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Summary

In the past years, wildfires have been both inside as outside The Netherlands a very current topic. The question is how, also due to climate change, wildfires in The Netherlands are changing. This is not only the case for the number of wildfires, their fire behaviour and size, but also for the possible impact of these fires. Bearing these issues and questions in mind, a consortium was formed with experts in the field of wildfires from the institutes NIPV, KNMI, WUR, VU and Deltares, who have written this report together. In order to gain a better insight in the (future) developments, the following research question is posed: *How is the wildfire risk in The Netherlands developing?* This main research question is divided in a number of sub-questions:

1. How is the susceptibility for the occurrence of wildfires changing?
2. How is the susceptibility for the development of wildfires changing?
3. How is the impact of wildfires changing?

The required information for this report has been gathered by interviews with the members of the consortium and the exchange of knowledge documents, including scientific research and publications. Next to this, two workshop days were organised, during which the consortium physically met in order to discuss this gathered information and, when this was required, translate the information to the field of wildfires. Because relative humidity an important factor for the occurrence and development of wildfires, but in the current literature a generally overlooked parameter is, is for this report an additional analysis performed on the historical weather data at the KNMI weather station in De Bilt.

How is the susceptibility for the occurrence of wildfires changing?
It appears that wildfires in The Netherlands are changing. In the past decades, the climate has become warmer, drier and sunnier and according to the current forecasts, this trend will only continue. Because of this, the mean lowest groundwater level will also lower. As a result, more vegetation will more often become flammable and the number of fire-prone days will increase. Next to this, it is expected that the number of potential ignition sources will also increase. The combination of these two developments results in an expected increase in the number of wildfires during both spring and summer.

How is the susceptibility for the development of wildfires changing?
Because of the climatological developments, wildfires are able to become more intense and as a result they will become more difficult to fight with the current methods of combatting fires. Although vegetation is an important factor in the development of wildfires, it is unclear how this will develop in the future. However, there are some concerns regarding vegetation, for example that climate change causes an increase in vegetation stress, which can increase the flammability of nature. With the current prospects, uncontrollable wildfires will become more common and cannot be fought with the current tactics, techniques and capacity of the fire service. Next to this, the simultaneity of wildfires will increase as well.

How is the impact of wildfires changing?
The increase in the number of wildfires and their intensity, together with a further densification of The Netherlands, will lead to an increase in the impact of wildfires: people will have to flee more often, direct and indirect damages will occur more often, failure of vital infrastructure, which will lead to cascade-effects, will become more frequent and irreparable damage to flora and fauna will occur more often. Next to this, human health will be threatened more frequently.

The current way of preventing and fighting of fires in The Netherlands is mainly focussed on the limited and relatively short-lived building fires. Wildfires, however, are more often large-scale and take longer than building fires. A point of attention with this is that, due to an increase in (simultaneous) wildfires, an increase in pressure on the fire service is likely as well, resulting in the increasing possibility that the need for resources in certain areas will become higher than the availability of it.

Final conclusion
A larger part of The Netherlands will be confronted with an increasing amount of wildfires. Although the wildfire risk used to mostly manifest itself during spring in The Netherlands, a (prolonged period with a) high wildfire risk during summer will become increasingly likely as well. Wildfires will more frequently develop into fires that cannot be fought, but only stop when there is no fuel available anymore. The increase in the number of fires and their intensity, together with a further densification of The Netherlands, will lead to an increased chance of wildfires with a large impact on health, welfare, nature and economy.

The development of the wildfire risk is not a linear process. Because the factors drought, warmth and (low) relative humidity reinforce each other, the speed at which the wildfire risk increases will be higher than the speed at which climate change is happening.

Recommendations
Based on the conclusions, the following points that, based on the current scientific insights regarding the future developments, can assist in managing the wildfire risk are recommended:
- Managing wildfires must become a structural component of the system surrounding fire safety;
- The risk of wildfires must be included in the considerations for landscape planning;
- The call for an action strategy by governments, fire service and land managers leads to a need for a better understanding of the development of the wildfire risk in order to better and quantitatively describe it.

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Introduction

Motivation

In the past years, wildfires have been both inside as outside The Netherlands a very current topic. The (increasing) urgence of the topic is also visible in the recently published *Rijksbrede Risicoanalyse Nationale Veiligheid*. In the category climate and natural disasters of this renewed analysis, wildfires are the only disaster that are classified as a 'zeer waarschijnlijk' (EN: 'highly likely') scenario. Next to this, the impact of wildfires is seen as 'ernstig' (EN: 'severe'), resulting in wildfires being in the highest risk-category. Hence, the report stated that according the experts, it is not the question if, but when an uncontrollable wildfire with severe consequences will occur (ANV, 2022a, p. 22).

Wildfires in the Netherlands are already a current issue. The fires in 2020 at the Deurnese Peel and the Meinweg are examples of this; during the latter fire, the village of Herkenbosch was evacuated. Also during a smaller wildfire such as the one in Ouddorp in 2022, where approximately 4 hectares was burned, a holiday park was evacuated as a precaution. Also in the countries surrounding The Netherlands that have a comparable climate, wildfires are becoming a more prominent problem. For example, On the 19th of July 2022 the conditions in the United Kingdom were on such an extreme level, that the fire service experienced their busiest day since the Second World War, resulting in a shortage of resources to attend all incidents and 60 houses being burned (Walton & Hedley, 2022).

Figure I.1 A photo of the wildfire near Ouddorp (2022). Source: Staatsbosbeheer

Goal and research questions

The question is how, also due to climate change, wildfires in The Netherlands are changing. This is not only the case for the number of wildfires, their fire behaviour and size, but also for the possible impact of these fires. Next to this, it turns out that lessons and recommendations after previous wildfires are not always followed (Dam, 2022), which leads to additional concern with the consortium. Bearing these issues and questions in mind, the consortium was formed with experts in the field of wildfires from the institutes NIPV, KNMI, WUR, VU and Deltares, who have written this report together. The goals of this Wildfire Signal ’23 are:

1. To gain insights in the future developments of wildfires
2. To present recommendations in order to limit the development of the wildfire risk
3. To identify research topics that need to be addressed in the next few years in order to timely supply in the needed knowledge in order to limit the wildfire risk.

In order to get a better insight in the (future) developments, the following main research question is posed:

How is the wildfire risk in The Netherlands developing?

This main research question is divided in a number of sub-questions:

1. How is the susceptibility to the occurrence of wildfires changing?
2. How is the susceptibility to the development of wildfires changing?
3. How is the impact of wildfires changing?

Reading guide

In Chapter 1, the research methodology of this report is discussed. Chapter 2 serves as an introduction on the topic of wildfires, containing an explanation of various aspects that recur in the following chapters. Chapters 3, 4 and 5 are answering research questions 1, 2 and 3 respectively. In chapter 6, the conclusions of this report are drawn and the three research questions, together with the main research question, are answered. Finally, Chapter 7 contains recommendations based on three overarching themes and discusses some uncertainties in this report.

1 Methodology

This report brings the current state of research and knowledge together, mainly consisting of previous work from the members of the consortium, consisting of experts from various scientific disciplines[1]. An exception with this is an analysis of the relative humidity, as this is an important factor for wildfires and, for the purpose of this report, requires an additional analysis.

1.1 Literature study and interviews

With help of interviews and exchanges within the consortium, as many relevant scientific researches and reports as possible were gathered. These are both reports that were (co-)written by the expert members of the consortium, as well as external (scientific) work and knowledge and insights from not yet published work by members of the consortium. Because the goal of this Wildfire Signal is to bring the available and up-to-date data and knowledge together and interpret this to wildfires, a complete literature study was not performed.

For the paragraphs in this report where the climatological developments are of importance, this report made use of the KNMI'14 Climate Scenarios (KNMI, 2014) and the KNMI Climate Signal '21 (KNMI, 2021b). In these reports, four climate scenarios are distinguished:

- GL: Moderate global temperature rise, small change in air circulation pattern.
- GH: Moderate global temperature rise, large change in air circulation pattern.
- WL: High global temperature rise, small change in air circulation pattern.
- WH: High global temperature rise, large change in air circulation pattern.

1.2 Workshop days

In anticipation of writing this report, two workshop days have taken place, during which the consortium physically gathered at the Netherlands Institute for Public Safety (NIPV). During these days, the structure of the report and the available knowledge was discussed. Next to this, the input for this report was collectively translated to the topic of wildfires and the recommendations were discussed.

The added value of the consortium for this process is that all members are closely involved in the topic of wildfires, but are doing this from different fields of expertise. This creates complementarity, which strengthens the analyses of the available data and knowledge.

[1] See Annex 2 (pages 41 & 42)

1.3 Analysis of relative humidity

The relative humidity (RH) is a parameter that describes the amount of water vapour that is available in the air at a given temperature and thus describes how moist the air is. It is a percentual value for which a value of 100 % means that the air is saturated. In the analyses of the KNMI (KNMI, 2014; KNMI, 2021b) the relative humidity was less extensively analysed than other parameters such as temperature. For instance, in the KNMI Climate Signal '21 (KNMI, 2021b), relative humidity is only discussed as an annual average value. Regarding both spring and summer, little was yet known about the observed and future (daily minimum) relative humidity. As relative humidity is an important factor for the occurrence and development of wildfires (Teie, 2018), an additional analysis was performed for this report.

This analysis looked at historical weather data at the KNMI weather station in De Bilt, which is also the main station in the Netherlands. The daily minimum relative humidity has been recorded there since 1950. This data was then used for two analyses. Both analyses were performed for three periods: the whole year, meteorological spring (March to May) and meteorological summer (June to August).

For Chapter 3, the change in the number of fire-prone days was examined. Here, based on Van Wagner (1972) and Flannigan & Harrington (1988), it was assumed that days with a minimum relative humidity of 50 % or lower can cause sufficient desiccation of small (dead) vegetation for it to potentially burn. These days can therefore be called fire-prone. For Chapter 4, the average daily lowest relative humidity was analysed.

For both analyses, a 30-year running average was then calculated for each period: the climate average. Trends were then determined over these climate averages to understand the effect of climate change on the relative humidity.

2 An introduction to wildfires

2.1 From ignition to impact: wildfires are complex

This paper builds on the concept of the risk-driven approach, in which (wildfire) risk is expressed as the probability of occurrence times exposure and effect (impact) (IPCC, Kinney & Wiruth (1976)). In order to better understand wildfires, we split this risk-driven approach into three aspects, which are also reflected in the sub-questions:

1. The occurrence of a wildfire (up to and including ignition).
2. The development of a wildfire (from ignition on, during the fire).
3. The potential impact of a wildfire (during and also after the fire, and both directly and indirectly).

In this report, we define susceptibility to the occurrence of wildfires as *wildfire susceptibility*, as was also done in Van Marle & Agricola (2021). We also consider the susceptibility to the development of wildfires. When adding the third aspect, the impact of a wildfire, we refer to it as *wildfire risk* (Goldammer et al., 2017).

2.1.1 The occurrence of a wildfire

Wildfire susceptibility can be described by three factors that are based on Bradstock (2010), Chambers et al. (2019) and Van Marle & Agricola (2021); biomass and its availability to burn, weather conditions and ignitions. These are discussed below. Some of the factors are also discussed in section 2.1.2. For a wildfire to occur, all three factors must apply before ignition is possible.

Biomass and its availability to burn

Biomass includes all natural materials that are present at a given location and have the potential to burn (fuel). Natural fuel refers to both dead and living plant material. This can be vegetation as well as organic material in the litter layer. An example of living vegetation is heather plants, whereas dead needles or leaves can be part of the litter layer. Dried out peat can also serve as fuel.

In addition to the presence and quantity of natural materials, the wildfire susceptibility depends on their availability to burn. Some materials ignite more easily than others and, in addition, the rate at which biomass becomes available to burn heavily depends on the type of fuel. The thicker the materials, the longer it takes to ignite. For example, fine, dead materials, such as grass, can dry out in as little as one hour (Teie, 2018) and are therefore often the first to become available to burn. In addition, for living vegetation, seasons affect the availability to burn: in (early) spring, a lot of fuel may be available because the vegetation's sap flow has not yet (fully) started.

Weather conditions

This factor describes the meteorological conditions that influence the ignition of a wildfire. These include temperature, precipitation deficit and humidity. Weather conditions also indirectly affect the wildfire susceptibility by affecting soil and groundwater systems. Depending on soil characteristics, this can be reflected larger or smaller changes in soil moisture content and groundwater levels.

If there is a prolonged drought, this may result in improved flammability of vegetation. In addition, weather conditions can cause ignition to be faster. For example, in warm and sunny weather, biomass gets a higher temperature, requiring less heat for ignition.

The climate at a given location partly influences daily weather, e.g. because of the presence of dry seasons. This means that climate change also translates into a change in daily weather conditions.

Ignitions
This last factor, ignitions, deals with potential ignition sources and, when conditions allow, their role in igniting vegetation. It is very rare in the Netherlands that the ignition of a wildfire is due to a natural phenomenon such as a (dry) lightning strike. The majority of ignitions are man-made. This can be caused, for example, by carelessness with a campfire or barbecue, sparks from (braking) trains, or youth playing with fire in nature. In addition, arson sometimes occurs.

2.1.2 The development of a wildfire

The development of a wildfire is the process that occurs after ignition and is related to the intensity of the fire, the rate and direction of spread and the duration of a fire. This process can also be described by several factors.

Biomass and its availability to burn
What matters most for the development of wildfires is the amount of biomass in one place and the properties of that biomass. More available fuel means more heat that can be released, which can give the fire a higher intensity. Higher intensity means more radiant heat, allowing the fire to expand faster and making it more difficult to stop. In addition, the more the vegetation is dried out, the higher the intensity of the fire becomes, as less heat needs to be used to evaporate the remaining moisture in the vegetation.

Next to this, some vegetation types cause a faster rate of spread than others. When wildfires also burn (parts of) trees, coniferous forest is generally more flammable than deciduous forest. The presence of a litter layer or dried-out peat is also important for the duration of the incident, for instance when the fire continues to smoulder underground for a long time. Especially smouldering fires generally cause prolonged smoke development and nuisance (Van Marle et al., 2021).

Weather conditions
Wind plays a major role in the development of wildfires. When wind speeds are high, more oxygen reaches the fire. In addition, the flames are ‘flattened’, bringing them closer to vegetation that has not yet burned. These aspects accelerate the spread of a wildfire.

In addition, changes in meteorological conditions during a wildfire are also important for its development. In the evening, when it often cools down and humidity levels rise again, the intensity of the fire often drops, making the wildfire easier to control. On the other hand, a (spontaneous) change in wind direction, for example, can intensify the spread of a wildfire because a (stretched) flank of a wildfire can suddenly turn into the head of the wildfire.

Topography
Topography is not one of the aforementioned factors, but it does affect fire behaviour: in general, fire spreads upslope and slower downslope. Of course, this plays out on a smaller scale in the Netherlands than in, say, mountainous areas abroad.

Whether or not a wildfire becomes large not only depends on fire behaviour through the abovementioned factors, but also on the following:
> The layout of the landscape and the presence of 'natural' boundaries. The layout of the landscape may have consciously or unconsciously included measures that slow down a fire or create a barrier against the spread of a natural fire.
> The speed with which the fire is detected and reported.
> The response time of the fire brigade.
> The speed with which the fire service actually found the fire.
> The accessibility of the location of the fire.
> The extent to which the fire can be delayed and stopped, for example with water, fire or by removing fuel.

Once a wildfire has started, four types of fire can be distinguished. These are described in Table 2.1.

Table 2.1 An overview of the different types of fire in wildfires, based on Schneider (n.d.)

Type of fire	Description
Ground fire	Fire burning in soils (e.g. peat). This is usually a smouldering fire with a strong and prolonged smoke production.
Surface fire	Fire raging in vegetation directly on the ground. This can be, for example, the litter layer, herbaceous vegetation such as heather or purple moor-grass, or shrubby vegetation such as buckthorn.
Crown fire	Fire raging in the crowns of trees (mostly conifers). In this type of fire, the highest intensity occurs with metres-high flames.
Spot fire	Small pieces of still-burning or smouldering vegetation that are carried away with the wind and land further down the road again, allowing secondary fires to form dozens to sometimes more than a hundred metres from the wildfire.

This report sometimes refers to more extreme fire behaviour. This refers to an increase in heat release expressed as longer flames with more radiant heat. This is especially true for surface fire, crown fire and spot fire.

2.1.3 The impact of a wildfire
In order to be able to withstand the impact of wildfires and to recover quickly ('resilience'), it is important to understand the possible consequences of natural fires. This will help determine which measures or future investments would best help the Netherlands to become more resilient to those consequences.

The Netherlands is a densely populated country in which various functions in the same area are closely intertwined. Think of nature, agriculture and recreation, but also health care, housing and vital infrastructure such as telecom or electricity. Therefore, the potential impact and damage of a wildfire can quickly become significant.

From a risk-based approach, the impact of a wildfire can be expressed in terms of direct and indirect damages. Direct damages deal with impacts that come from direct exposure to the fire or associated smoke. Indirect damages, on the other hand, are about the impact that can take place in space or time away from the wildfire. A distinction is made here between tangible and intangible damage. Tangible damage in this case means damage to which a certain monetary value can be given, whereas with intangible damage this is not (easily) possible. Some examples of this division into damages are described in Table 2.2.

Table 2.2 An overview of the potential impact of a wildfire, divided into direct and indirect damages (based on Scussolini et al., 2016)

Direct damages	Indirect damages
Tangible: > Damage to buildings or objects. These are often in or near nature (known as the Wildland-Urban Interface or WUI) > (Irreparable) damage to nature > Damage to infrastructure > Damage to firefighting equipment	**Tangible:** > Socio-economic damage caused by infrastructure failure. For example: disruption of transport of goods in case of closed highways or railroads > Damage from failure of other vital functions such as electricity, water or telecommunications > Damage from business interruption due to evacuation > Fire department deployment costs
Intangible: > Injuries or fatalities > Damage to cultural heritage > Damage to ecosystems	**Intangible:** > Evacuations due to the imminent threat of fire or smoke development and the associated exposure to noxious gases > Damage to the mental well-being of residents and emergency responders due to traumatic experiences > Loss of confidence in the emergency services > Loss of recreational activities in and around the affected nature and a decline in tourism

2.2 Why can wildfires be dangerous?

Some wildfires can be dangerous because of the flames and the smoke they produce. A complicating factor here is that wildfires are constantly moving and can behave unpredictably, partly under the influence of weather conditions, such as an unexpected turn or increase in wind. This makes entrapment of emergency responders and civilians a real risk. This shows that wildfires are a different incident type than fires in the urban environment and therefore require different methods of response. What may be considered a relatively safe place for civilians and emergency responders at one moment, is a dangerous and possibly life-threatening place to be a few minutes later due to, for example, the wind changing. Wildfires can also spread to other combustible materials and buildings.

In addition, smoke can be a hazard. In both flaming and smouldering fires, for example, (prolonged) exposure to and inhalation of fine soot particles is a risk to incident responders and citizens downwind of the smoke plume. In addition, the smoke can cause poor visibility, leading to accidents.

2.3 Why can wildfires be difficult to fight?

Although most wildfires in the Netherlands remain small (Figure 3.1), some are still difficult to fight. As a result, even small fires can require a large firefighting effort (equipment and people). There are a number of factors that contribute to the difficulty of fighting this incident type:

- **Difficult to localise and get an overview of the fire**
  The location, actual size and impact of the fire are sometimes difficult to determine because a fire is not located at a specific address and, especially in nature, it is difficult to orient through smoke.
- **Inaccessibility**
  The road network in some natural areas is coarse and sometimes difficult to drive through for standard fire trucks.
- **Dynamic movement**
  A wildfire is dynamic and moves in both space and time.
- **Long duration**
  A wildfire continues to spread until it is extinguished or until there is no more fuel (available) to burn. Especially where there is no or little compartmentalization in nature, the fire can continue to spread for a long time due to the presence of a large area of combustible vegetation. The duration of a developed wildfire can be counted in hours and sometimes days.
- **Limited amount of available water**
  A larger fire requires an enormous amount of water to lower the temperature to the point where the burning process stops. There is a lot of fuel in nature and this means that, with a large fire, it is not possible to extinguish the fire: the fire department cannot bring up enough water everywhere over such a large area, partly because there is limited additional extinguishing water in addition to what is present in the vehicles themselves. As a result, solely using water for extinguishing only works for small fires. Therefore, for larger fires, firefighters will usually use the available water to stop or slow the spread of the fire by wetting unburned fuel (NIPV, n.d.). However, this tactic is also vulnerable: wind and heat quickly evaporate this water. It is therefore difficult to fight larger natural fires with the urban method of firefighting used in the Netherlands.
- **Complex logistics system**
  Large wildfires require a complex logistics system, partly because of the often high demand for additional firefighting water and the exhaustion of firefighters during (extremely) hot days. A complex logistics system is vulnerable given the dynamic nature of wildfires.

Wildfire is a type of incident that comes on top of regular incidents. This means that during fire-prone days there is more pressure on the fire department, especially when it comes to a large-scale deployment. On fire-prone days, multiple (large) wildfires can also rage simultaneously. It is precisely this simultaneity that potentially poses a major problem. This is especially true when the fires occur in the same vicinity and there is a risk that they require so much firefighting capacity that insufficient resources remain for regular incidents such as building fires or traffic accidents. This is something that has already previously occurred abroad, for example in the summer of 2022 in the United Kingdom (Walton & Hedley, 2022), and is known as a "collapse" of the fire system (Castellnou et al., 2019).

Although wildfires have frequently occurred, the Netherlands is only limitedly equipped for this type of incident. The fire service system is primarily set up for the urban environment with building fires. This is reflected throughout the system, from turnout times, legislation and (personal) equipment to training. For example, the primary focus on building fires can be seen in the vehicles that are not or not well deployable in the natural environment and in protective clothing designed for urban fires and is extra thick (Brandweer Nederland, 2019). This puts firefighters in wildfires at additional risk of exhaustion and overheating during a prolonged incident. This contributes to the difficulty of fighting wildfires.

3 The susceptibility to the occurrence of wildfires

3.1 The Netherlands already has many wildfires

3.1.1 Hundreds of fires per year

A wildfire in the Netherlands is not a unique incident; hundreds of wildfires occur every year, although the numbers differ between wet and dry years. This can also be seen in Figure 3.1. Wildfires are already frequent in the Dutch landscape. During the period between 2017 and 2021, three out of five years were (very) dry and several hundred to almost a thousand wildfires occurred annually. The relatively wet years 2017 (321 wildfires) and 2021 (212 wildfires) were relatively quiet, while in 2018, for example, there were 949 recorded wildfires (Stoof et al., 2022). As the figure below shows, most wildfires remain relatively small, meaning smaller than one hectare. On some days with high fire danger, sometimes dozens of wildfires can occur. Most wildfires in the Netherlands occur in low and fine vegetation such as grass, heather and some shrublands (category 'other, non-wooded' in Figure 3.1).

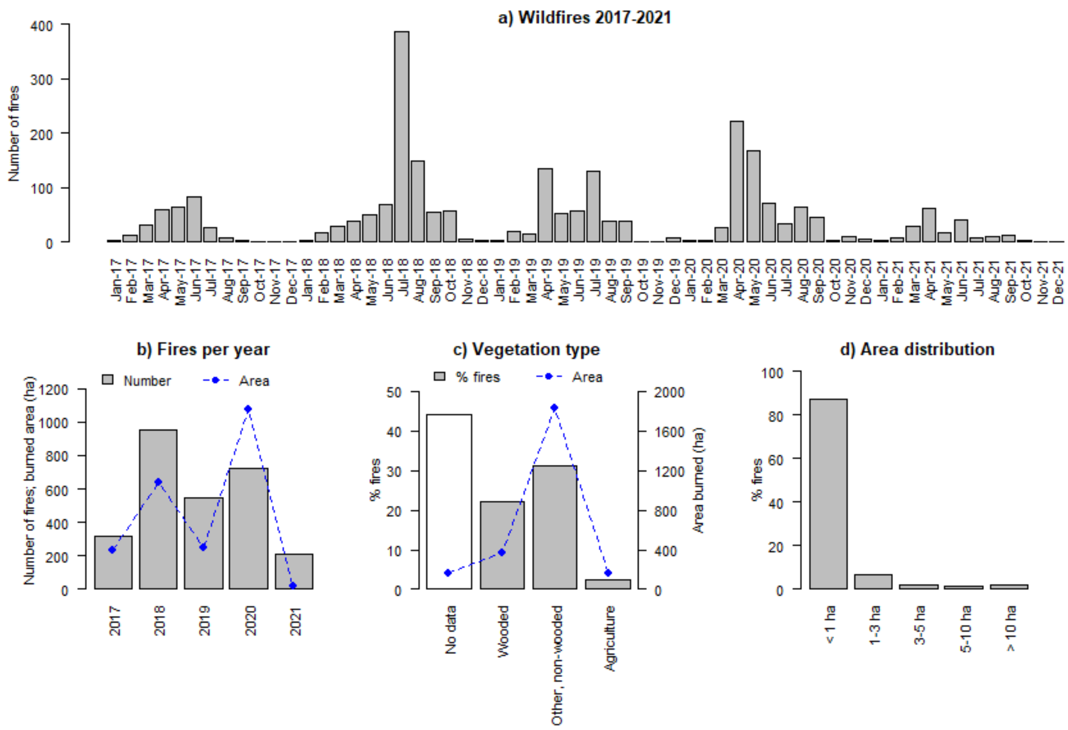

Figure 3.1 Wildfires in The Netherlands based on the WUR and NIPV database (Stoof et al., manuscript in preparation). The figure shows the number of wildfires per month (a) and per year (b), the percentual share per vegetation type (c) and the distribution of the total area of wildfires (d)

3.1.2 Climate change is already happening

Over the past 60 years, the climate in the Netherlands has changed. The trend is showing increasingly warmer and drier weather (see Table B1.1 - Appendix 1). The annual mean temperature has increased by 1.1 °C between the two climate periods 1961-1990 and 1991-2020. Average temperatures increased in each season, with the increase being greatest in spring and smallest in autumn. In absolute terms, average annual precipitation has also increased, but there are increasing differences within the year. Spring and autumn have become drier, while winter and, to a lesser extent, summer have become wetter. Still, the average precipitation deficit has increased. This is due to an increase in evaporation as a result of higher temperatures and additional solar radiation (KNMI, 2021b). All in all, this means that, on average, weather conditions lead to greater fire susceptibility in nature. As the climate has become warmer and drier, vegetation can dry out more quickly, making it available as fuel.

An additional analysis of relative humidity shows that the number of fire-prone days has increased. Since 1979, this has increased by about 30% in both spring and summer (Figure 3.2). The trendlines show a highly correlated increase with an R^2 of 0.80-0.86 (the R^2-value expresses the strength of a statistical relationship and varies between 0 and 1; a value higher than 0.8 indicates a strong relationship). No indication was found that the number of fire-prone days outside spring and summer also increases. It can be concluded that the number of fire-prone days within the wildfire season has increased, but the wildfire season has not become longer.

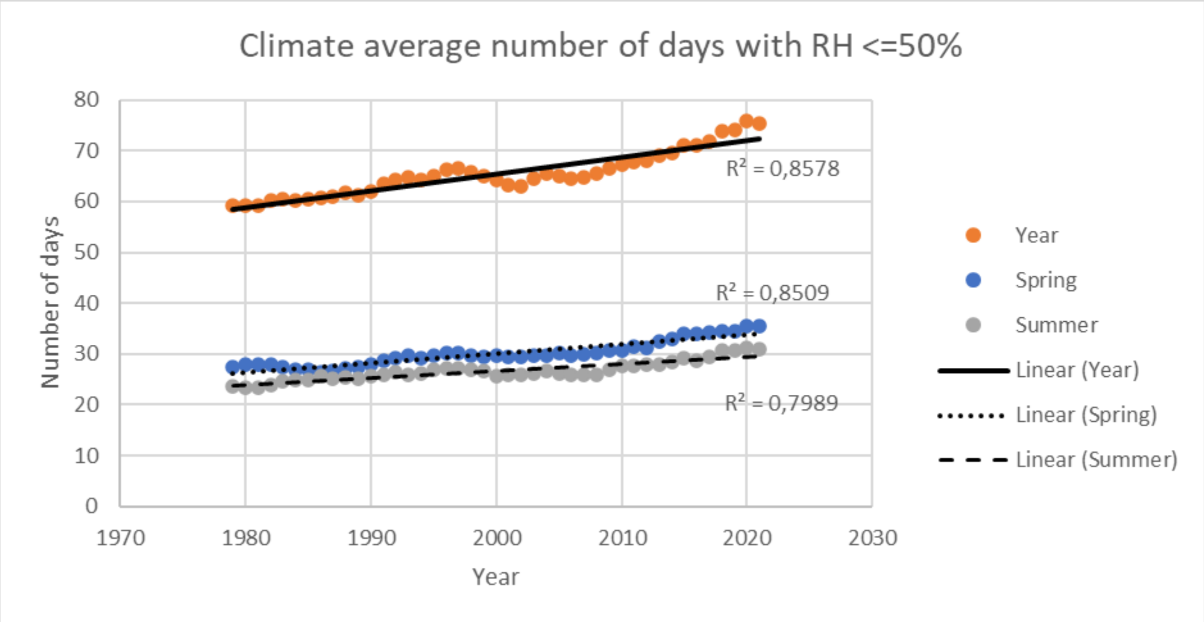

Figure 3.2 Summary of the climate mean number of days per year with minimum relative humidity (RH) equal to or below 50 % for the KNMI weather station in De Bilt. The black lines show the trend line. To each trend line, the corresponding R^2 is added

3.2 A more flammable nature

3.2.1 Even hotter and drier: more vegetation becomes available to burn faster

The climate projections indicate a continuation of the observed trend described in Section 3.1.2. Table B1.2 (Appendix 1) summarises some meteorological parameters and their expected change according to the four KNMI'14 Climate Scenarios (KNMI, 2014). For the future, this report assumes a warmer, drier and sunnier climate. This corresponds to all four climate scenarios for 2050, except for solar radiation in the WL scenario, which decreases slightly. However, observations show that the Netherlands has become sunnier in recent years (Table B1.1, Appendix 1), which makes it plausible that the trend for this parameter also continues.

However, the difference between the scenarios is significant, especially regarding a low or high value in atmospheric circulation. Under the scenarios with that change in atmospheric circulation, an easterly wind would become more common in summer. Those easterly winds are often typical for (large) wildfires in The Netherlands as they often produce some wind while the weather is generally warm, dry and sunny. Should the scenario with that changing circulation materialise, this could have a major impact on the susceptibility to the occurrence of wildfires (Table B1.2, Appendix 1).

For instance, a small increase in precipitation is expected for summer under the GL and WL scenarios. In contrast, a sharp decrease in precipitation is calculated for the GH and WH scenarios. This is also reflected in the number of wet days in summer, which strongly decreases in the GH and WH scenarios. Therefore, this would mean that there will be more dry days with changing circulation. This mainly manifests itself in the average precipitation deficit, which, under these scenarios, could increase by 20-30% during the growing season. The GL and WL scenarios, despite the absolute increase in precipitation, also foresee an increase in this precipitation deficit to a lesser extent. Developments according to these scenarios could therefore have a (large) impact on the susceptibility to the occurrence of wildfires.

Apart from changes in individual parameters, KNMI (2021b) also describes in its Climate Signal '21 that the persistence of weather systems (high and low pressure areas) plays a role in the development of dry spells. Due to a change in the jet stream, high-pressure areas can persist longer in summer, allowing dry, sunny and warm periods to last longer.

Changes in the climate also translate to changes in groundwater levels. An analysis of the mean lowest groundwater level (MLG) for the Klimaateffectatlas (n.d.) looked at this change for 2050. The WH climate scenario was used for this purpose. The results are shown in Figure 3.3. It shows that the MLG is expected to decrease in a large part of The Netherlands. In contrast, an increase in MLG is calculated, especially for the (high) sandy soils (e.g. the dunes in the west of the country and the Veluwe). This increase can be explained by an increase in winter precipitation. Groundwater levels in these areas are far below the surface, so the increasing evaporation due to climate change has less effect on the groundwater level. In these areas, therefore, a rising MLG will also have little effect on the wildfire susceptibility. The decreasing MLG in large parts of The Netherlands means that these will become more sensitive to drought, which may contribute to an increasing wildfire susceptibility of these areas (Klimaateffectatlas, n.d.).

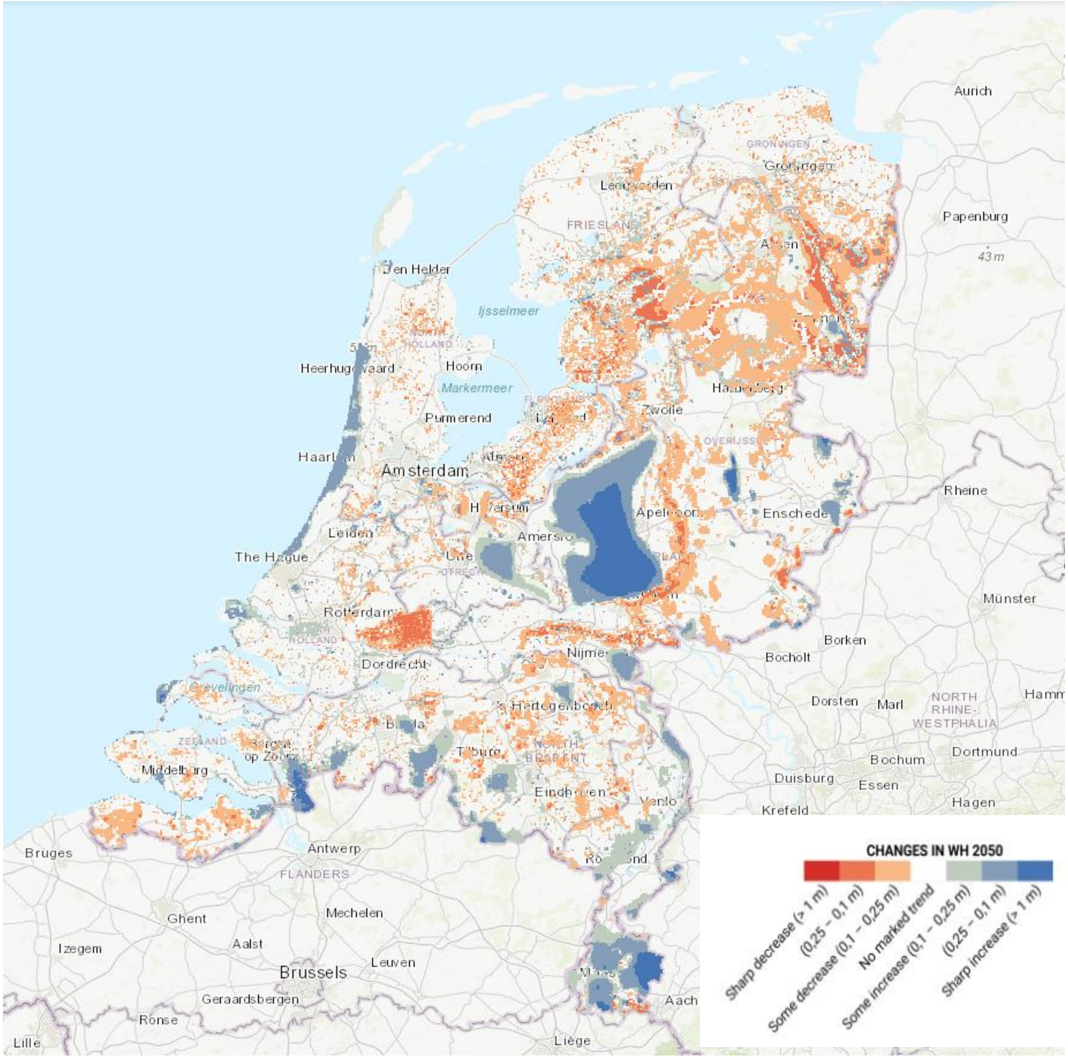

Figure 3.3 The change in mean lowest groundwater level (MLG) for 2050 under the WH climate scenario. Source: Klimaateffectatlas (n.d.)

Moreover, climate change is not uniformly distributed across The Netherlands. In particular, the daily maximum temperature increases faster in the east of the country than in the west due to the moderating effect of the sea (KNMI, 2022). This causes an amplified increase in wildfire susceptibility in the eastern part of The Netherlands.

3.2.2 More wildfires due to an increase in biomass

Over the next ten years, as articulated in the national government's *Bossenstrategie* (EN: Forest Strategy; Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2020), the Netherlands is expected to get about 10% more forest. The implementation of this may involve converting areas with limited combustible vegetation that is sometimes irrigated (agricultural areas) to areas with vegetation that is not or hardly irrigated and therefore becomes more sensitive to drought and may become more combustible. This potentially creates a larger area of combustible vegetation and increases the biomass that can become available for burning during dry periods. On fire-prone days, it is therefore plausible that more wildfires could occur as a result. However, the current trend is a limited decrease in the total area of forest in The Netherlands, which contrasts with the stated ambitions from the Forest Strategy.

Little is still known about future changes in vegetation (species, growing season and its length, vegetation stress and the amount of dead plant material on the ground). This is therefore an uncertain factor, as it depends not only on climate change, but also on the management of natural areas, among others. Based on current vegetation and in a warmer and drier climate, it is likely that vegetation will dry out faster and more and thus become more flammable.

3.3 From potential ignition source to wildfire

A warmer and drier climate leads to more fire-prone days. Assuming that the number of potential ignition sources is not substantially reduced, more fire-prone days mean that more wildfires can occur. This is also shown in an analysis by Deltares (Van Marle & Agricola, 2021) that looked at the sensitivity of Dutch nature to wildfires in the current situation and in the WH scenario for 2050. This sensitivity was determined by using characteristics on the fire sensitivity of vegetation, drought and potential ignition factors (Figure 3.4 on the next page). To determine future climate sensitivity, only changes in climate characteristics were considered. This shows that there is a sharp increase in wildfire sensitivity under this scenario. The percentage of The Netherlands falling under 'moderately sensitive' or 'highly sensitive' increases from 39 % to 63 %. In addition, the share of 'high sensitivity' will almost double: from 5 % to 9 %. Virtually every location in The Netherlands remains the same in sensitivity or moves into a higher sensitivity class.

Much of The Netherlands also shows an increase from 'not to little sensitive' to 'moderately sensitive' (from green to yellow). This concerns, for example, the eastern and northern Netherlands, but also the Groene Hart (EN: Green Heart) area. It is also notable that a significant part of the Veluwe comes under 'highly sensitive'. This contrasts with the rising GLG of Figure 3.3 and has to do with the depth of the groundwater. In the Veluwe, among other places, the groundwater level is many to tens of metres below the surface. A rise of around 2 metres thus does not bring the groundwater high enough to be accessible to vegetation and therefore does not cause a decreasing effect on wildfire susceptibility.

Figure 3.4 thus shows that a larger part of The Netherlands is becoming more susceptible to wildfires. For this reason, (existing) potential ignition sources in areas that were previously less sensitive may indeed lead to actual ignition in the future. As wildfires often occur on the same days and under the same combination of meteorological conditions, there is therefore a chance that the number of wildfires on a single day will increase and more fires may occur simultaneously.

The analysis by Deltares (Van Marle & Agricola, 2021) shows that, among other things, recreational pressure has a predictive power for wildfire susceptibility as shown in Figure 3.4. The recent article by Pointer (2022) describes that recreation in and near natural areas has also increased. However, the maps in Figure 3.4 only consider the effects of climate on wildfire vulnerability. If non-climatic factors such as recreational pressure or forest strategy were also taken into account (section 3.2.2), ignition rates could increase even more.

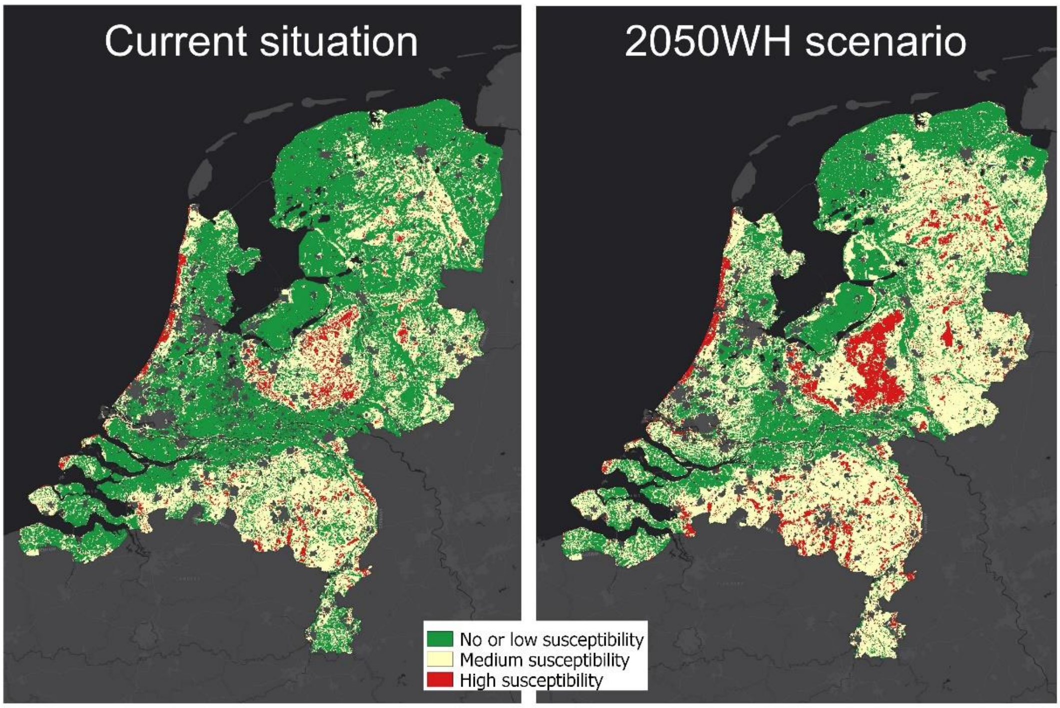

Figure 3.4 The wildfire susceptibility map from an analysis by Deltares (van Marle & Agricola, 2021). Due to a limitation in data, the Wadden islands are not included in this analysis and therefore, like the urban areas, are coloured grey on the map

As mentioned in Chapter 2, the majority of wildfires in The Netherlands are human-caused. According to CBS (2022), The Netherlands is projected to have a population of about 19.5 million by 2050. On the 1st of January 2022, there were about 17.6 million. It is therefore plausible that, ceteris paribus, a larger population also means more ignitions. This factor then contributes to the expectation of more wildfires in the future as well.

Summary

The Dutch climate has changed in recent decades. Warmer and drier weather has increased the number of fire-prone days per year, and nearly 1,000 wildfires now take place in The Netherlands during some years. This trend is expected to continue in the future. Even warmer and drier (in both air and soil) conditions means that more nature can become flammable and therefore more wildfires may occur. The effect of more biomass and an increasing risk of ignition further enhance this increase in wildfires.

4 The susceptibility to the development of wildfires

4.1 A look at fire behaviour from the past

When looking at wildfires, large uncontrollable fires are not just something of the past few years. As recently as 1976, for example, a large wildfire raged near Arnhem and in 1995 near Kootwijk. Several dune fires near Schoorl occurred in 2010 and 2011. A large fire also raged on the Strabrechtse heide in 2010. In 2014, there was another large wildfire in National Park De Hoge Veluwe. The 2020 wildfire in Deurnese Peel, with a size of over 700 hectares, is the largest known wildfire in The Netherlands since statistics have been re-established (Stoof et al., 2020). Simultaneously, the large wildfire in the Meinweg raged that year.

Due to drier and warmer conditions as a result of the changing climate, it is plausible that fire has become more intense on average, causing less energy to be required to evaporate (remaining) moisture in the vegetation and more heat to be produced. The drying out of the air in recent decades is also visible in Figure 4.1. The figure also shows that the air dries out faster in spring than in summer.

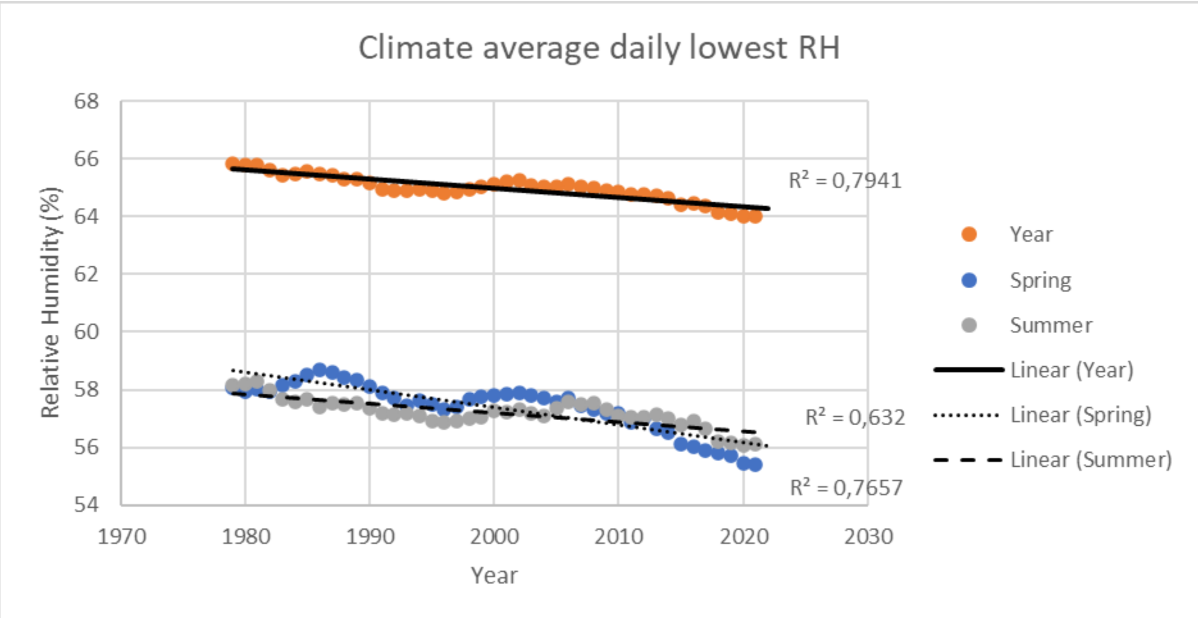

Figure 4.1 Summary of the climate average daily lowest relative humidity (RH) per year for the KNMI station in De Bilt. The black lines show the trend line. To each trend line, the corresponding R^2 is added

4.2 Changing fire behaviour

4.2.1 Climate change: increasing intensity and complexity

The change in meteorological parameters as also described in chapter 3.2 affects not only the number of wildfires, but also the fire behaviour. The individual factors increasing temperature, decreasing relative humidity and increasing precipitation deficit will likely make wildfires behave more extreme. When it comes to wildfires, these factors (heat, drought, low humidity) also accumulate. Wildfires are therefore very sensitive to climate change. It can therefore be argued that wildfires are changing faster than the climate itself as this accumulation causes an amplified increase when it comes to fire behaviour.

An additional concern is the complexity of wildfires. For example, the KNMI writes in its Climate Signal '21 (KNMI, 2021b) that decreasing relative humidity can cause thunderstorms to produce downbursts more frequently. These winds can move away from the storm and possibly reach a wildfire, causing the wind to (unexpectedly) increase in strength and change in direction, causing unexpected fire behaviour and resulting in dangerous situations. This is a process that has occurred more frequently abroad (Achtemeier & Goodrick, 2021; Potter & Hernandez, 2017).

4.2.2 Vegetation: an important but uncertain factor

As indicated earlier, the state of future vegetation is an uncertain factor. There are a number of issues that may pose a risk for the future:

> The Forest Strategy (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2020) aims to connect more pieces of nature (about half of the targeted 10% increase). This means wildfires could become larger due to a continuity in fuel.
> Climate change (warmer, drier and sunnier weather) may also cause an increase in vegetation stress, increasing the availability of flammable material.
> The declining MLG in many areas (Figure 3.3) may contribute to increasing vegetation stress and hence vegetation flammability, resulting in more intense fire behaviour.
> The effect of nitrogen deposition can also impact wildfires. For instance, nitrogen promotes the growth of more productive species such as grasses and ferns, which are highly combustible under dry conditions and provide additional biomass. This can increase the spread rate and intensity of a wildfire.
> The accumulation of dead wood in nature can also have an effect on fire behaviour. On the one hand, dead wood can be a problem during prolonged droughts by serving as additional fuel. On the other hand, during shorter periods of drought, it can actually retain moisture and thus slow down the development of wildfires.

4.3 More often uncontrollable

It is expected that there will be more days in the future with conditions unfavourable for fighting wildfires, as these conditions lead to fuels becoming available faster and more fire power and thus more intense fire. As a result, more wildfires may become uncontrollable, logically leading to an additional increase in the percentage of uncontrollable wildfires. This process is shown schematically in Figure 4.2.

Figure 4.2 shows three lines: the extinguishing capacity, the fire intensity in the current climate and the fire intensity in a future climate. At some point, the development of the extinguishing capacity flattens out due to limiting factors such as the supply of water. When the fire intensity becomes higher than the extinguishing capacity, a wildfire becomes uncontrollable unless it is stopped by natural barriers. The area where the lines of fire intensity and extinguishing capacity cross, is therefore called the crossover point. Crossing this point means that a long-term deployment is required to fight a wildfire. In the future climate, the fire intensity is expected to rise faster. As a result, the line of fire intensity is more likely to cross the line of extinguishing capacity more quickly, making a wildfire more likely to become uncontrollable and requiring a prolonged deployment to stop the fire.

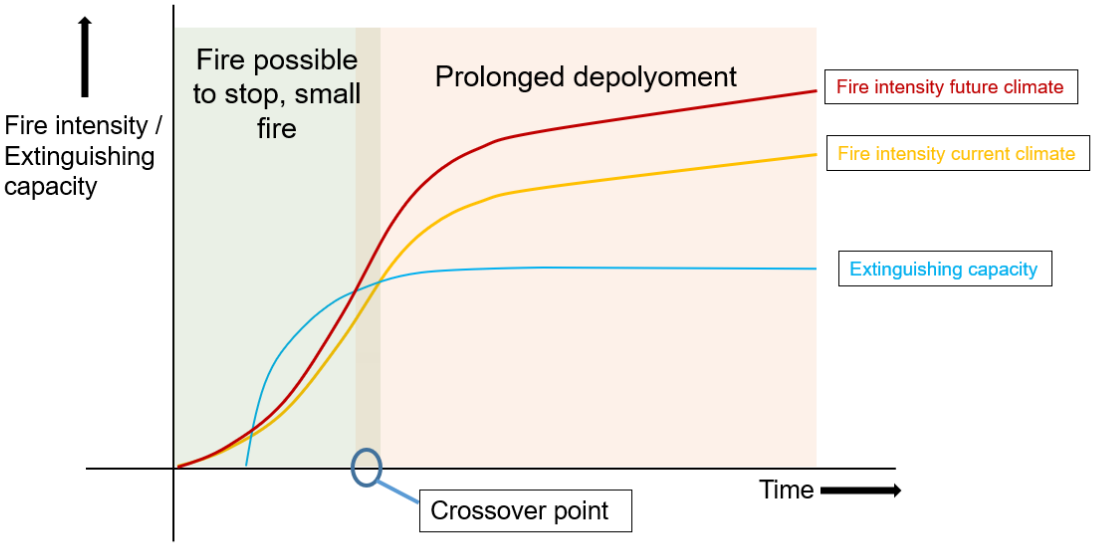

Figure 4.2 A schematic representation of wildfire development and the crossover point from a small, controllable wildfire to a large, uncontrollable wildfire. Figure is adapted from Brandweer Nederland (n.d.)

To prevent an uncontrollable wildfire, it is therefore essential to stop it in its early stages. In the future, without mitigating measures in the landscape and vegetation, this is likely to become increasingly difficult, leading to more frequent uncontrollable wildfires.

The size of a wildfire also depends on the size of the nature area where the fire is raging. Dutch nature is relatively fragmented, so there will be large differences in the size of fires on certain days. The vegetation type of different natural areas also plays a role in this.

Finally, the accessibility of some natural areas is an issue. If, in the early stages of a wildfire, the fire cannot be reached by the standard means of firefighting because it is, for example, in a peat bog or there is too much loose sand, a wildfire can also develop into an uncontrollable fire.

Summary
Due to drier and warmer conditions as a result of the changing climate, it is plausible that fire has become more intense on average. All signs point to this trend continuing into the future. With the combination of more biomass, higher temperatures and drier conditions, the change in wildfires is expected to be faster than the change in climate itself. Although the change in vegetation in the future is still uncertain, there are a number of possible factors that are important. For example, vegetation stress may play a role in fuel availability and increasing nitrogen deposition may cause an increase in combustible vegetation species such as grasses and ferns, with a more flammable nature as a result. This all adds to the expectation that wildfires will become faster and more often uncontrollable.

5 The impact of wildfires: the wildfire risk

5.1 Wildfires already have consequences

5.1.1 (Large-scale) evacuations

Although not every wildfire is impactful, there have been fires in The Netherlands with a (large) impact. Due to the high population density and the density in functions, the likelihood of severe consequences of a fire for people, animals and nature is relatively high. For example, in recent years there have been a number of cases of (large-scale) evacuations:

> During the Ouddorp dune fire in August 2022, the manager of a holiday park was forced to pre-emptively evacuate the residents of the most endangered houses (Gaspar et al., 2022).
> During the fire in Nationaal Park De Meinweg in April 2020, Herkenbosch, a village of over 4,000 inhabitants, was evacuated due to potential smoke exposure. Two healthcare facilities in the village had already been evacuated the day before (Brandweer Nederland, 2020; NU.nl, 2020).
> During the Deurnese Peel fire, all residents from a care home and residents in parts of Griendtsveen and Helenaveen had to be evacuated (Eindhovens Dagblad, 2020; RTL Nieuws, 2020).
> During the dune fire in Schoorl in 2010, approximately 550 people had to leave their homes (NH Nieuws, 2019).

5.1.2 Quantifying the economic impacts of wildfires

The impact of wildfires can be quantified with both direct and indirect tangible damages. Direct damages include, for example, damage to buildings and objects, (irreparable) damage to nature or damage to infrastructure and fire equipment. Indirect damage can be determined by calculating socioeconomic losses, for example due to damaged infrastructure or outages of other vital and vulnerable functions such as telecom and electricity.

Economic damage also occurs when businesses are unable to operate due to evacuations, closures or burning of buildings or supplies. It is known that approximately half of the companies affected by major fires go out of business within two years. This may also be because customers go to competitors after a fire (AMweb, 2018). Therefore, if a wildfire spreads to a business premises, there is a significant risk of bankruptcy.

The deployment of fire personnel and equipment and other parties such as the military also costs money and thus creates indirect losses for society. Based on an estimation of the social impact of the drought in 2018, which in turn is based on the fire service deployment and nature restoration, this can amount to at least several million euros (Kok et al., 2022). This calculation does not take into account socio-economic losses, such as economic damage to businesses, or the loss of species and nature quality.

5.1.3 Failure of vital and vulnerable infrastructure and cascading effects

Infrastructure for transporting people and goods is already experiencing the impact of wildfires. For example, roadside fires can cause (rail)roads to have to be closed because of, for example, the space needed for emergency services or poor visibility due to smoke. In the dry year of 2018, more than 250 reports of roadside fires or fires in the close vicinity of a road were made to Rijkswaterstaat. Even these smaller fires can potentially have a large social impact if they occur at critical points on our main road network, such as heavily used highways and junctions. In addition, much of the main road network is susceptible to closure by smoke from prolonged flaming or smouldering wildfires in the further vicinity (Van Marle et al., 2021).

For the main road network, a number of analyses have been conducted on the impact of highway outages, for example, where travellers experience delays due to congestion or rerouting. The annual foreseeable repair and congestion costs due to roadside fires can reach into the tons as a result (Bles et al., 2019). Parts of the main road network that are most vulnerable to this are mostly located in the east and south of The Netherlands and in the dune area in Zeeland (Bles et al., 2021). In response to these estimates, Rijkswaterstaat has drawn up an overview of measures to mitigate the impact of wildfires.

Wildfires also affect other vital functions. Failure of vital processes causes daily life to be disrupted and may result in lack of basic necessities. Examples are effects on electricity, telecommunications or drinking water supply. During an uncontrollable fire, these functions can also be affected outside the directly affected area and cause cascading failures. A wildfire near a hazardous materials site, for example, could result in large-scale evacuation. If a critical transformer fails, a local wildfire could cause regional electricity outages with residents and workers being without power for an extended period of time, including cascading effects such as loss of internet access and data traffic or failure of the C2000 network (ANV, 2022b).

5.1.4 Costs and damages to flora & fauna

Damage to nature reserves can be quantified by estimating restoration costs per hectare. These costs include replanting and the creation of paths and have been estimated at 900-1200 euros per hectare. However, in specific situations such as the fire on the Kalmthoutse Heide in 2011, these costs can be as high as 6000 euros per hectare (Kok et al., 2022).

The impact on flora and fauna by wildfires does not always have to be damaging. Especially for flora, if the intensity of the fire is not too high, the damage is often limited. Sometimes it even provides opportunities, for example for biodiversity in a heathland area (Staatsbosbeheer, 2022). If slow or intense wildfires on dry soils heat the topsoil, especially when the litter layer is dry and burns as well, a loss of nutrients and water holding capacity in the soil occurs. This can be particularly problematic for flora and fauna on poor sandy soils.

Wildfires, on the other hand, can be dangerous for fauna and especially for smaller animal species that cannot easily flee. Especially in the case of small and local populations, for example those of sand lizards, wildfires can have a big impact (Mart-Jan Schelhaas, personal communication, 21 September 2022).

5.1.5 Impact on human health and well-being

Wildfires can have a lot of impact on people. Firefighters mostly work in wildfires with relatively high air temperatures. As a result, there is a risk of exhaustion and overheating. This can have an impact not only physically, but also mentally. For instance, physically demanding activities can cause a decrease in alertness and thinking capacity (Xu et al., 2018). Because wildfires often involve working in fuel (vegetation), it is precisely alertness and awareness of the hazards present that are very important. Reduced alertness while working in wildfires can therefore create dangerous situations.

Although smoke from wildfires is sometimes still seen as not (very) harmful, there are indeed risks associated with, for example, exposure to particulate matter. This applies to both firefighters and civilians. Poor visibility due to smoke formation can also be a hazard. For example, there were several accidents involving vehicles on the road during the Deurnese Peel wildfire in 2020 (NOS, 2020; Stoof et al., 2020).

There have been fatalities from wildfires in The Netherlands. As far as is known, a total of 29 deaths have occurred since 1833; 22 of these were victims of three peat fires that raged between 1833 and 1917 and the remaining seven occurred between 1922 and 2021. The latter seven casualties occurred while fighting a wildfire, during an exercise or through the use of fire in nature (Stoof et al., 2022).

5.2 More and higher intensity wildfires: more impact

Due to an increasing number of wildfires in a highly densified The Netherlands landscape, it is inevitable that the social impact and damage will also increase: people will have to flee more often, campsites will have to be evacuated more often, there will be more frequent inconvenience due to closed roads, and cascading effects will also occur more often in, for example, utilities.

In addition, the growing Dutch population (CBS, 2022) and increasing recreation in and around nature reserves (Pointer, 2022) contribute to the increasing impact of wildfires. This applies not only to human health through exposure to smoke and flames, but also to the complexity of wildfires. With more people and recreation, it becomes more likely that it will be necessary to evacuate people from a nature reserves or, for example, campsites. This requires extra time, resources and coordination skills, which in turn can come at the expense of fighting the fire itself.

Due to an increasing number of (sometimes simultaneous) wildfires, increasing pressure on the fire service system is expected. This means that 'triage' may be needed more quickly in case more resources are needed for wildfires and other incidents than are available. Choices will then have to be made about where to prioritise, which by definition means that some incidents may not be dealt with optimally or safely. This increasing pressure on the fire service system is inevitable unless specific measures are taken to reduce the number of wildfires or the vulnerability of other functions.

Summary
Currently, damage has been quantified for only a part of the impact of wildfires. With this incomplete picture, which does not include damage to objects, cascade effects and user failure of e.g. electricity supplies, damages can already amount to several million euros per year. In addition, there are intangible damages resulting from evacuation during wildfires as well as physical and mental consequences for citizens and firefighters confronted with wildfires.

The impact on nature can be negative due to species loss and soil damage, but also offers opportunities. The impact of a wildfire is not necessarily limited to the location of the fire, but can also have supra-regional effects, affecting larger parts of society.

With the increasing number of higher-intensity wildfires in a highly densified Dutch landscape, it is inevitable that social impact and damage will also increase in the future.

6 Conclusions

This chapter will first answer the sub-questions and then answer the main question. The main and sub-questions are answered by combining existing studies and expertise from the research partners within this study.

6.1 Sub-questions

6.1.1 How is the susceptibility to the occurrence of wildfires changing?

A change in wildfires is taking place in The Netherlands. As the Dutch climate becomes warmer and drier and the number of wildfire-prone days increases, more vegetation becomes flammable and wildfires may become more frequent. A larger part of The Netherlands will become susceptible to the occurrence of wildfires. The likelihood of wildfires starting in spring increases. In addition, the likelihood of the occurrence of such fires in summer will also increase more often in the future.

6.1.2 How is the susceptibility to the development of wildfires changing?

Warmer and drier conditions mean that wildfires may burn more intensely and become increasingly difficult to fight with current suppression method(s). Uncontrollable wildfires are more likely to occur and cannot be fought with current firefighting tactics, technology and capacity. There is also a greater likelihood of such fires occurring simultaneously.

6.1.3 How is the impact of wildfires changing?

The increase in the number of wildfires and their intensity, coupled with further densification of The Netherlands, will lead to an increase in the impact of wildfires: people will have to flee more often, direct and indirect damage will occur more often, vital infrastructure will fail, leading to cascading effects and irreparable damage to flora and fauna. In addition, human health will be threatened more often.

Fire prevention and suppression in The Netherlands is now mainly focused on limited and relatively short-lived fires in buildings. In contrast, wildfires are more often large-scale and last much longer. A point of attention here is that an increase in (simultaneous) wildfires may also put such increasing pressure on the fire service system that the demand for help in certain places may exceed the availability of firefighting resources.

6.2 Answering the main research question

How is the wildfire risk in The Netherlands developing?

A larger part of The Netherlands will face more wildfires. The wildfire risk manifested itself in The Netherlands mainly in spring, but in the future there will be an increasing (prolonged) risk in summer as well. Wildfires will more often develop into fires that cannot be stopped, but only stop when there is no more fuel. The increase in the number of fires, coupled with further densification of The Netherlands, leads to a high risk of wildfires with a large impact on health, welfare, nature and economy.

The development of wildfire risk is not a linear process. Because the factors of drought, heat and (low) relative humidity reinforce each other, the wildfire risk is increasing faster than climate change.

7 Recommendations and uncertainties

Based on the conclusions, the following recommendations are made that, from the point of view of the current scientific understanding, can contribute to controlling wildfire risk in the future. These recommendations are grouped in three main topics: the wildfire management system, landscape design and developing more knowledge.

7.1 Wildfires must become a structural part of the system surrounding fire safety

While wildfires will always occur and The Netherlands will have to learn to live with them, it is important to keep wildfires manageable and minimise their impact. However, if current climatic, demographic and geographical trends continue without intervention, the wildfire risk will continue to increase. This reinforces the need to intervene and means that The Netherlands will have to learn to look differently at the relationship between fire, nature and the landscape.

To mitigate the impact of wildfires and reduce hazards, it is necessary for wildfire prevention and suppression to become a structural part of the fire service system, which until now has mainly focused on preventing, limiting and fighting (limited) fires in buildings. Other firefighting tasks such as technical assistance, water accidents and also wildfire fighting are in fact a 'by-product' of the system. However, this means that the system currently deployed to control wildfires is not actually designed to do so. Think of things like turnout times, prevention policies, training and (personal) equipment. This means that concessions are now being made in everything - training, equipment, personal protection - regarding the effectiveness of controlling wildfires. It is therefore recommended that wildfire management is integrated into the broad spectrum of the fire service system - from fire safety legislation and requirements for activities or businesses that will take place in or adjacent to nature reserves to training for firefighters and land managers.

Currently, there is no national action strategy to mitigate the consequences of wildfires. This is partly due to a lack of understanding of the impact of such fires, including their cascading effects, and partly due to the lack of an existing framework. The potential impact of wildfires therefore needs to be better understood by better mapping tangible and intangible damage and cascading effects. With this, a national wildfire action plan can be drawn up for different user functions. This action plan will need to focus on adaptation and mitigation to reduce the impact of wildfires, but also on the response phase, where it should be clear to firefighters which incident to prioritise. This action plan can be based on the system of multi-layer safety, where measures in different layers complement and reinforce each other:

- Layer 1: Measures that try to reduce the susceptibility for the occurrence of wildfires (to a certain level).

- Layer 2: Measures to reduce the impact of a wildfire: landscaping, compartmentalisation, adaptation of vegetation, adapted building in risk areas, drought measures and mowing management.
- Layer 3: Measures to improve incident response and crisis management in a wildfire: new tactics and techniques, training, adaptive strategies.

A prerequisite for this principle is visibility of all actors and stakeholders involved and that this must land in the various government organisations.

7.2 Topography and weather conditions cannot be changed, but landscape design and vegetation can

All current insights suggest that wildfire risk in The Netherlands is dominated by the close relationship between nature, housing, care, recreation and other functions. Controlling wildfire risk should therefore start by including wildfire risk in environmental visions and plans, so that the interrelationship between nature, wildfire risk and other functions in a given area are considered as in early as the landscape design stage. After all, if (vulnerable) functions are less closely intertwined with nature, the wildfire risk decreases.

In those areas where the close relationship of functions cannot or cannot yet be avoided or reduced, to counter the growing problem of wildfires, gains can be made in changing conditions around vegetation. There are a number of possibilities listed below:

- The effects of drought in nature can be mitigated by, for example, rewetting the area where this is possible. This will reduce to a lesser extent the typical spring fires in parched dead vegetation (from the previous season), but will reduce the increasing number of summer fires.
- By applying prescribed burning more regularly and extensively as a measure to reduce the amount of combustible biomass, the intensity during a wildfire will be lower. This is also an opportunity for firefighters, site managers and other users of the area to meet before an incident and can be used for networking, so that during an incident they no longer have to. It also provides an opportunity to learn more about fire in practice and fire behaviour in a controlled environment.
- A cost-benefit analysis is needed per nature area, including potential intangible damage, to see which measures can be taken on both the preventive and repressive side. Customisation is important; no single measure will work for the whole of The Netherlands.
- Education and awareness in the wider societal perspective is needed. All residents and users in or around nature reserves will also need to take their own measures to reduce the flammability of their garden, house, business or activity, and know what to do if a wildfire occurs.

With all these measures, one must constantly bear in mind that nature is a living organism: it is constantly growing and changing. This means that the degree of manageability of the wildfire risk is also constantly changing and that nature is only marginally engineerable.

7.3 More knowledge about wildfires needs to be developed

The calls from governments, fire brigades and land managers for action perspectives lead to a need for more knowledge to provide further and also quantitative interpretation of the development of the wildfire risk. However, more knowledge is a general concept and hence is specified below:

- In fact, very little is still known about most wildfires taking place now. Only a very limited amount of wildfires in The Netherlands is investigated. In order to gain insight into the actual (current) situation, information on wildfires in The Netherlands should be systematically recorded and analysed, paying attention to the following issues, among others:
  - The exact location and origin of the fire, burnt area, vegetation and meteorological conditions. Knowledge of these not only strengthens our knowledge of wildfires in The Netherlands, but also helps to better estimate CO2 emissions from wildfires in Europe.
  - The applied methods used to fight the fire and the reason why a wildfire did not eventually spread further. Was this due to different vegetation, different management measures, pure luck or the firefighters' deployment?
  - If an unexpected event or (near-)accident has occurred at a wildfire, for example if firefighting equipment was burned or people had to flee, this should be linked to the data around wildfires. In this way it is possible to get a better picture of the (run-up to) risky situations in wildfires.
- The development of the climate and nitrogen deposition lead to a change in vegetation types, but the exact impact of these influences is still unknown. However, in order to understand the wildfire scenario of the future, more clarity about the (desirable) vegetation present then is necessary.
- To help forecast periods of increased wildfire risk, research into patterns is needed by, for example, systematically looking at common air pressure distributions on days with many and/or large wildfires. A focus here is also research into the conditions that can cause extreme fire behaviour, including convective fires that can create their own weather.
- In order to better understand the future impact of wildfires, it is necessary to understand their recurrence times and duration and cascading effects.
- Further analysis is needed into the consistency of developments of nature areas, buildings and other functions placed or accommodated in or adjacent to nature reserves.
- Research is needed into alternative tactics and techniques to control wildfires, both from a risk management and incident response perspective. This includes both individual tactics and techniques and the coherence of tactics and techniques within the overall system of wildfire management. This also requires a better picture of future fire behaviour.

7.4 Uncertainties

Several aspects of this report require further discussion. First, the future climate is uncertain to some extent. Although all scenarios (KNMI, 2014) paint a similar picture with warmer and drier weather, they differ in how strong these changes are. This also leads to uncertainty regarding the speed and extent to which wildfire risk in The Netherlands increases.

In addition, it was indicated earlier in this report that future changes in vegetation are difficult to concretise, partly due to their complexity. The uncertainty in future vegetation can have a major impact on wildfire risk, and thus the amount and composition of vegetation is also one of the starting points for managing wildfire risk. While a number of possible changes in vegetation have been indicated and some of these may provide more flammable conditions, the actual development is also very much dependent on land management. Hence, there are also gains to be made with vegetation adaptation and management. However: without vegetation adaptation and perpetuation of measures through management, all scenarios show a deterioration of the wildfire risk.

In addition, throughout the report, most of the factors discussed and conclusions were approached from a qualitative point of view. Although some inputs were quantitative, for now it has not been possible to express the changes in wildfire susceptibility and risk quantitatively. Ultimately, all inputs were used to get the best possible qualitative picture of changes around wildfires.

Finally, most information used in this report are about averages , especially when related to climate change. However, actual weather shows outliers and it is precisely these outliers, for example in extreme heat and drought, that are important for wildfires. How extreme these outliers are, on the other hand, is still uncertain.

As more is known about climate change, more - possibly also quantitatively - can be said about the development of wildfire risk on the basis of this progressive understanding. The publication of the KNMI'23 Climate Scenarios should therefore be reason to re-examine the development of wildfire risk.

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Annex 1 Tables current and future climate

Table B1.1 Overview of old and new climate normals according to the KNMI Climate Signal '21 (2021b)

Season	Variable	Climate 1961-1990	Climate 1991-2020
Year	**Average temperature**	9,4 °C	10,5 °C *(+1,1 °C)*
	Average number of summer-like days per year	19 days	28 days *(+9)*
	Average number of tropical-like days per year	2,4 days	5,0 days *(+2,6)*
	Average amount of solar radiation	364 kJ/cm²	379 kJ/cm² *(+4,1 %)*
	Average amount of precipitation	780 mm	851 mm *(+9,1 %)*
	Average relative humidity	82,7 %	81,8 % *(-0,9 %)*
	Average wind speed	5,2 m/s	5,0 m/s *(-3,8 %)*
Spring			
	Average temperature	8,4 °C	9,9 °C *(+1,5 °C)*
	Average amount of solar radiation	120 kJ/cm²	128 kJ/cm² *(+6,7 %)*
	Average amount of precipitation	163 mm	153 mm *(-6,1 %)*
	Precipitation deficit at the end of spring	53 mm	65 mm *(+22,6 %)*
Summer			
	Average temperature	16,2 ºC	17,5 ºC *(+1,3 ºC)*
	Average amount of solar radiation	156 kJ/cm²	164 kJ/cm² *(+5,1 %)*
	Average amount of precipitation	207 mm	235 mm *(+13,5 %)*
	Maximum precipitation deficit during the growing season (average)	143 mm	160 mm (+11,9 %)
	Maximum precipitation deficit during the growing season (average); 5% driest years	228 mm	247 mm (+8,3 %)

Table B1.2 A selection of key figures from the KNMI'14 climate scenarios (KNMI, 2014)

Season	Variable	Climate 1981-2010 (reference period)	Change for the climate around 2050 per scenario			
			GL	GH	WL	WH
Year	Average temperature	9,4 ºC	+1,0 ºC	+1,4 ºC	+2,0 ºC	+2,3 ºC
	Average amount of solar radiation	354 kJ/cm^2	+0,6 %	+1,6 %	-0,8 %	+1,2 %
	Average amount of precipitation	851 mm	+4 %	+2,5 %	+5,5 %	+5 %
Spring						
	Average temperature	9,5 ºC	+0,9 ºC	+1,1 ºC	+1,8 ºC	+2,1 ºC
	Average amount of precipitation	173 mm	+4,5 %	+2,3 %	+11 %	+9 %
Summer						
	Average temperature	17,0 ºC	+1,0 ºC	+1,4 ºC	+1,7 ºC	+2,3 ºC
	Average amount of solar radiation	153 kJ/cm^2	+2,1 %	+5 %	+1,0 %	+6,5 %
	Relative humidity	77 %	-0,6 %	-2,0 %	+0,1 %	-2,5 %
	Average amount of precipitation	224 mm	+1,2 %	-8 %	+1,4 %	-13 %
	Number of wet days (0,1 mm or more)	43 dagen	+0,5 %	-5,5 %	+0,7 %	-10 %
	Maximum precipitation deficit during the growing season (average)	144 mm	+4,5 %	+20 %	+0,7 %	+30 %

Annex 2 Background information of the authors

ir. Brian Verhoeven (NIPV):
Brian Verhoeven is a junior researcher at NIPV's department ‘Brandweerzorg’. He completed the MSc Earth & Environment at Wageningen University, specialising in the interaction between meteorology and wildfires. After his studies, he spent a period in Catalonia, where he exchanged knowledge and gained experience in wildfire management and analysis with wildfire specialists.

dr. Margreet van Marle (Deltares):
Margreet van Marle works at Deltares as a researcher on wildfires and climate risks. Her expertise includes wildfires, deforestation, climate change and multi-hazard risk analyses. She obtained a PhD with a focus on wildfires, (tropical) deforestation and fire dynamics worldwide. She developed a global dataset of emissions from wildfires. Her work has been used as input to the climate models in IPCC AR6. She currently has a strong interest in the impact of natural disasters on outages of vital systems and to develop long-term strategies for this.

drs. Hans Hazebroek MCPm (NIPV):
Hans Hazebroek is senior researcher and project leader at the NIPV's department ‘Brandweerzorg’. He coordinates research on wildfire management and command and control within the department. Besides various substantive research projects, including on fire and smoke development, Hans has acted as project leader of the ‘toekomstverkenning brandweer’ (EN: future exploration of the fire service) and has been involved in the evaluation of the Safety Regions Act. In addition to his position as senior researcher, Hans also acts as chief officer on duty (Dutch: ‘Hoofdofficier van Dienst’) at the Gelderland-Midden fire brigade and is available nationwide as wildfire advisor.

dr. ir. Cathelijne Stoof (WUR):
Cathelijne stoof is specialized in pyrogeography - the interdisciplinary study of the distribution and functioning of wildland fire. Dr. Stoof is the national delegate of The Netherlands to the EU Expert Group of Forest Fires, and served on the board of the International Association of Wildland Fire. She is the creator and leader of Innovative Training Network PyroLife, that trains 15 PhD candidates to become the our new generation of integrated fire management experts. PyroLife fosters knowledge transfer from Southern Europe to the temperate regions of Europe, and from cross-risk approaches including water management to fire. It thereby combines how the North solves community problems with fire knowledge from the European South, with a strong focus on diversity in terms of interdisciplinarity, science-practice links, geography and gender. Dr. Stoof works at Wageningen University, where she combines research, teaching, and science communication. She also led a study on the relationship between land management and fire safety in the Deurnese Peel wildfire.

dr. ir. Peter Siegmund (KNMI):
Peter Siegmund is a physicist and has over 35 years of experience as a climate researcher at the KNMI. His main interest is climate and climate change as observed in recent decades, worldwide and in The Netherlands.

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Nienke Brouwer is project leader and researcher at the NIPV's department 'Brandweerzorg'. Her research interests include wildfire spread, validation of fuel models and vegetation maps, and early recognition of wildfire risk. Nienke completed the Forest and Nature Management degree at Van Hall Larenstein University of Applied Sciences.

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Sander Veraverbeke is associate professor in Climate and Ecosystem Change at VU University Amsterdam. Sander researches the relationship between climate change and wildfires in boreal and arctic regions. He also has a strong interest in the role of fire in ecosystems and society and has previously researched wildfires in The Netherlands, Belgium, Greece, Russia, Canada and the United States.

dr. Linde Egberts (VU):
Linde Egberts works as an Assistant Professor in the interdisciplinary field of heritage studies. She was trained as a social geographer and cultural historian at Utrecht University and Vrije Universiteit Amsterdam, where she defended her PhD thesis 'Chosen Legacies' in 2015. Her research interests lie in critical historical approaches to landscapes, spatial planning, climate change and resilience. Linde Egberts is the research strategy advisor for the research institute CLUE+, where she co-leads the research programme 'Inclusive Landscape Transformations'. She combines her research efforts with coordinating the master's programme in heritage studies, teaching and supervising PhD and master's students.

drs. Rob Sluijter (KNMI):
Rob Sluijter has worked at KNMI as a climatologist for 22 years. Since 2020, he is active as programme manager of the Early Warning Centre at KNMI.