as harmful algal blooms (HABs) (67). An increase in sea surface temperature is thought to contribute to the increased geographical distribution of HABs; climate change will further increase this expansion of toxigenic algae into areas previously inhabited only by non-toxic forms (72).

There is limited evidence that few contaminants, such as methylation of mercury and arsenic or metabolites of PAHs and pesticides, might increase the toxicity risk for humans under climate change (9). Further studies are recommended, and priority contaminants should be identified (9). The vulnerability of humans to chemical exposures affected by climate change-induced shifts together with a number of other stressors that are themselves being altered by climate change, is one of the principal areas requiring more research (10). The need for further studies focusing on both occupational and environmental exposures and their related health risk assessment of pesticides to better understand pesticide use and management in the future has been previously recognised (44). The outcomes of these studies should be communicated to provide scientific training for pesticide application, to prevent adverse health effects of pesticide use and to promote safety for applicators and communities (44).

3.3 Existing interventions

Although a rise in human health impacts associated with increased exposures to agricultural chemicals as a result of climate change may be anticipated, it can potentially and largely be managed through undertaking research on identified gaps and by implementing policy changes once there is a clearer understanding of actions required to reduce exposures to humans (36). Processes can also be put in place to develop targeted surveillance schemes for monitoring agricultural chemicals and their health effects, as well as by creating experimental data sets and models for airborne dust transport and other exposure pathways.

The first UK National Adaptation Programme (NAP) aimed to increase the resilience of agriculture by effectively managing the changing chemical volatility from increased dispersal in the environment, stemming from changes in occurrence and severity of rainfall which impacts on water availability, flooding, soil erosion and pollution due to run-off (73). As part of the Clean Growth Strategy (74), the second NAP (2018 to 2023) sought to explore targeted use of sustainable fertilisers to reduce potential future negative impacts on water quality (75). There are also national adaptation plans for Scotland (76), Northern Ireland (77) and Wales (78), which are specific to the devolved administrations. In addition, the new Environmental Land Management schemes will aim to deliver a range of environmental benefits such as agricultural mitigation and adaption to climate change (75).

Global warming-driven changes in practises and the environment are forecasted to generally increase pesticide and other chemical use. It is also acknowledged that changes in agricultural practices (for example, organic farming, agroecology, conservation agriculture, rewilding or biological controls, such as wasps being released into glass houses to reduce pests and honeybees being taken to crop areas that need pollination) can reduce pesticide and veterinary pharmaceutical use and their associated releases into the environment. Ultimately, this can decrease environmental exposure to these chemicals. Additionally, the introduction and adoption of new technologies like GPS guided field sprayers, biopesticides and botanical alternatives to antibiotics can have a positive impact. Alongside these changes, the establishment of appropriate legislation (such as withdrawing registration of highly hazardous chemicals and chemicals of concern, regulating through a hazard-based approach, promoting sustainable food systems) can be beneficial. Movement towards increased consumption of plant-based foods may reduce pesticide and veterinary pharmaceutical use, and therefore further reduce environmental exposure to these chemicals. In addition, pesticide residues in food are controllable by legislative actions, such as replacing highly toxic pesticides by less toxic ones and supporting sustainable production and consumption systems. Similarly, the additional safety requirements to minimise chemicals present in consumer and household products may result in reductions in down-the-drain emissions of harmful chemicals (25). Although the potential climate change-related issues to food safety and increased exposures requires more evidence before firm conclusions on the impacts can be drawn, there is ample information to start reducing risks through legislation and mitigation strategies.

A greater adoption of organic farming has been suggested, although there are limits on the available space to do this. Integrated pest management (IPM) is necessary, in addition to limited use of biocides, to reduce some of the risk of exposure by reducing the level of hazardous chemicals introduced into the environment. However, it is noted that IPM tends to promote chemical use rather than as a last resort as initially intended. Composting is an attractive mitigation option for greenhouse gas reduction; it offers an alternative to landfill disposal and provides nutrient recycling as a cost-effective fertiliser (79). It would also prevent many of the effects of using chemical fertilisers (such as water and crop contamination). However, currently municipal composting sites are often opposed due to odours or the perceived risk of bioaerosols and vermin. Legislative support for farmers to shift agricultural practices from reliance on intensive chemical inputs to sustainable agricultural practices, such as agroecology, is needed to reduce the impact of climate change on chemical exposures (80).

Updating and revising pesticide risk assessments and pesticide exposure models is required given the altered properties, increased distribution and increased toxicity of many pesticides under climate change conditions (51). Models are also required to predict the fate and behaviour of the other chemical contaminants in the environment mentioned in this section, which may assist in predicting the occurrence of HABs, exposure to mycotoxins and understanding the fate and behaviour of chemicals in the environment. However, it is unrealistic to expect to have models for the myriad of chemicals in use today, so focusing on selected groups of compounds related by structure or behaviour may be more useful, as well as moving toward a system of regulating similar compounds without conducting a costly risk assessment.

That is, moving away from conducting a risk assessment per pesticide. Costs could be cut, and time saved if pesticides (and other chemicals) first went through a hazard assessment evaluation process (for example, the Globally Harmonized System of the Classification and Labelling of Chemicals (GHS)).

In addition to monitoring programmes for contamination of water, soils and food products with chemical residues, biotoxin monitoring should also be established to heighten the situational awareness of increased risk of chemical exposure from the environment and identify any emerging issues of climate-mediated human exposure (72). Currently there is only limited quantitative analysis of global warming on crop pathogens (field, laboratory or modelling studies) and a more systematic approach is necessary to develop early warning systems, to inform the development of disease management plans and increased monitoring for new disease risks (81).

The NAP includes actions to address risks from public water supply shortages, including for agriculture (75). In 2016, the government published its roadmap to improving long-term resilience of the water sector, highlighting the challenges the sector faces from climate change and its potential impacts and laying out a policy framework for future decisions and actions. In addition, the 2018 NAP includes actions with the agricultural sector, including the Clean Growth Strategy, to encourage the use of low-emission fertilizers (74). Furthermore, efforts to better target fertilizer application will reduce the potential for negative water and air quality impacts. The CCRA3 recognises IPM as a particularly important cross-cutting approach as it promotes more sustainable biological controls to pests and pathogen vectors as an alternative to excessive use of chemicals which have various long-term adverse health impacts, as well as having further benefits regarding pesticide resistance and other side-effects (81). Some of the other suggestions provided above to reduce chemical exposure risks in a changing climate should be considered and included in future adaptation programmes and strategies.

4. Climate change, land deposited contamination and human exposure

4.1 Determinants of exposure

Historic and current contaminated land uses, and waste disposal activities result in local and diffuse accumulation of chemical stressors in the environment, potentially posing risks to the environment and human health, by altering air and water quality and hindering soil functions. Scientific and policy concerns have been expressed about the known or suspected negative health impacts of these sites (82). Climatic changes, such as heavy rainfall and increased flooding may lead to the mobilization of hazardous chemicals from storage, or remobilization of chemicals already in the environment, within contaminated land sites and diffuse settings such as pesticides. The UK has a considerable legacy of contaminated land related to industry, dispersed pollution and historical landfill sites (65).

Toxic substances, including heavy metal(loid)s (such as arsenic, mercury, lead, cadmium, chromium (VI)) and organic contaminants (for example, PAHs such as benzo(a)pyrene, POPs such as PCBs, per- and poly-fluoroalkyl substances (PFAS) and polybrominated biphenyls (PBBs)) are the major groups of contaminants detected in soils (9). The available fractions of these soil contaminants are often toxic to humans, and the fate and behaviour depends on their chemical properties, speciation, and soil properties (9). With predicted high-intensity winter rainfall events in the UK, destabilisation of waste, surface runoff and leaching of contaminants are expected to occur, increasing human health risks (41).

The impact of sea level rise, increased winter precipitation and drier summers (see Chapter 1) could alter the risk level to contaminants in situ, such as those contained in landfills or in containment cells, some remediated sites or in uncontrolled soil environments, and increase hazardous chemical releases from these environments (83, 84), resulting in increased health risks. Where active landfills exist, the leachate system has been designed for local conditions, however many have been overwhelmed by sudden high intensity rainfall events. Odorous waste is produced which may contain high levels of vapours including hydrogen sulphide and impact on local residents.

These impacts can destabilise hazardous contaminants and include engineered waste disposal sites, where the main infrastructure includes surface covers, bottom liners, embankments, leachate and gas collection and monitoring systems. These are generally designed based on local environmental conditions and have a service life of approximately 100 years; however, they have not been designed to accommodate changes caused by climate change, such as long-term exposure to seawater rises and tides, which may shorten the landfill lifetime (41). Similarly, the design of remediation solutions which do not remove or destroy the contamination, such as containment cells, engineered covers, stabilised or solidified soil systems, may be irreversibly altered by climate change (32, 83). For example, engineered cover and stabilization or solidified soil systems become extensively damaged under severe wet-dry and freeze-thaw cycles, remarkably reducing their mechanical properties and effectiveness (32).

Increased temperatures and low humidity deteriorates landfill liners and covers and accelerate contaminant diffusion through liners, leading to unexpected toxic gas releases, leachate and solid waste releases and landfill slope failures, toxic waste accumulation following flooding and rapid spreading of waste fires (41). Similarly, at mining sites, contaminant runoff can occur following damage to hydraulic structures such as dams, ditches and holding ponds during heavy rainfall and flooding events under climate change scenarios (9). In addition to infrastructure damages, the waste degradation process itself may be affected by temperature rises, potentially leading to inappropriate releases of landfill gas to the atmosphere. Increased temperature and moisture content have also been reported to accelerate waste leaching (41).

Prior to modern environmental regulation, many landfills in the UK were constructed in low value land in low-lying coastal environments, with limited or non-existing physical pollution prevention controls, such as leachate control (85). Landfill leachate forms when excess rainwater percolates through landfill waste layers. A combination of physical, chemical and microbial processes in the waste materials transfer contaminants (such as dissolved organic matter, heavy metals and xenobiotic organic compounds) from the waste to the percolating water, which migrates off-site in an un-engineered landfill site (86). The number of these historic landfills built without any engineered waste management in England alone is estimated to be approximately 20,000, of which about 4,000 are located in coastal areas across the UK (85). Approximately 1,200 of these are located in tidal flood zones with a 0.5% annual probability of coastal flooding (85). Due to rising sea levels and repetitive tides, approximately 10% of these (around 122 landfills) could start to erode by 2055 if not adequately protected (87), potentially releasing liquid and solid contaminants (for example, dioxins, heavy metals, cyanide, hydrocarbons) to previously uncontaminated environments (36, 41). The CCRA3 recognises the potential risks of chemical contamination from sea level rise and coastal erosion associated with historic landfill sites located in coastal areas (H4), potentially exposing new hazards and increase the risk of soil, water or air contamination (65). It is further stated that the adaptation or relocation responses to climate change may further exacerbate the problem (65).

Historic waste disposal sites and contaminated land in UK coastal areas are at higher risk of inundation due to increased flood risk, resulting in mobilisation of contaminants in floodwater and sediments (24). Metals associated with historical leachate are enriched at depth near the historic landfill boundaries, and although the total metal load is understood to be low, historic landfills in UK coastal areas could potentially represent a source of diffuse pollution (85).

To assess soil erosion rates, the physical movement of contaminants through water erosion processes was modelled for a spoil tip on a disused tin mining site in South West England under low- and high emissions scenarios using the UK 2002 (UKCIP02) climate change predictions (32). The results suggested that soil erosion rates could increase to nearly 25% by the 2080s, with approximately a 30% increase in arsenic mobilisation under the high-emissions climate scenario for the 2080s (32). The results further demonstrated the significance of climatic changes to physical pathways and the risks of pollutant linkage, as well as highlighting the need for modelling of soil erosion processes at a localised scale (32).

Increased wind speed in future, especially after dry periods, could significantly increase the volume of wind-blown dusts that can carry contaminants (32). Sudden changes in atmospheric pressure may also contribute to the advection of gas from historically buried waste, also facilitating waste fires. Similarly, more frequent wildfires due to increased wind speeds and dry periods may affect uncovered waste sites, resulting in greater release of hazardous gases and particulates and posing increased risks to health (41).

4.1.2 Water quality

It is not uncommon for contaminated sites to be located near or on water resources due to historic industrial activities and current population densities near surface water courses. Contamination of near surface soils from atmospheric deposition, releases from landfills, agriculture, and industries is a common problem that is estimated to affect approximately half of the EU's land surface (42). Metal contamination (including iron, lead, copper, zinc and cadmium) of UK river water by historic mining sites continues to occur and spikes after heavy rainfall. More frequent and intense rainfall could increase metal contamination levels in UK rivers, floodwater and surface water run-off, resulting in contamination of nearby land, as well as the river environment (88). Migration of contaminants and associated contaminated soils to groundwater and further downstream impacts drinking water quality, which can have health consequences. There is increasing concern that the present contaminant loading of groundwater and surface water systems may be altered, and potentially exacerbated by climate change.

The CCRA3 highlights risks related to water quality and household water supply (H10) and the increased risk of contamination of drinking water via increased runoff and flooding events, in addition to potentially increased health risks from contact with bathing water and HABs (65). Private water supplies are identified as most vulnerable to climate change-related hazards affecting water contamination with chemicals (65). Sea level rise, heavy precipitation and coastal erosion are noted as potential causes of increasing pollution from historic landfills; and treatment failures associated with extreme events have been reported across the UK. In addition, elevated levels of dissolved organic carbon may interfere with disinfection processes, increasing human exposure to contaminants. Furthermore, wildfires mobilise chemicals and contaminate reservoirs with ash, organics and heavy metals from the soil; in addition, firefighting water and chemicals used can also pose a risk along with fire gases and particulates (65).

Although there is only limited literature available about the potential impact of climate change on water quality, in general, extreme weather events can lead to water quality degradation, with groundwater being generally more resilient than surface waters (89). Nevertheless, climatic changes will alter groundwater recharge, flows and levels, potentially impacting upon contaminant levels in both groundwaters and surface waters (42). For climate change scenarios where global temperature increases are below 2°C, the projected UK scenario could lead to a 30% decrease in river flows during dry periods, and 5% to 20% increase in river flows during wet periods. Increased water temperatures will enhance dissolution, solubilisation, degradation and evaporation, leading to higher concentrations of dissolved substances in water (90). Furthermore, human activity, including land use changes or growing demand for drinking water or agricultural land, are likely to intensify the climate change effects on water resources (89).

Warming effects can increase dissolved organic carbon concentrations in surface waters, particularly in areas with extensive peatlands in drinking water catchment areas, which impacts water treatability in drinking water treatment plants (91). The amount of dissolved organic carbon is a precursor for the formation of disinfection by-products such as trihalomethanes (possibly carcinogenic to humans) when chlorine is added to kill waterborne pathogens (91). Levels of dissolved organic carbon in UK upland waters increased by 91% between 1988 and 2003, increasing trihalomethane formation (91). Further climate change-associated effects on UK surface water will complicate the treatment of drinking water in future (91). In addition, the treatment chemicals themselves can be affected by temperature; for example, chlorate levels are higher during summer as the treatment chemical (sodium hypochlorite) broke down easier (92). Similarly, lead dissolution into drinking water from lead pipework could increase if warming of the surrounding soil occurred (93).

Increased frequency and intensity of rainfall may release contaminants present in both uncovered waste disposal sites and near surface soils, resulting in downstream contamination spread, impacting drinking water quality and ultimately human health (42, 90). Climate-driven changes in groundwater level alone (excluding possible additional changes in leachate production) can significantly affect metal mobilisation (42). In addition, micropollutants (including pharmaceuticals, pesticides and metals) are likely to increase in concentration or number in drinking water following heavy precipitation in temperate countries and rises in temperature in all environmental media (90).

4.2 Health impacts

Contaminated land in general is an important public health issue for several reasons, including the simultaneous presence of multiple and heterogenous hazards and exposure pathways, and often a lack of verifiable knowledge on what is present. In addition, sites contaminated by historical industrial activities are often located near urban or deprived areas, making exposure patterns more complicated and resulting in interactions with other health determinants (82). It is, therefore, challenging to assess the possible health impacts associated with contaminated land or waste disposal sites, particularly in relation to climate change, as each site has its own characteristics and exposure scenarios, various deposited waste or multiple contaminative activities, and related scarcity of available evidence of causal associations. The variability in the composition of waste material within landfills in particular makes predicting the presence of chemicals and their potential migration into the surround environment challenging. Therefore, systematic data is necessary to improve the human exposure assessment (82).

In contrast to the above findings, a report by the Health Protection Agency (HPA) found that several epidemiological and ecological studies investigating the prevalence of adverse health impacts (such as cancers and congenital abnormalities) in populations living near landfills come with methodological problems (94). It is possible that the health outcomes in study populations are due to other factors, such as socioeconomic and lifestyle factors, as well as lack of individual exposure data, and not to the landfill sites (94). Intensive research on landfill emissions exposure in the UK suggests that chemical exposure is typically low and unlikely to present a significant health risk (95). Whilst effects cannot be ruled out for hazardous waste sites, the report concluded that well run non-hazardous landfill sites (municipal waste) should not impact physical human health (94).

As modern engineered landfills are subject to strict controls, such as being lined and capped, thereby restricting emissions and making exposure to chemicals less likely, concerns regarding adverse health impacts associated with landfills typically stem from historic landfills (94). However, due to the large variability of wastes entering these historic sites, as well as operation design, lack of engineered linings or leachate collection systems, their potential health impacts are unknown. Therefore, site-specific monitoring and modelling of historic sites is recommended to aid any risk assessments and to address the uncertainties regarding any emissions and associated negative health impacts (94).

The main exposure pathway of local people to landfill emissions is via inhalation of airborne emissions or dusts (94), which may be exacerbated by increased wind speed and dry seasons. Exposure to particles which may contain metals such as arsenic, cadmium, chromium, cobalt, copper, lead and manganese for example, is associated with many adverse health effects (94). People with pre-existing lung or heart disease, children and the elderly are particularly sensitive to this particulate air pollution.

Given that landfill leachate composition depends on deposited waste type, solubility, and the state of decomposition, it may contain a wide range of contaminants (such as arsenic, fluoride, cyanide, phenols, methyl tert-butyl ether (MTBE), PAHs, naphthalene, ethylbenzene, toluene, xylenes), some of which are potentially harmful to human health. However, exposure to drinking water contaminated with leachate is not considered as likely due to monitoring of drinking water supplies, as well as their operational controls and strict regulations (94) and the strict regulations around leachate discharge as part of the site's environmental permit. Nevertheless, evidence of health effects from odorous landfills is a growing concern; this can be due to the leachate plant being overwhelmed by a high intensity rain event, so water remains in the landfill cell causing methanogenic conditions, or due to bad practice (96, 97). Evidence of the health effects of odour are provided in other studies (98).

Overall exposure to chemicals could increase due to climate change; desorption and remobilisation of soil contaminants (including to the air; for instance, mercury evaporation will increase with temperature) were considered key mechanisms for this risk (9). However, there is great uncertainty on any direct effects on the magnitude of chemical toxicity due to the limited availability of studies (9) and further research is required to identify priority contaminants.

There is currently a lack of understanding, and very little experimental evidence of potential direct impacts of climate change on contaminated land and their remediation methods (32). However, there is growing evidence of indirect effects such as days lost to wet weather making sites inaccessible (99 to 101). There is a pressing need for systematic, empirical investigation of wastewater systems to improve understanding of how the sector is preparing for climate change impacts (102). Thus, standards and policy guidelines regarding limits for emerging contaminants in soil and water need to be developed, to enable the science of contaminated land together with contributing disciplines to adapt to the changing climate impacts in a timely manner (54, 83).

More site-specific assessments, and research of potential interactions between receptors and contaminants are necessary to improve understanding and reduce potential adverse health impacts of climate change on remediation methods, waste disposal sites and other engineered facilities containing hazardous waste and contamination (41, 83). Understanding the potential impacts on contaminant speciation and adsorption is vital to the development of appropriate risk mitigation strategies, for example, increased redox potential associated with drier soil conditions may result in the oxidation of reduced metal species (generally insoluble), increasing their solubility (32).

4.3 Interventions

Based on the predicted impacts of climate change on contaminated land and landfills, hazardous material containment cells and other remediation methods, it is vital to ensure these sites are adapted to climate change-associated impacts to avoid increased chemical releases (41). To do so, the contaminated land sector should increase research and development to better understand and reduce the adverse impacts of climatic change on existing remediation methods (83) and any structures used to contain contaminated material or liquids. The long-term climate, hydrogeological and hydrological changes need to consider future design, maintenance and risk mitigation of waste disposal sites and remediation strategies for contaminated environments (41). Decision-makers considering the designs for contaminated land and waste disposal sites should be aware of regional factors potentially impacting the site in the context of climate change. These could include changes in local groundwater, sea levels and ground stability, adaptations in the design and management of any containment structure containing waste or contaminated soil, and procedures implemented to ensure the sites will be able to adapt to the predicted impacts (83).

The current contaminated land risk assessment is based on predetermined levels of risk of exposure, toxicity and pathways based on data from the last 10 to 30 years (24). However, there is currently significant research and development with respect to further understanding the impacts of future climate change on land contamination risk assessment (103). Conceptual site models (source-pathway-receptor linkages) may be affected by climate change; for example, chronic changes involving increased leachate generation or acute changes such as contamination source erosion, destabilisation of structures, flooding and all current and future potential pollutant linkages should be accounted for (83, 103). A key guidance document on land contamination (104) required characterisation and risk assessment of potentially contaminated sites which should include climate change impacts (as part of sustainable approach) within a conceptual site model (103). In cases where potentially unacceptable risks are identified, a site-specific risk assessment should be prepared considering climate change effects. Furthermore, considering climate change within Local Plans and Local Development Plans is a requirement of the National Planning Policy Framework (NPPF) (National Planning Framework 4 for Scotland) meaning that Plans could be a mechanism for requiring climate change to be considered in land contamination risk assessment (103). With the government policy encouraging recycling, recovery and re-use of waste, landfilling for waste disposal in the UK is reported to be decreasing (94) and the Department for Environment, Food and Rural Affairs (Defra) aim to limit municipal waste going to landfill to 10% or less of the total amount of municipal waste generated (by weight) by 2035 (105). This all leads to a change in landfill composition over time, with low gas production, but potentially increased toxicology or potentially corrosiveness of waste products, affecting liner integrity.

The third NAP (2023 to 2028) includes actions to improve the health and management of soils by addressing the cause of soil degradation, such as erosion, which will therefore have co-benefits for managing a range of climate-related risks (106). However, there is an adaptation gap due to the lack of consideration of climate change in the risk of chemical contamination of water supplies and no specific policies or strategies have been identified to address this as additional actions will be necessary to maintain water quality standards (65).

5. Climate change, chemicals in industrial settings and human exposure

5.1 Determinants of exposure

Populations located in close vicinity to point sources of chemical contamination (primary sources such as chemical manufacturing, storage and waste sites), are potentially exposed to higher concentrations of harmful substances over a long period of time, placing them at higher risk of negative health outcomes than the average population (14). Therefore, climate change could increase future exposure to POPs and other contaminants in industrial areas, particularly through outdoor air inhalation and transfer to the indoor air environment, and emissions to water sources. This section aims to address how climate change could increase exposure to chemicals released from industrial processes, whether the chemicals are involved in production or storage.

Primary POP emissions (intentionally produced) include direct dispersal and volatilisation into air from initial applications of semi-volatile industrial chemicals, such as PCBs and PBDEs, and leaching into water from initial applications of water soluble industrial chemicals such as PFOS or perfluorooctane sulfonyl fluorides (PFOS-Fs) (14). PFOS and PFOS-F are used in many applications and PBDEs are present in large amounts in new products and stockpiles of obsolete substances being stored. Exposure to PBDEs and perfluorinated compounds via indoor air and dust has been recognised as an important route for low background exposures, especially for children who are close to ground level (14).

Temperature rises are likely to be key drivers of primary releases (84), resulting in increased chemical volatility. Temperature increases of 1°C increases the volatility of typical semi-volatile POPs by 10% to 15% (14). However, temperature may increase locally by more than 10°C, resulting in a 3-fold increase in the volatility of a typical POP (14). It is thought that this would result in increased releases during chemical usage in open applications and from stockpiles, such as joint sealants and PBDEs used as flame retardants (84). The increased mobilisation and volatilisation will be most relevant in the case of chemicals with relatively low direct emissions during manufacturing and chemicals which are not readily incorporated into materials (84).

In addition to primary and secondary emissions produced during the use and storage stages of chemicals in facilities, extreme natural hazards (such as fires and flooding) which are exacerbated by climate change, disrupt infrastructure, including chemical manufactures, waste and wastewater management activities and transport infrastructure, resulting in fires, explosions and hazardous chemical releases, posing a risk to human health (84, 107). Some examples of natural hazards causing accidental releases include flooding inundating tanks and pipelines, the loss of power due to flooding or fires, or fires that may affect the safe operation of facilities (84, 107). In Texas, USA, communities adjacent to concentrated areas of industrial land use are exposed to elevated levels of chemicals from stormwater runoff discharge from industrial land uses (108).

Significant risks to infrastructure (in particular, energy, transportation and communications systems) have been identified, particularly those located near rivers and along the coastal areas, from flooding, rising sea levels, erosion and increasing intensity and frequency of extreme weather events, although changes in temperature and rainfall are recognised to create additional pressures on infrastructure across all sectors (38). In addition, impacts from flooding and coastal erosion on industrial plants (including chemical processing plants) and factories, landfill sites and agricultural land (B1 and B2 in CCRA3) are expected to increase across the UK (109). The risks also include the significant environmental threat associated with industrial assets being flooded, resulting in the release of toxic chemicals to water courses, urban areas and long term ground contamination (109). Epidemiological evidence shows that chemical material has the potential to contaminate homes during flooding (H3), with increased risk in areas where industrial land adjoins residential areas (109). Therefore, the importance of gaining a better understanding of those risks and their potential mitigation is acknowledged.

In addition, changes in rainfall and higher temperatures will lead to droughts and fluctuating moisture contents in swelling and shrinking soils, potentially cracking sewer systems and pipelines, and increasing pollutant concentrations. Increased precipitation may result in overflows of untreated sewage water entering the surface waters, changing treatment effectiveness and decreasing the absorptive capacity of receiving waters (84, 102). For example, summer floods in the UK in 2007 demonstrated how wastewater systems could become overwhelmed, putting hundreds of systems temporarily out of service; climate change is expected to exacerbate these failures (102).

In relation to POPs, it is unclear how climate variables will affect the transition rate from primary to secondary sources and how the environmental reservoir capacity will change. Furthermore, another area of unknowns regarding POPs relates to the reaction of micro-organisms to changing temperature and humidity in soils and their capacity to degrade POPs and other chemicals (14). Soils are complex systems combining biological, chemical and physical processes which are sensitive to climate change, land management and pollution. There is insufficient knowledge of these processes under climatic changes. Hence improved knowledge of the controlling properties and processes that regulate change (such as organic matter, microbial activity) would be extremely useful (81) as degradation may lead to more harmful break down products (for example, tricholorethylene degrades to the more toxic vinyl chloride).

5.2 Health impacts

POPs negatively impact human health, causing cardiovascular disease, cancer, metabolic disorders, and effects on neurobehavioral, endocrine and reproductive systems (14). A link between contaminant exposures and suppressed immune system function has been previously demonstrated, with immunotoxicity being a sensitive endpoint for several POPs (for example, heptachlor, PCBs, and 2,3,7,8-tetrachlorodibenzo-p-dioxin) which may decrease the human ability to fight infections (10). Perinatal exposure to dioxins, PCBs and organochloride pesticides could lead to increased autoimmune disease and immune suppression later in life, potentially increasing vulnerability to climate change-drive shifts in vector-borne and infectious diseases. However more research is needed in this area (31) but with potential increased exposure to POPs, risks associated with these adverse health effects would also increase.

Floodwater release and associated transportation of toxic contaminants may pose health risks to nearby communities (110). A range of illnesses have been linked to toxic floodwaters, including respiratory distress and diseases affecting the brain, blood, kidneys and gastrointestinal system. However, while the dangers of certain biological contaminants are fairly well-known, more research is required on the long-term health effects of chemicals in floodwaters (110).

5.3 Interventions

Various climate change mitigation measures, such as those undertaken under the Stockholm Convention, are likely to reduce secondary POP emissions which occur as a result of incomplete combustion or chemical reactions (for example PCDD and PCDFs, HCB, PCBs) and several non-POPs, including mercury and other metals (14). However, these mitigation measures may also involve some negative impacts, such as increased emissions of unintentionally produced POPs associated with biomass fuel (such as treated waste wood) and potential increases in unintentionally produced POPs in fly ash (14). Despite this, measures to stop waste wood burning (for example), as well as the use of Best Available Technology and Best Environmental Practices (BAT and BEP), and conversion of motor vehicles to alternative sources of power (electricity, fuel cells, solar) could significantly reduce unintentional POP emissions (14).

Due to the potential increased volatilization of POPs from current primary sources as a result of climate change, together with a potential increase in global use, the overall future POP emissions may rise despite global mitigation measures as a result of counteracting impact related to climate change. However, there is a lot of uncertainty in these predictions (14).

Based on the above, to prevent hazardous chemical releases in the future, facilities using and storing chemicals need to be designed to be resilient to future climate impacts, whilst historical sites need to be evaluated to determine remediation and mitigation requirements, as well as modifying infrastructures to increase climate change resilience (84). Climate change resilience is considered in some areas of environmental assessment, including the Environment Agency’s guidance on ‘Adapting to climate change: risk assessment for your environmental permit’ (111), which requests that risk assessment considering climate change adaptations is completed when applying or renewing an environmental permit for sites assumed to be occupied in 2050 (103). The National Infrastructure Commission’s National Infrastructure Assessment identified that focus was required on key priorities including reducing extreme weather risks to make ensure the UK is resilient to drought and flooding (75). To meet these priorities, infrastructure must be located, planned, designed and maintained to be resilient to climate change and to reduce the risks of failures which could be worsened by climate change, to build a better picture of the systems management of these services. Also, there are likely to be benefits for further actions in the next 5 years to improve water quality by reducing the risk of surface water flooding, with a need for further emergency planning regarding chemical incidents during flooding events (65).

The use of circular economy and life cycle approaches in product and process designs has the potential to reduce hazardous chemical releases through waste minimisation, product and process changes, and using lower hazard alternatives (84). Air quality policies based on structural changes, including energy efficiency improvement measures in power stations, increased use of renewable energy sources and improvement of combustion processes can provide co-benefits to reduce unintentionally produced POPs (14).

The most common suggested resilience improvements for wastewater systems are added capacity (buffering), equipment backup, maintenance and repair, and asset protection, whilst the recommended adaptions include improved monitoring, planning, maintenance and vulnerability analysis, installation of more sustainable drainage systems and construction of floodwalls (102).

New computational and analytical tools are required to produce more efficient and accurate projections of chemical exposure (34). These include non-targeted analysis, where mass spectrometry is used to characterise complex mixtures of unknown chemicals, without prior knowledge of the compounds present in the mixture, and mathematical models which forecast chemical exposures through changes in use of chemicals, environmental fate and exposure pathways (34). These methods, particularly modelling, require innovative ways to generate more data on climate change-mediated chemical exposures, which would strengthen these models. For example, integration of chemical exposure surveillance data with the models would provide more detail on the types and frequency of chemical exposures, allowing more accurate models to be developed. Such data could be generated through greater collaboration between exposure scientists and others for a more holistic global environmental monitoring. These collaborators could include volunteer programmes which collect environmental data, engaging with the military and their environmental monitoring programmes, crowdsourcing within scientific communities and members of the public and engaging ‘citizen scientists’ (34).

For a summary of the relevant UK-focused reports and studies referenced in this chapter, see Table 3.

Table 3. Summary of the UK-focused studies and reports used in this chapter

Reference	Summary of links between climate change and exposure to chemicals
(3)	Provides evidence, analysis and recommendations in relation to climate change and health effects associated with air pollution (indoor and outdoor), flooding, food- and vector-borne diseases, based on previous climate change projections for the UK (UKCP09).
(22)	Reviews how climate change may impact the fate and transport of pesticides in surface and groundwaters, focusing on climate change scenarios and case studies from the UK.
(36)	Assesses the implications of climate change for changes in human exposures to pathogens and chemicals in agricultural systems in the UK and discuss the subsequent effects on health impacts.
(52)	Provides evidence of the practice of using sewage sludge in agriculture. It does not focus on climate change but is relevant to the chapter section discussing water use in agriculture.
(57)	Disucsses the irrigation practices and water sources currently used in the UK, and how they may impact crop contamination levels, future changes to agricultural water use due to environmental legislation and climate change.
(65)	Assesses the climate risks and opportunities, considering both the current climate and projected future climates within the UK and worldwide. Also assesses the extent to which current UK adaptation plans will manage these risks.
(75)	Sets out what government and others will be doing over a 5-year-period to be ready for the challenges of climate change.
(103)	Presents clear and practical advice on including the potential effects of climate change in the assessed stages of controlled waters risk assessment for land contamination.
(85)	With predicited sea level rise and coastal erosion, the historic coastal landfill sites may represent a source of diffuse pollution. Examines the extent of metal contamination in saltmarsh sediments surrounding a historic landfill in the UK.
(87)	Climate change is increasing the likelihood that the historic coastal solid waste landfills will be inundated or eroded resulting in the release of soluble contaminants (metals) to the coastal zone. With the predicted rise in sea level and repetitive tides in the UK, it is estimated that, without intervention, approximately 10% of the historic landfills could start to erode by 2055 if not adequately protected.

Reference	Summary of links between climate change and exposure to chemicals
(88)	Focuses on UK river catchments that experienced flooding and associated metal contamiantion by historic mining sites. Climate change is predicted to result in more frequent and intense precipitation events, thereby increasing metal contamination levels in rivers, floodwater and surface water run-off, resulting in nearby agricultural land contamination.
(32)	Summarises the work carried out as part of the Sustainable Urban Brownfield Regeneration: Integrated Management (SUBR:IM) research consortium, including provision of a preliminary technical evidence of potential impacts of climate change on contaminated land and remediation systems and discusses potential technical adaptation strategies. It refers to the UKCIP02 climate change predictions to forecast climate change effects on contaminant sediment movement via soil erosion processes by water. Erosion estimates were modelled for a spoil tip on a disused tin mining site located in South West England under the 2 scenarios tested (low- and high-emissions scenarios).
(94)	Review of the links between landfill emissions and health effects, acknowledging that further research is needed to improve toxicological and exposure assessment in the vicinity of landfills, particularly historic landfills. While there is not a focus on climate change, it is highly relevant to the section on contaminated land.
(38)	The Adaptation Sub-Committee has summarised the results of the independent analysis presented in the CCRA Evidence Report, and identified 6 key priority areas of climate change risk: flooding (releasing chemicals) and coastal change risk; impact of high temperatures on health and wellbeing; risks to natural capital; risks of future water shortages; impacts on the global food system; and risks arising from new and emerging pests and diseases.
(111)	Resilience to climatic change is considered, including how to plan for climate change impacts to and from an industrial site and how to integrate climate change adaptation into management system under an environmental permit.
(39)	Provides an overview of the quality of public and private water supplies in England and Wales.

6. Conclusions and future priorities

6.1 Conclusions

Based on this literature review, although there is a lack of scientific data on the adverse health effects caused by climate change-induced increases or changes in chemical exposure, it is almost certain that the changes in the climatic and environmental conditions will affect human exposure to chemicals, and the potential subsequent negative impacts on health. Contaminants that are more likely to increase or change in the UK environment due to climate change are POPs, pharmaceuticals, VOCs, pesticides and heavy metals, and activities that are most likely to alter the fate and behaviour of these contaminants in the environment due to climate change include agricultural processes, waste management and chemical-producing industrial processes.

In this chapter the effects of climate change on chemical use and potential health effects of humans exposed to these chemicals have been explored. While there are many negative effects on human exposure to chemicals due to a changing climate, there are some positives which accompany these changes. However, this relationship is complex and while certain meteorological conditions positively impact chemical contaminants (such as increased degradation of certain pesticides caused by increased temperatures) they can lead to other negative effects (such as drying out the soil and increasing run-off of applied pesticides, leading to increased contamination in water). This chapter also provides suggestions to mitigate some of the risk associated with human exposure to chemicals (Section 3), such as changing agricultural practices to reduce pesticide and veterinary pharmaceutical use, new technologies to control the amount of chemicals applied to agricultural settings and increased use of environmentally friendly alternatives (such as composting) to reduce fertiliser application.

6.2 Research priorities

The development of methods and collection of scientific data are required, both at a UK and international level, for any potential direct effects on the magnitude of chemical toxicity as a result of climatic change. Also important is research for the identification of priority contaminants, their fate in a changing climate and risks of human exposure to them. Another important area already recognised by researchers (10) is the routine geographic, demographic, socio-economic and ecological analysis of the wider drivers of human vulnerability to chemical exposures affected by climate change-induced shifts together with a number of other stressors that are being altered with changing climate, for example monitoring the invasive disease vectors which can be affected by changes in pesticide use.

It is necessary to continue to foster extensive collaborations among relevant institutions, academia, and organisations within the UK and internationally. These collaborations would facilitate the collection of required scientific data and provide experimental evidence of potential direct impacts of climate change on sites that are susceptible to or pose a potential health risk. These includes areas such as contaminated land, waste management sites (such as landfills and wastewater treatment facilities), and agricultural land. The UK requires additional research to address the implications of climate change for chemicals in the agricultural setting and food safety, including increased use of pesticides or more harmful alternatives, causing chemical contamination which may enter the food chain through many sources, such as increased runoff resulting from heavy rainfall events.

There is also the need to conduct research into potential effects of chemicals of emerging concern on humans and the environment, to allow the development of standards and guidelines regarding limits of emerging contaminant concentrations in soil and water, to enable timely adaptations to the changing climate to be made.

Given that climate change impacts can be incremental (with the exception of accidents caused by extreme weather events), difficult to detect and vary depending on location, assessment and prediction of impacts and their probabilities in relation to chemical exposure is challenging. Hence, human health risk assessments will need to include prediction models of risk associated with chemical exposure driven by climate change. Further research is required to develop more accurate models for making these predictions.

6.3 Implications for public health practice

The third NAP highlights the importance of effective monitoring and evaluation when addressing future uncertainties so that adaptation strategies can be reviewed and adjusted to remain within an acceptable level of risk (106). UKHSA already has a targeted surveillance programme for other climate change-related adverse health outcomes, such as invasive disease vectors (see Chapter 8). There are also plans to update cross-governmental contingency plans for specific vector-borne diseases to ensure rapid, co-ordinated responses to detections of invasive mosquitoes or diseases (106). Such frameworks could be developed and used for monitoring the impact of changes in chemical exposures on human health due to climate change.

A combination of approaches should be implemented to reduce environmental contamination with pesticides and subsequent potential effects on health and the environment. These approaches could include novel scientific methods, technologies, improved legislation, and other measures, such as IPM, legislation banning high risk pesticides, the development of UK implementation plans, as well as development of biopesticides. The potential increase in both frequency and intensity of flooding and storms resulting in increased POP releases, use patterns and the risk of remobilization from waste disposal sites, soils and sediments needs to be addressed by all stakeholders (14). The management of stockpiles and landfills, as well as remediation of contaminated sites in areas prone to flooding and water intrusion, needs improvement to reduce the risk to health and the environment and the location of new landfills in such areas should be subject to consideration of climate-induced risks, or be prevented.

Acronyms and abbreviations

Abbreviation	Meaning
CCRA	Climate Change Risk Assessment
HABs	harmful algal blooms
HBCD	hexabromocyclododecanes
IPM	integrated pest management
NAP	National Adaptation Programme
PAHs	polycyclic aromatic hydrocarbons
PBDEs	polybrominated diphenyl ethers
PCBs	polychlorinated biphenyls
PFOS	perfluorooctane sulfonate
PFOS-Fs	perfluorooctane sulfonyl fluorides
PM	particulate matter
POPs	persistent organic pollutants
SOC	soil organic carbon
SOM	soil organic matter
UV	ultraviolet light
VOCs	volatile organic compounds

Glossary of terms

Term	Meaning
Aerobic conditions	An environment which is characterized by the presence of free oxygen
Anaerobic ground conditions	An environment which is characterized by the absence of free oxygen
Basic cations	A positively charged ion from group 1 or 2 of the periodic table (the alkali metals or alkaline earth metals). Environmentally abundant examples include sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg)
Bioavailable	The proportion of a drug or other substance which enters circulation when introduced into the body and so is able to have an active effect
Biota	The animal and plant life of a particular region or habitat
Chemical fate	How chemicals can change and where they go as they move into and through the environment
Cold-trapping effect	When gases are condensed on a surface or in a medium. For example, in the earth's troposphere, the temperature of the air drops with increasing height reaching a low point. This region is called a cold trap, because it traps ascending gases with high melting points, forcing them to drop back into the earth
Effluent	Liquid waste or sewage discharged into a river or the sea
Endocrine-disrupting	Natural or human-made chemicals that may mimic, block, or interfere with the body's hormones, which are part of the endocrine system
Half-life	The time taken for a chemical to reduce or decrease by half the amount
Hydrophobicity	A chemical which tends to repel or fail to mix with water (such as oil)
Influent	Something that flows into a reservoir, lake or other stream, such as a tributary stream
Leaching	When chemicals drain away from soil, ash, or similar material by the action of percolating liquid, especially rainwater
Metabolites	A substance made or used when the body breaks down chemicals such as food or drugs
Non-point chemicals	Water contaminants that don't come from a pipe, well, construction site, or any other well-defined, specific source
Partitioning	The distribution of chemicals among phases or compartments (for example, in air, on surfaces and elsewhere)
Persistent chemicals	Chemicals which are slow to break down in the environment

Term	Meaning
Partition coefficients	The ratio of the concentration of a substance in one medium or phase (C1) to the concentration in a second phase (C2) when the 2 concentrations are at equilibrium (no net change between the 2 substances)
Redox state	The balance between oxidants (or pro-oxidants) and antioxidants (or reducing agents)
Re-emission	To emit (produce, release or discharge) something again
Remediation methods	Actions to return to normal service after a confirmed contamination incident, for example removing pollutants or contaminants from groundwater, soil or sediment.
Resuspension	The removal of deposited material from the ground to the atmosphere because of wind, traffic, soil cultivation, and other activities
Salting out effects	Salting-out is the effect when adding a salt to a solvent containing an organic solute reduces the solubility of that solute and may result in precipitation of the solute
Sorbed	To take up and hold by either adsorption (forms a thin film on a surface) or absorption (taken in or soaked up)
Toxicokinetic	Encompasses rates of absorption, distribution, metabolism, and excretion (ADME) of toxicants or toxins. It deals with time-dependent transport and modification of toxic foreign molecules by an organism
Volatilisation	The transition of chemicals from the solid or liquid phase into the vapour phase
Xenobiotic	Chemicals found but not produced in organisms or the environment (for example, drugs, pesticides, cosmetics, fragrances, food additives and industrial chemicals)

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