Key opportunities for KNMI to enhance its role in wildfire risk management in the Netherlands

Exploring insights from stakeholders and literature review

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Abstract
Wildfire occurrence and intensity are increasing globally as a result of climate change. This trend is also observed in the Netherlands and wildfire risks and impacts are projected to worsen in the near future. It is evident that current wildfire strategies are not sustainable with the increasing risks, resulting in a call for a transition in wildfire management in the Netherlands. This research explores the current role and responsibilities of KNMI in the organizational landscape of wildfire management and aims to identify wildfire-related research and development opportunities. Literature reviews were conducted and nine sessions with stakeholders were organized to examine current and future wildfire risks and impacts, and to get an overview of relevant parties and national collaborations and developments on the topic of wildfires. Results show that despite KNMI's legal responsibility to warn and protect Dutch society from weather-related dangers, KNMI currently has no official warning duties or other services for wildfires. Regarding the institute's expertise in weather- and climate-related research and developing data-driven technologies, stakeholders perceive KNMI as a potential valuable contributor to wildfire research and developments. This research concludes that KNMI can enhance its role by further stimulating the development of products like wildfire quantitative impact-forecasts and tailored fire weather hazard maps for the Netherlands, working towards operationalization of services in close collaboration with stakeholders like NIPV, and consequently stimulating the shift from reactive to proactive wildfire management in the Netherlands.

Disclaimer
The goal of this report is not to create a complete overview of topics regarding the wildfire theme - the matter is so complex and dynamic that it would be nearly impossible to achieve that. Rather than that, the overviews and knowledge presented in the report can be seen as building blocks: the aim of constructing them was to organize the broad knowledge on wildfires that I gathered throughout my internship and communicate it in a clear and structured way. This will hopefully aid anyone who is interested in contributing to the theme of wildfires in the Netherlands in providing a solid background or base, upon which they can continue to build their own work.

List of abbreviations

Institutes, ministries and organizations	
ANV	Analistennetwerk Nationale Veiligheid (*Analystnetwork Public Safety*)
CBS	Centraal Bureau voor de Statistiek (*Central Office for Statistics*)
EFFIS	European Forest Fire Information System
EGFF	EU Expert Group of Forest Fires
GGD	Gemeentelijke Gezondheidsdienst (*Public Health Service*)
GHOR	Geneeskundige Hulpverleningsorganisatie in de Regio (*Medical Emergency-response Organization in the Region*)
KNMI	Koninklijk Nederlands Meteorologisch Instituut (*Royal Netherlands Meteorological Institute*)
KCR2	Knooppunt Coördinatie Regio's-Rijk (*Focal point Coordination Region-Nation*)
LOCC	Landelijke Organisatie Crisis Coördinatie (*National Organisation Crisis Coordination*)
Min. I&W	Ministerie van Infrastructuur en Waterstaat (*Ministry for Infrastructure and Water Management*)
Min. J&V	Ministerie van Justie en Veiligheid (*Ministry of Justice and Security*)
Min. LVVN	Ministerie van Landbouw, Visserij, Voedselzekerheid en Natuur (*Ministry of Agriculture, Fishery, Food security and Nature*)
Min. VWS	Ministerie van Volksgezondheid, Welzijn en Sport (*Ministry of Health, Welfare and Sport*)
NIPV	Nederlands Instituut Publieke Veiligheid (*Netherlands Institute for Public Safety*)
OM	Openbaar Ministerie (*Public Prosecution Service*)
VBNE	Vereniging van Bos- en Natuureigenaren (*Association of Forest- and Nature owners*)
VIK*	Veiligheidsinformatieknooppunt (*Safety information focal point*)
VNOG	Veiligheidsregio Noord- en Oost Gelderland (*Safety region North- and East Gelderland*)
VR	Veiligheidsregio (*Safety region*)
VRU	Veiligheidsregio Utrecht (*Safety region Utrecht*)
WUR	Wageningen University & Research
Other	
EWC	Early Warning Centre
FWI	Fire Weather Index/Indices
GRIP	Gecoördineerde Regionale Incidentbestrijdingsprocedure (*Coordinated Regional Incident Management Procedure*)
IbF (IbW)	Impact-based Forecasting (/Warning)
NBVM	Natuurbrandverspreidinigsmodel van NIPV (NIPV's wildfire propagation model)
QIF	Quantitative Impact Forecasting

*also referred to as VIC or VICC

1. Introduction

Over the past decades, extreme wildfires have been occurring more frequently and with higher fire intensities. This is a global trend, but also in the Netherlands and other temperate regions in Europe, more and increasingly impactful wildfires are occurring, and this is projected to continue in the near and further future (Cunningham et al., 2024; El Garroussi et al., 2024; Stoof et al., 2024). Significant wildfires can have large ecological, economic and social consequences globally. These include biomass loss, mortality, carbon emissions, mental and physical health issues and damages of vital infrastructures and built environment (Cunningham et al., 2024; EEA, 2024). Some striking examples from recent events illustrate the impacts that wildfires can have: the 2023 wildfire season in Canada burned approximately 15 Mha and resulted in several fatalities, the evacuation of more than 200 communities and the destruction of many homes and vital infrastructure (Jain et al., 2024); the very recent wildfire events in Los Angeles of January 2025 caused 29 reported fatalities so far as well as the destruction of thousands of structures and evacuation orders for thousands of residents. For both examples, the recovery period will likely last years to even decades, with the focus on rebuilding structures and communities, as well as recovering from social impacts like emotional traumas (Gimello-Mesplomb, 2025). In the Netherlands, wildfire events have already resulted in tens of fatalities over the past centuries, as well as large areas of burnt land, material damages adding up to millions of euros, and other negative consequences related to traffic and health (ANV, 2022; Stoof et al., 2024). The ANV (2022) lists additional potential risks from wildfires such as mental health issues, disruption of daily life, chaos and panic during evacuations and it mentions the vulnerability of elements at risk like main roads, internet distribution networks, prisons, camping sites, hospitals and other healthcare centres.

1.1 Increasing urgency

Dutch experts are warning about the increasing risks related to wildfires. In a report on climate-related threats in the Netherlands, the ANV (2022) appointed a disastrous wildfire event as threat with the highest level of probability. The chances of a lethal wildfire happening before the year 2028 are 'very likely' (Stoof et al., 2024; RTV Utrecht, 2024). Especially events from the recent wildfire seasons of 2018 and 2022 have induced an increased feeling of urgency in the Netherlands. In 2018, a total of 949 wildfires were reported, of which 428 took place in the month of July alone. In 2020 the Netherlands experienced 724 wildfires in total, with the month April standing out as there were five days in a row with a high number of wildfires (94 in total). Two of these fires lasted for multiple days and burned almost 1000 ha together (Deurnese Peel and De Meinweg) (Stoof et al., 2024). Particularly when wildfires happen synchronously, it puts fire control capabilities and resources under enormous pressure, and the 2018 and 2020 wildfire events were demonstrative of that. This raises questions on whether the Dutch emergency services are currently prepared for potentially even more disastrous future wildfire events. The situation in the Netherlands is unique: the high population density results in a large interface between natural and urban areas, and vulnerable assets like prisons, campsites and nursing homes are often located in forestry areas (ANV, 2022). Therefore, if evacuations are required, vulnerable communities are likely affected. More and increasingly intense wildfires enhance the chances of evacuations being necessary, which requires improving mitigation strategies like evacuation planning.

Also on European level, increased wildfire risks are stressed; in January 2024, the first European Climate Risk Assessment (EUCRA) was published by the European Environment Agency. This is a broad assessment covering all climate-related risks and how those impact facets like health, ecosystems and food security. In the report, wildfire impacts on health and ecosystems are mentioned and the report states that readiness is medium, and stronger policy action and/or implementation are urgently needed to reduce risks (EEA, 2024).

1.2 The role of climate change

Climate change is considered the major driver behind the observed rising trends in wildfire intensity and frequency. Weather patterns are changing globally; extreme weather events are occurring more frequently and with higher intensities, resulting in higher occurrences and severity of natural hazards like wildfires (Boult et al., 2022; EEA, 2024). In the Netherlands, an increased number of days with extreme weather are expected. In all four climate scenarios described by the KNMI (2023), extreme heat and longer dry periods as well as increased precipitation in winters are projected. Heat and drought play a crucial role in ignition and spread of wildfires. Concurrently, the abundance of moisture in the cold season will result in more vegetation growth in the following spring, more biomass or fuel to be available for burning. This phenomenon of rapidly alternating extremely wet and dry periods is also referred to as “weather whiplash” and was also seen as one of the major drivers of the recent disastrous wildfire events in Los Angeles (January 2025) (Fig. 1) (Francis et al., 2023). Climate change will thus induce increased frequency of wildfire occurrence in the future, as well as an increased risk of uncontrollable wildfires in the Netherlands (ANV, 2022; Verhoeven et al., 2023).

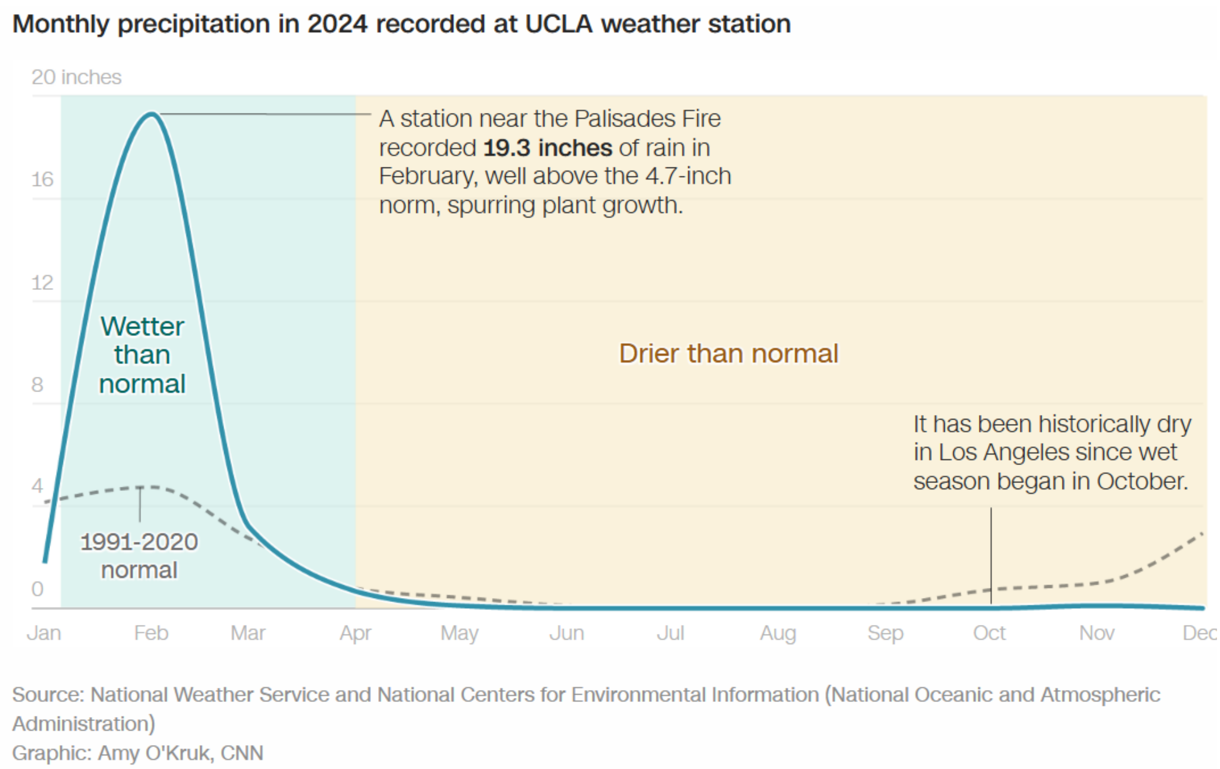

Figure 1: Weather whiplash in Los Angeles in 2024, illustrated by the monthly precipitation records from the UCLA weather station (Gilbert and Fritz, 2025)

Figure 2 shows wildfire sensitivity maps of the Netherlands, illustrating high sensitivity in natural areas: the North Sea coastal dunes, the Utrechtse Heuvelrug, the Veluwe and large areas of the provinces Noord-Brabant and Limburg all are regions with medium to high sensitivity to wildfires. The figure also highlights a projected increase in sensitivity in the year 2050; Van Marle and Agricola (2021) describe an increase from 39% to 63% of moderate and high sensitive areas, and a 5% to 9% increase in high sensitive areas.

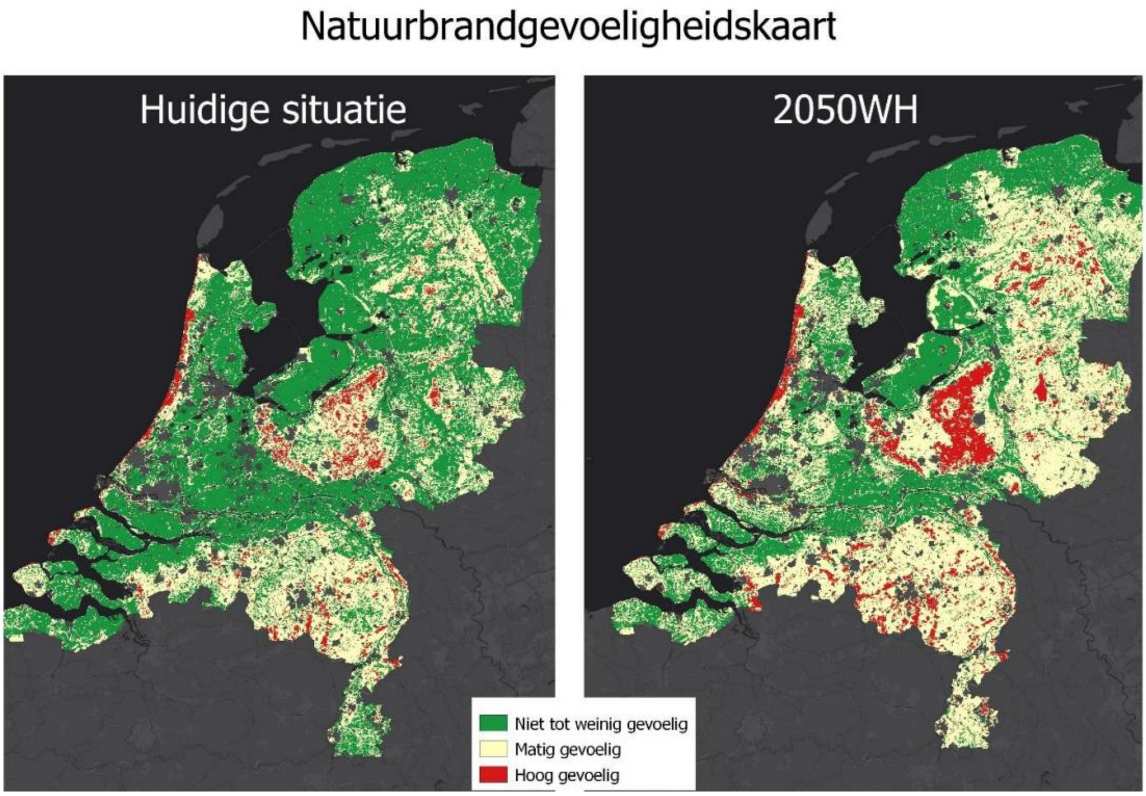

Figure 2: Wildfire sensitivity maps of the Netherlands of the current situation (left, 2021) and the projected situation (right, 2050) as computed by Deltares (Van Marle and Agricola, 2021)

1.3 Responsibility KNMI

KNMI is by law responsible for protecting and warning the Dutch citizens against '*society-disrupting weather of such an intensity that a high impact on safety in society is expected'* (Staatscourant 2021, 2021). This means that KNMI issues warnings (through colour codes) for society-disrupting weather such as extreme rainfall and expected floodings, heat or prolonged dry conditions with extreme imminent water shortages. Additionally, KNMI aims to increasingly act as an Early Warning Centre in partnership with stakeholders, issuing adequate and effective warnings for the Netherlands with the purpose to limit damage and victims of weather conditions and climate change. Wildfires is mentioned in the Ambitions 2035 report as one of the upcoming risks that deserves extra attention (KNMI, 2024). Wildfires have the potential to largely disrupt communities and cause chaos, trauma, health effects, and many more impacts (Verhoeven et al., 2023). This illustrates that the effects on society that dangerous wildfire weather can have, are comparable to those of hazards like floodings or storms that KNMI is already issuing warnings for. Currently, the national organizational landscape around wildfire management is developing rapidly, generating a perfect timing for KNMI to get involved and explore research and warning opportunities regarding wildfires.

1.4 Research gaps and objectives

1.4.1 Research gaps

Climate change is inducing a change in wildfire regime in the Netherlands. As a result, the urgency to radically change the way the wildfire theme is managed is increasingly felt by the fire services and many other parties dealing with wildfires. Despite the extensive experience that fire brigades have gained over the years, fire control through suppression does not always suffice anymore, and therefore embracing and developing new strategies is required in order to handle the increasing risks. Stakeholders in the field including KNMI are increasingly working together on the topic, as close collaborations are necessary to better coordinate wildfire management. Having a clear overview of all parties involved is crucial in understanding where opportunities lay for new research to support wildfire management. In literature, the complexity of the organizational landscape in the Netherlands of wildfire management has not yet been structurally mapped out, and KNMI's role in wildfire management has not been described into detail.

1.4.2 Research objectives and questions

From these research gaps, the following three research objectives and associated questions are formulated:

- **Objective 1:** to assess current and projected wildfire risk and impacts in the Netherlands
  - *Question 1.1: What key factors drive wildfire risk in the Netherlands?*
  - *Question 1.2: What considerations need to be made when defining and assessing wildfire impact in the Netherlands?*
  - *Question 1.3: How are wildfire risk and impact projected to evolve with climate change?*
- **Objective 2:** to map the organizational landscape of wildfire management in the Netherlands and identify key stakeholders
  - *Question 2.1: Which organizations play a role in wildfire management and the safety chain in the Netherlands, and what responsibilities do they have?*
  - *Question 2.2: What collaborations exist between stakeholders in wildfire management, and where do gaps or challenges in coordination appear?*
- **Objective 3:** to evaluate KNMI's current role and responsibilities and potential future opportunities in wildfire risk management
  - *Question 3.1: Where does KNMI currently stand in the organizational landscape?*
  - *Question 3.2: What are the key challenges and requirements regarding wildfire management in the Netherlands according to stakeholders?*
  - *Question 3.3: How do stakeholders perceive KNMI's role and responsibilities?*
  - *Question 3.4: What concrete recommendations emerge from stakeholders' insights regarding wildfire research opportunities?*

Ultimately, this report addresses the main research question: *"How can KNMI enhance its role in wildfire risk management in the Netherlands, considering stakeholder insights and its position in the organizational wildfire landscape?"*

1.5 Report structure

Following this introduction, the report is structured as follows:

- **Section 2: scientific and historical context.** This section elaborates on the scientific and historic background regarding wildfire management in the Netherlands. Wildfire terminology, risk factors and monitoring history are described, as well as fire weather indices, impact-based forecasting and the general structure of the safety chain in the Netherlands.
- **Section 3: methods and materials.** This section describes the qualitative approach that was used to carry out this research.
- **Section 4: key findings.** This section introduces and describes the main themes identified from the qualitative data gathered during the research highlighting various perspectives of experts from stakeholders. Several visual overviews are presented illustrating these findings.
- **Section 5: discussions and conclusion.** This section discusses the main themes by placing them into a broader context, connecting the stakeholder insights to the responsibilities and competencies of KNMI and describing the emerging recommendations.
- **Section 6: other activities.** This section provides concise summaries of the various other internship activities that took place but have not been incorporated into the rest of the report.

2. Background

2.1 Terminology

A quick word on the terminology of wildfires ('natuurbranden') in literature and reports: in the end of the last century, the term 'forest fire' was commonly used, but the use of the term 'wildfire' has become more popular. The terms 'landscape fire', 'vegetation fire' and 'natural fire' are also used but are less common. A wildfire is defined by the Dutch Rijksoverheid as "fires that occur in natural areas and/or agricultural areas and burn in natural vegetation." (ANV, 2022).

2.2 Factors in wildfire risk

The risks that wildfires pose is a combination of the risk of *wildfire occurrence* and the risk of wildfire spreading or *wildfire propagation*. These two risks are in turn dependent on a wide variety of factors. Wildfire occurrence depends on the availability of biomass, several meteorological factors (i.e. temperature, relative humidity, precipitation deficit) and ignition sources (NIPV, 2023). In the Netherlands, the ignition rarely has a natural source; wildfires are predominantly ignited by humans, either deliberately or unintentionally (Stoof et al., 2024). Wildfire propagation is influenced by fire intensity, spreading rate and –direction, and fire duration. These aspects are largely influenced by vegetation type, amount and state, as well as wind direction, speed and instability; winds can shift rapidly, complicating control efforts by fire services (UNEP, 2021; Verhoeven et al., 2023). The effectiveness of control efforts, i.e. efficiency of fire control in different attack phases or attack strategies, is another factor that influences wildfire propagation (Brandweer Nederland, 2023; Rapp et al., 2021). This sum up is only a fraction of the story; in reality, there are many more natural and human factors that play a role in wildfire risk. A larger selection of these is summarized in a visual overview presented in section 4.1 of this report (p. 16-18). The abundance of components that play a part in the matter, is demonstrative of the complexity of wildfire management.

2.3 Wildfire monitoring

Collection of data and statistics on wildfires plays a crucial role in assessing these increasing risks and subsequently improving wildfire management. There are two European organizations active in monitoring and managing wildfires in Europe and the Mediterranean regions as part of the EU Copernicus program: EGFF (EU Expert Group of Forest Fires) and EFFIS (European Forest Fire Information System). The organizations were founded in 1998 with the aim to stimulate international collaboration on wildfire risk management. EGFF is a team of experts from more than 40 countries that focuses on monitoring catastrophic wildfire trends and developing adequate European responses together with the EU Member States. The EFFIS collects up to date and reliable wildfire data and news in Europe, and provides fire danger maps, hotspots, burnt area and forecasts up to six days (Lelouvier et al., 2021; Stoof et al., 2024).

The recent history of wildfire monitoring in the Netherlands is depicted on the timeline in Figure 3. Monitoring commenced in 1922 and was executed in a collaborative effort by various land management agencies. It is imaginable that the monitoring was initiated in that year as it succeeded the severely dry year of 1921 (Van der Schrier et al., 2021). As shown on the timeline, systematic data collection was ended in 1994, as a result of a decrease in the occurrence of significant wildfires in the three preceding decades (Stoof et al., 2024). Potentially, the effects of climate change on wildfire occurrence in temperate regions was not showing in those years yet, explaining the reducing numbers and burnt area in wildfire statistics in the Netherlands. European legislation did not restrict the discontinuation of the monitoring in the Netherlands as it was not classified as a country with medium to high wildfire risk. Consequently, the Netherlands did not take part in EFFIS and EGFF when they were founded in 1998. The CBS (Centraal Bureau voor Statistiek) took over the data collecting in 1994 but did not subdivide wildfires from other open-air fires, which caused an apparent rise in recorded fires. Additionally, the CBS did not validate for cases like false alarms or training exercises. This all resulted in a situation where from 2002 onward, barely any fire prevention management or policies were in place in the Netherlands, and this is still the case: there are no national, regional, or local policies currently (Stoof et al., 2024). The Netherlands resumed data collection in 2017 and joined EFFIS and EGFF. Since 2023, this data collection and identification of wildfires in the Netherlands has been automated by filtering and confirming each potential wildfire event, this procedure is described in detail in the NIPV wildfire year-report of 2023 (Tanck et al., 2024). In an analysis within the report it is stated that the new method has likely reduced the number of errors in data collection.

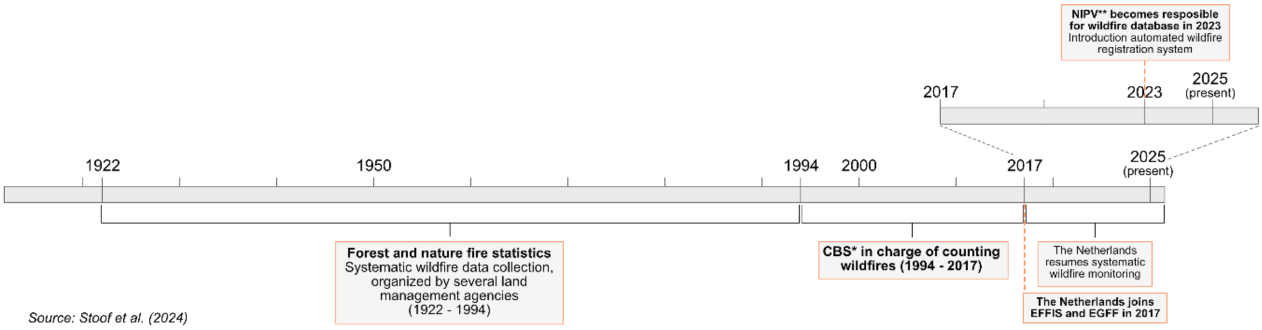

*Figure 3: Timeline showing the history of wildfire monitoring in the Netherlands (after Stoof et al., 2024). * see list of abbreviations (p.3)*

2.4 Fire Weather Index (FWI)

The Fire Weather Index (FWI) is a measure of estimated fire behaviour and intensity, and thus the potential fire danger. FWI is a numeric computation of how favourable the weather conditions are to start a wildfire. The system incorporates several weather features and was designed for Canadian forests with boreal forest fuel beds, but now it is universally used by scientists all over the world as the most accepted index for wildfire behaviour (El Garroussi et al., 2024; Mc Norton et al., 2024; Oom et al., 2022). The daily observations for temperature, relative humidity, wind speed and 24-hour precipitation are input features for calculating six components or codes, and when combined it computes the FWI (Fig. 4). Each of the components are also indications for specific aspects of fire weather or fire behaviour. For example, the FFMC (Fine Fuel Moisture Code) gives an indication of how flammable fine fuels are. The ISI is calculated from wind speed and the FFMC, and it indicates the expected spread rate (without incorporation of fuel types) (Van Wagner and Pickett, 1985). Fire weather indices are used daily by wildfire analysts, firefighters and landscape managers globally to assess the wildfire risk and danger (Oom et al., 2022).

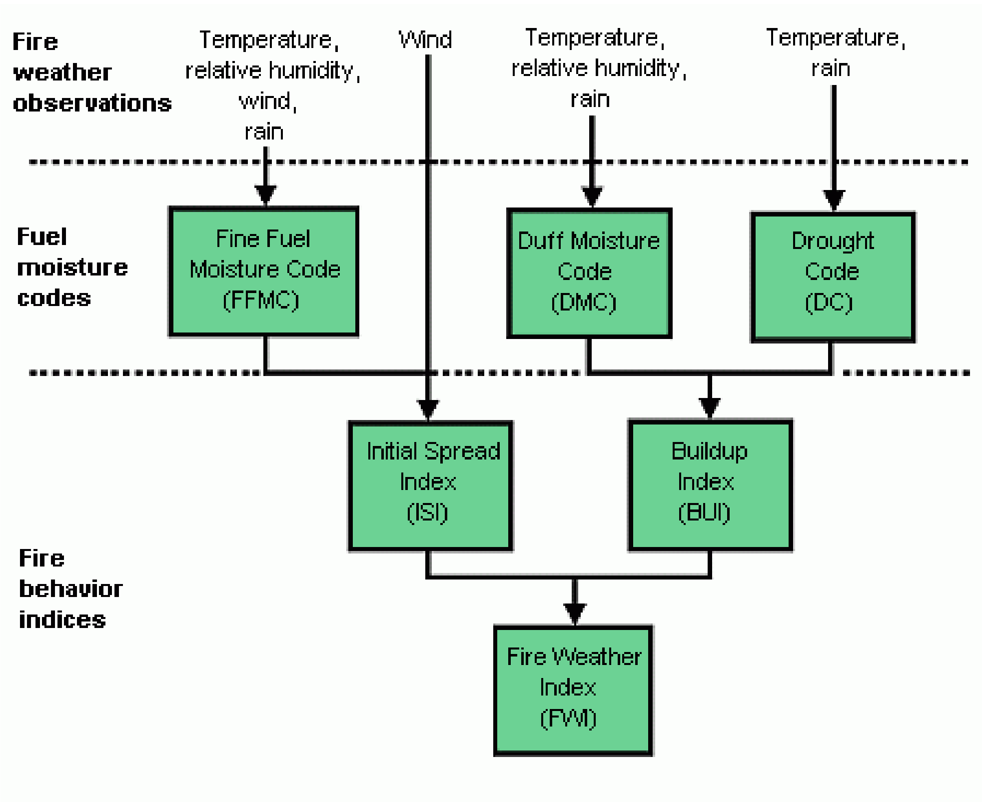

Figure 4: Structure of the Canadian FWI System (Van Wagner and Pickett, 1985)

2.5 Impact-based forecasting (IbF)

With extreme weather changing worldwide, traditional warning systems are not always sufficient anymore. The World Meteorological Organization (WMO) suggests the use of impact-based forecasting (IbF) or impact-based warnings (IbW) as an approach to reduce impacts of extreme weather and natural hazards, providing a first guidance document in 2015 and an update in 2021 due to the rapid advancements in this field. The WMO describes it as a method that can help bridge the gap between science and action and encourage relationships between partners. This type of forecasting communicates "what the weather will do", rather than "what the weather will be", thus providing accessible and actionable information to emergency responders that can help improve decision-making processes and increase the likelihood that protective actions will be taken (Boult et al., 2022; Harrowsmith et al., 2020; Potter et al., 2025). IbF requires local knowledge and expertise to help match the impacts to a hazard (WMO, 2015). The technique is still in its infancy and longer and more sufficient impact-datasets are needed. Additionally, further research and explorations are required before systems that quantitatively forecast any type of dangerous weather impact can become operational (Schroeter et al., 2020; WMO, 2021). Various challenges that come with IbF are described in literature: large amounts of data on hazard, vulnerabilities, exposure and impact are required; difficulties regarding forecast uncertainties in future impacts based on historical data; responsibility gaps in IbF development (Harrowsmith et al., 2020; Robbins et al., 2022; Merz et al., 2020).

2.6 Wildfire impact forecasts in literature

In literature, few efforts have been made in investigating the potential of developing wildfire impact-forecasts. Wildfire impacts are diverse and comprise economic and ecological damage such as infrastructure and biomass loss, societal aspects such as loss of human lives and physical and mental health issues, and pressure on emergency services and fire brigade personnel (Verhoeven et al., 2023; Cunningham et al., 2024; EEA 2024). When creating an impact-model, it is important to make informed decisions on the type of impact you want to forecast and communicate, and how this can be quantified in the model. Relevant literature exists on the development of fire danger indices and wildfire spread models to help inform and support fire managers in decision-making: Jolly et al. (2019) developed a metric for severe fire danger in the United States and describe its potential as a predictor for firefighter fatalities by comparing the index with historical data on firefighter entrapments. They propose the use of this metric within an operational system that can forecast severe wildfire danger as decision-support information. Radke et al. (2019) present FireCast as a new system that combines artificial intelligence (AI) and geographical information systems (GIS) to predict wildfire spread. They introduce it as a low-computational cost system that can support firefighters in their decision-making to reduce wildfire impacts. The system was tested on the Rocky Mountains in the United States, but the authors state it can be implemented on any region worldwide, provided that sufficient and suitable training data is available.

2.7 Structure of the safety chain in the Netherlands

In the Netherlands, national security is organized in a layered way, but due to the high number parties that play a part it can be complex to get an overview of all responsibilities, roles and collaborations. Here follows a concise description of the general structure, organizations and ministries involved in the safety chain and their roles and responsibilities.

First of all, it is important to describe which *ministries* are involved in national security. The Ministry of Infrastructure and Water management (Min. I&W) is responsible for climate resilience of The Netherlands. KNMI and Rijkswaterstaat are the two institutes that fall under this Ministry. KNMI's role is to advise and warn both the nation and crisis partners for weather situations that could have large impacts. The Ministry of Agriculture, Fishery, Food security and Nature (Min. LVVN) is responsible for heat- and drought related issues, including wildfire-control and –prevention. The Ministry of Justice and Security (Min. J&V) is responsible for the safety regions and crisis-control (Ministerie van Algemene Zaken, 2020).

The Netherlands is subdivided into 25 *safety regions* (Fig. 5). The safety regions play an operational and coordinating role in the deployment of emergency services. Their main task is to facilitate smooth cooperation between the municipalities within a region, the fire brigades and the GHOR. A large number of other crisis partners (including the police, the OM, water boards, provinces, GGD, Defence, energy companies, ProRail and Staatsbosbeheer) are also connected. The exact organizational structure can vary per safety region (Ministerie van Onderwijs, Cultuur en Wetenschap, 2021). Each of the safety regions has its own VIK (Veiligheidsinformatieknooppunt, VIC/VICC in some regions); the VIK departments were founded in 2024, and aim to provide up-to-date information about risks, threats and (emergency) events. The VIK deal with 55 themes regarding safety and potential crises, and wildfires is one of the themes that is receiving a lot of attention (Veiligheidsregio Zaanstreek-Waterland, 2023).

KCR2 (Knooppunt Coördinatie Regio's-Rijk) is a newly founded program which acts as a focal point between the national government and the safety regions in order to get a better view on information and security (Crisismanager, 2022). LOCC (Landelijke Organisatie Crisis Coördinatie) is a department of Min. J&V and has been responsible for supporting emergency services and crisis organizations during large-scale, national emergencies. Recently, there have been shifts in this organizational structure around crisis control in the Netherlands, and there is a plan to move LOCC to a new organization in 2026, with the aim to better support the KCR2 ambitions (Ministerie van Algemene Zaken & Ministerie van Justitie en Veiligheid, 2024).

The NIPV (Nederlands Instituut Publieke Veiligheid) is one of the agencies in the field of national security and can be seen as a supporting organization of the 25 safety regions. NIPV's task is to carry out specialisations and research, and to be a coordinating party in wildfire management (Ministerie van Algemene Zaken, 2023). Since 2023, the NIPV has been responsible for the wildfire database, in which wildfires are monitored and classified using a novel procedure (Stoof et al., 2024).

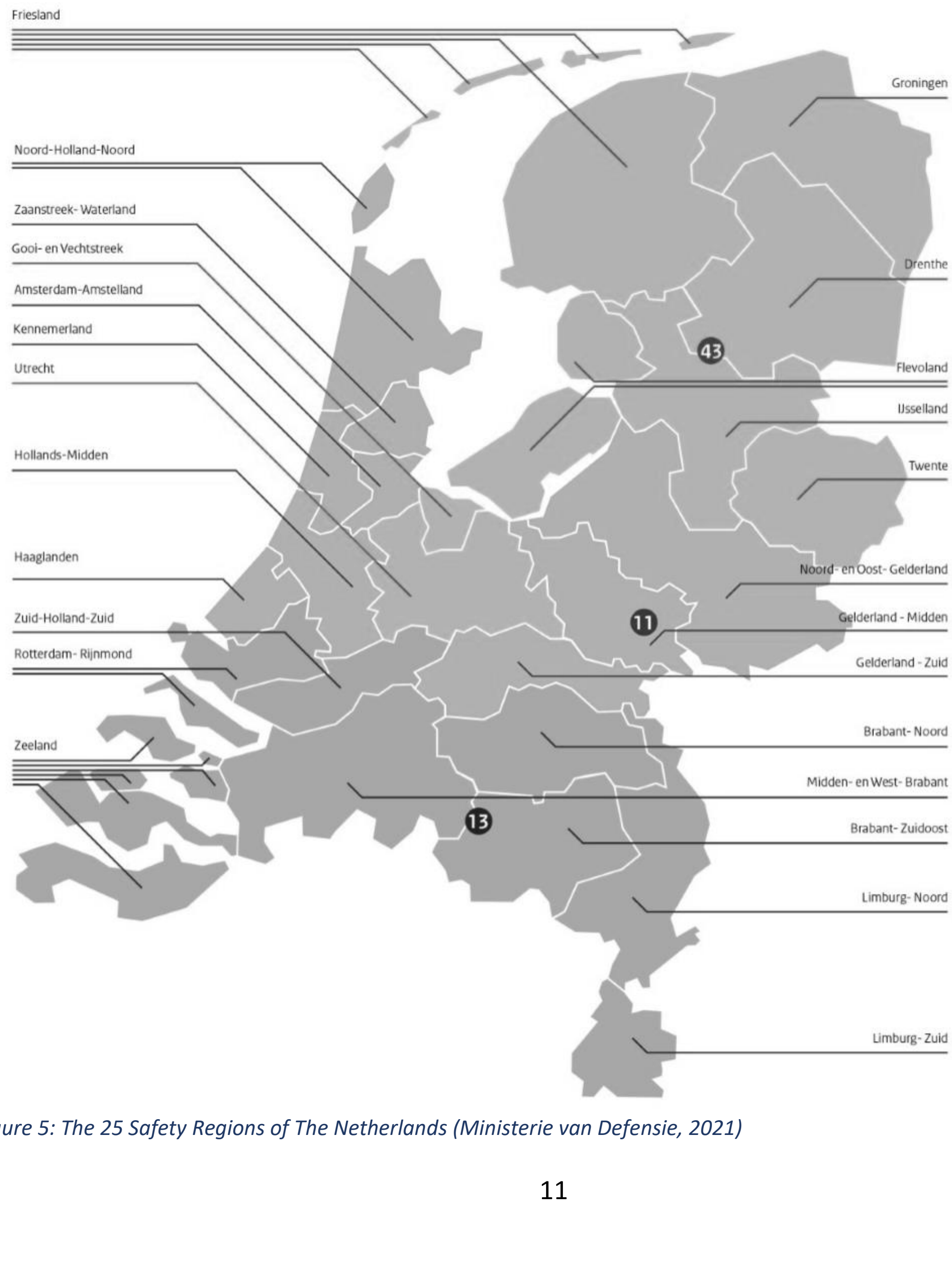

Figure 5: The 25 Safety Regions of The Netherlands (Ministerie van Defensie, 2021)

3. Methodology

To get a clear picture of the research and development opportunities for KNMI in wildfire management with respect to the national organizational landscape around wildfires, literature research was conducted and sessions with stakeholder representatives were held. Additionally, visual overviews were created to help organize and structure the information, combining the explorations from the literature reviews and the sessions analyses. A qualitative approach was chosen because it allows for easier analysis of the research outcomes and better depicting of the complexity of wildfire management and its organizational landscape. The outcomes from literature review and stakeholder sessions provided information to address the research objectives: assessing current and projected wildfire risk and impacts in the Netherlands; mapping the organizational landscape around wildfire management in the Netherlands and identifying key stakeholders; evaluating KNMI's current role and responsibilities and potential future opportunities in wildfire risk management.

3.1 Literature review

Academic literature and grey literature were studied to get an understanding of the wildfire issue in the Netherlands and to gain a better overview of various topics regarding wildfires. The following key words were used in the search for literature: wildfire monitoring, wildfire risk and impact, climate change and increasing risks, fire weather indices, impact forecasting and the safety chain in the Netherlands. Most of the literature used was academic literature on various topics. Due to the fact that the wildfire theme is evolving relatively rapidly, a lot of recently published articles were consulted. Grey literature consisted of i.e. NIPV, Brandweer Nederland reports and master theses carried out at safety regions as well as governmental websites providing information about roles of ministries. From the literature research, summaries were constructed on topics relevant to the research objectives.

3.2 Sessions with stakeholders

Between September 2024 and February 2025, a total of nine sessions were organized with various representatives and specialists from different stakeholders involved in wildfire management. The representatives invited for the sessions came from organizations: VNOG, VRU, NIPV, Staatsbosbeheer, KNMI and WUR. VNOG and VRU are safety regions and have operational experience with wildfires; NIPV also focuses on the operational side but additionally carries out specializations and research on i.e. crisis management; Staatsbosbeheer plays a large role in prevention and awareness; WUR and KNMI contribute from a research perspective. These different parties were chosen mainly because of their diversity in areas of focus and expertise on the topic, allowing for a wide range of insights and perspectives, and more practically, because most of them had previously collaborated on the wildfire topic with KNMI and contacts already existed. The types of sessions consisted of semi-structured interviews, a workshop, a group discussion and a meeting, and each session had a specific aim. Table 1 shows an overview of all sessions, dates and aims in chronological order. The participants were asked for consent and their names have been anonymized in the results.

During the sessions notes were taken and elaborated after each session to form a summary. The summaries act as main data sources for the results section of the report and are attached as supplementary materials. The data gathered from the sessions were analysed thematically and five main themes relevant to the research objectives were identified; wildfire risk and impact, methods used in wildfire risk analysis; wildfire management approaches in the Netherlands; role of KNMI in the wildfire theme; suggestions, requirements and opportunities. Information on the themes from the various sessions was extracted from the session summaries by colour coding, and the extracted information was grouped together in a separate document (Table 2). This document was examined to learn which topics were popular, and to determine similarities and differences between statements and perceptions from the different participants. The outcomes of the thematic analysis are presented in the results section.

Table 1: Overview of the sessions in chronological order.

Date	*Type of session*	*Organization*	*Aim*
23.09.24	Workshop	VNOG	To gain knowledge on the safety region and their expertise in the field of wildfires as well as recent developments
26.09.24	Interview	NIPV	To learn about NIPV's role in the wildfire issue, and introduce new research developments at KNMI
21.10.24	Interview	Staatsbosbeheer	To learn about the role of Staatsbosbeheer in the wildfire issue, and introduce research developments at KNMI
12.12.24	Interview	VRU	To present the set-up of an experimental research to a wildfire specialist and ask for feedback
17.12.24	Discussion	KNMI, VRU, VNOG, NIPV	A discussion arose after a presentation at KNMI on new wildfire research outcomes
07.01.25	Interview	KNMI	To gain insights into different wildfire-related projects at KNMI as well as past and current collaborations with stakeholders
14.01.25	Interview	KNMI	To gain a better overview of the political landscape around wildfires
24.01.25	Meeting	NIPV, KNMI	Present preliminary results of KNMI research and discuss ideas and advancements
04.02.25	Interview	WUR	To update on all ongoing wildfire projects at KNMI and discuss potential future developments and collaborations

Table 2: Thematic analysis of qualitative results from sessions, with colour coding of the main themes identified

Main themes	***Relevant topics***
Defining wildfire risk and impact	- What determines impact? (i.e. fire attack phases, control efforts effectiveness, weather conditions) - What factors are regarded as most important in risk? (i.e. wind, availability of fuel)
Wildfire management approaches in the Netherlands: currently + (future) developments	- Existing collaborations (i.e. weekly wildfire briefing) - Who makes decisions? - How well is meteorology integrated into emergency services/fire brigades? - What are plans and views on the national action centre for wildfires?
Use of fire indices and other methods for wildfire risk analysis	- Every analyst uses their own sources, no uniformity or guidelines - FWI: Canada vs NL; EFFIS shows FWI values that are an underestimation for the Netherlands - M8-index - NIPV wildfire propagation model
KNMI's role in wildfire issue: developments over time + future views/ideas	- Historically, currently, in the future - Expertise climate + weather - Open data and independency - Warning role in society - Future? I.e. role in landelijk actiecentrum natuurbranden?
Suggestions, requirements and opportunities	- Issuing more timely and local warnings - Where QIF could have a role (operationally) - More close collaborations - Further devel - opment suggestions for QIF

4. Results

Five main themes were identified from the information gathered during the semi-structured interviews, workshop and discussion. These themes are the following: 1) wildfire risk and impact; 2) methods used in wildfire risk analysis; 3) wildfire management approaches in the Netherlands; 4) role of KNMI in the wildfire issue; 5) suggestions, requirements and opportunities. The theme of 'suggestions, requirements and opportunities' reoccurred in all the other themes and therefore is not described in a separate section. For each of the themes, different comments and perspectives of the interviewees are discussed.

4.1 Defining wildfire risk and impact

This theme encompasses factors that influence wildfire risk that were mentioned by interviewees, and how wildfire impact can be defined. It was emphasized by various specialists how complex it is to properly define and assess risks and impacts as there are so many factors that play a role, and that it is important to continue to zoom out and keep in mind the bigger picture when doing wildfire research.

Specialists from NIPV explained that wildfire risk is a combination of the risk of ignition (*'ontstekingsrisico'*) and risk of propagation or spread (*'uitbreidingsrisico'*) (Fig. 6a). A common remark in the various interviews was the importance of wind; direction and speed of wind largely control propagation risk, and the fact that this can rapidly shift causes high uncertainty for firefighters (Fig. 6d). Therefore, accurate and up-to-date information about wind is required during operations. Fire officers from VNOG pointed out the relevance of vegetation type and state in fire ignition and propagation risk. A wildfire specialist from VRU indicated that because wildfires usually start on the ground, it is important to know which low vegetation types are present on the ground and thus the first fuel available for burning. Stratification of vegetation layers additionally influences the occurrence and spread of wildfires (Fig. 6e). All interviewees agreed that human activity needs to be taken into account when analysing wildfire risk, as humans are most often the source of ignition in the Netherlands (Fig. 6a&b).

With respect to wildfire impact, additional important insights were gained throughout several interviews. A wildfire specialist from VRU explained the importance of control efforts effectiveness in determining the risks and impact that a wildfire might have (Fig. 6c). He described the concept of initial and extended attack; if the fire is controlled during initial attack, impact on fire brigades often remains low, but if the fire escapes initial attack due to a high propagation risk, the control efforts have to be scaled up to extended attack and the chances of having a high-impact fire are much larger. According to him, this also means that the number of wildfires that happen on a day does not necessarily equal impact, as this number only says something about the risk of ignition and disregards the propagation risk. He emphasizes the importance of including propagation risk in estimating potential impacts. To really include propagation risk, a concrete recommendation given by the VRU specialist is modelling fire perimeter. On the other hand, NIPV specialists described that having a clear view of both the ignition risk and propagation risk will help evaluating what actions need to be taken, especially during periods when extreme wildfire weather is expected (i.e. long dry period, high temperatures, low relative humidity, strong winds). According to them, getting a better idea of which weather conditions could result in a high amount of wildfire ignitions can help anticipate on the potential impact.

Based on the information from the interviews and results from literature research, the visual overviews of factors in wildfire risk are depicted in Figures 6 a-e.

Key lessons

- Wildfire risk and impact are complex to define due to many human-related and natural factors that play a role.
- Wildfire risk is a combination of ignition and propagation risk, and both of these need to be taken into account when making a risk analysis and estimating potential impact.
- Effectiveness of control efforts (i.e. success during initial attack phase) is crucial in determining wildfire impact.

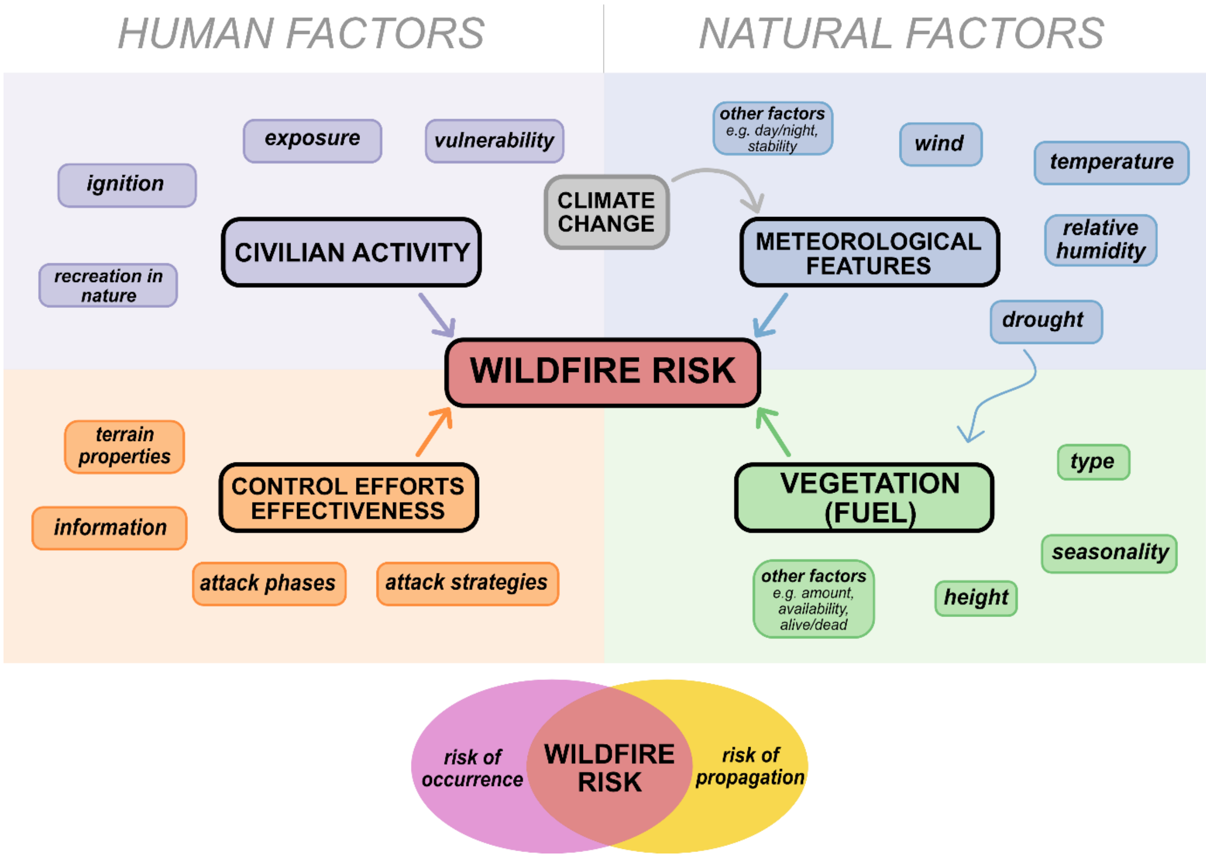

Figure 6a: Main overview of factors influencing wildfire risk

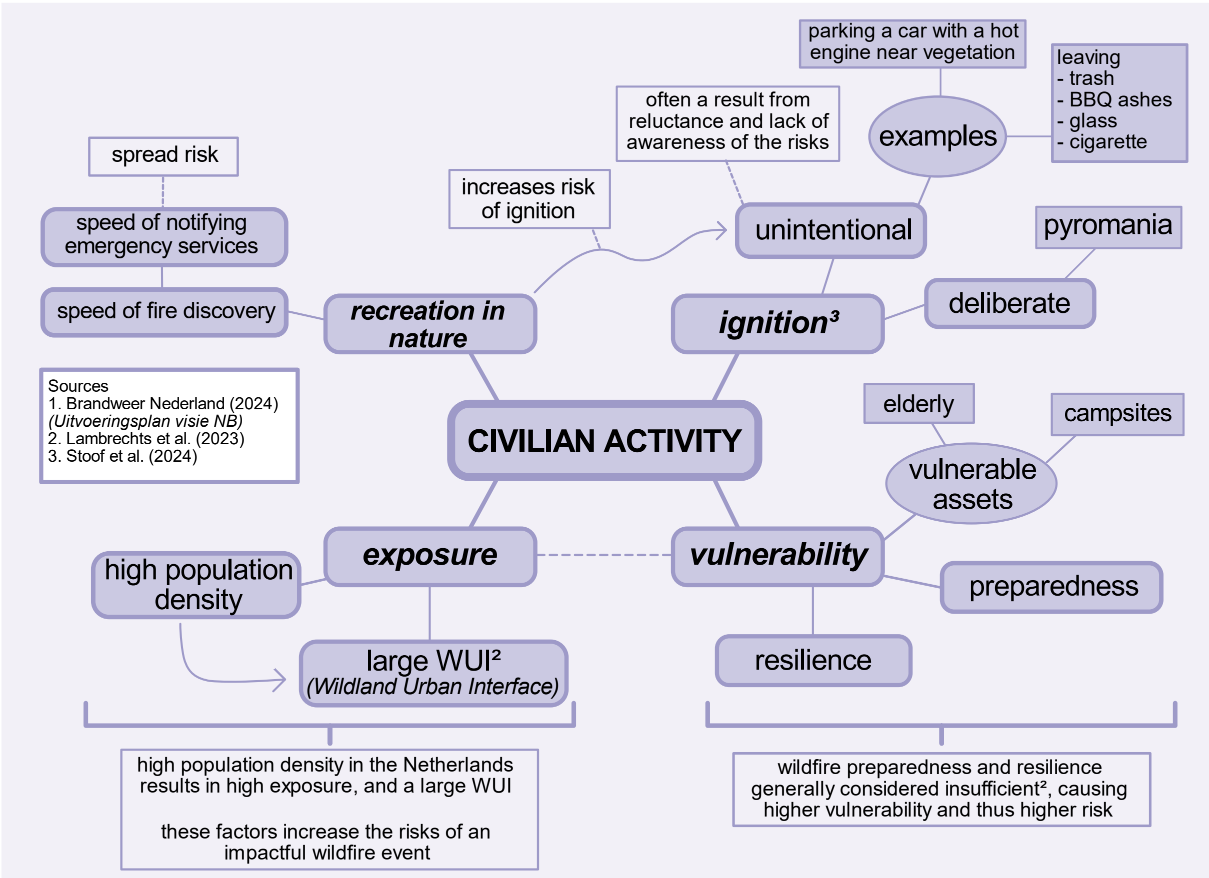

Figure 6b: Overview of factors related to civilian activity influencing wildfire risk

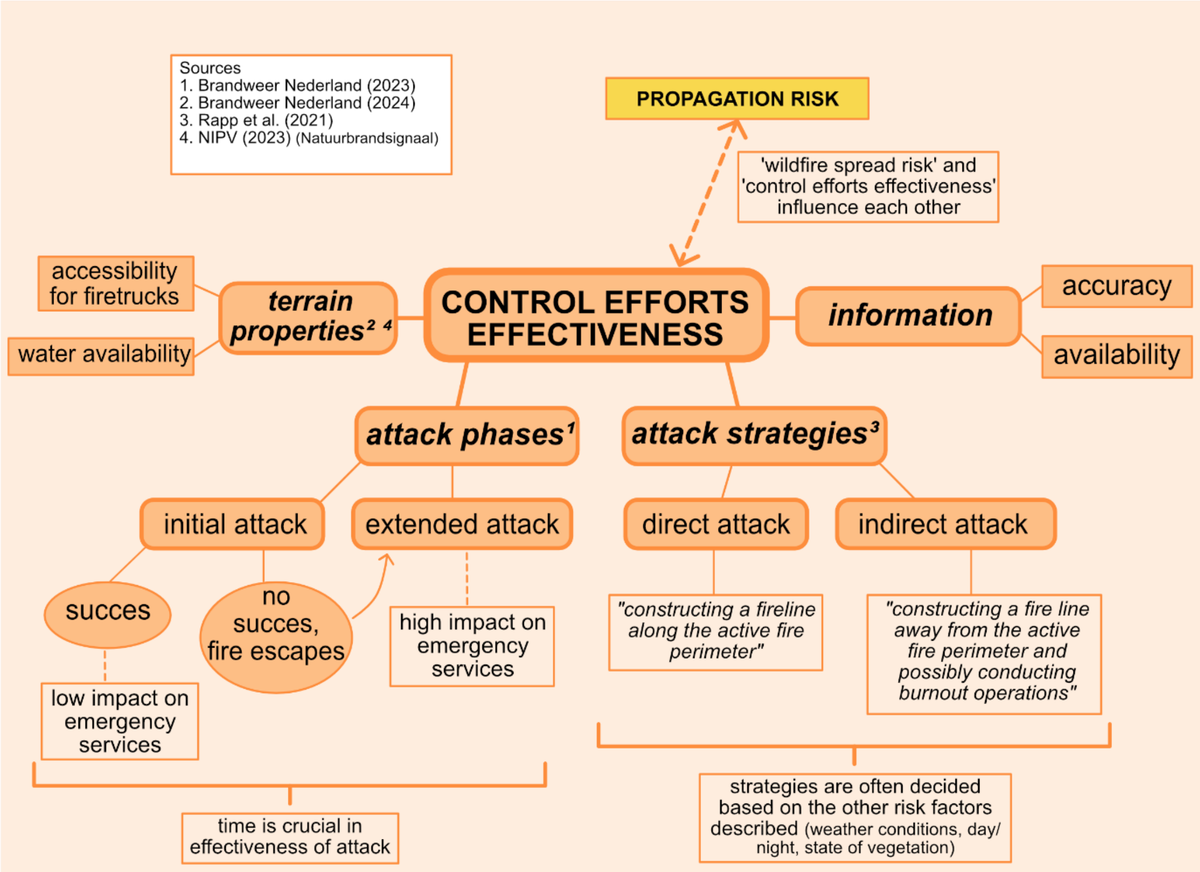

Figure 6c: Overview of factors related to control efforts effectiveness influencing wildfire risk

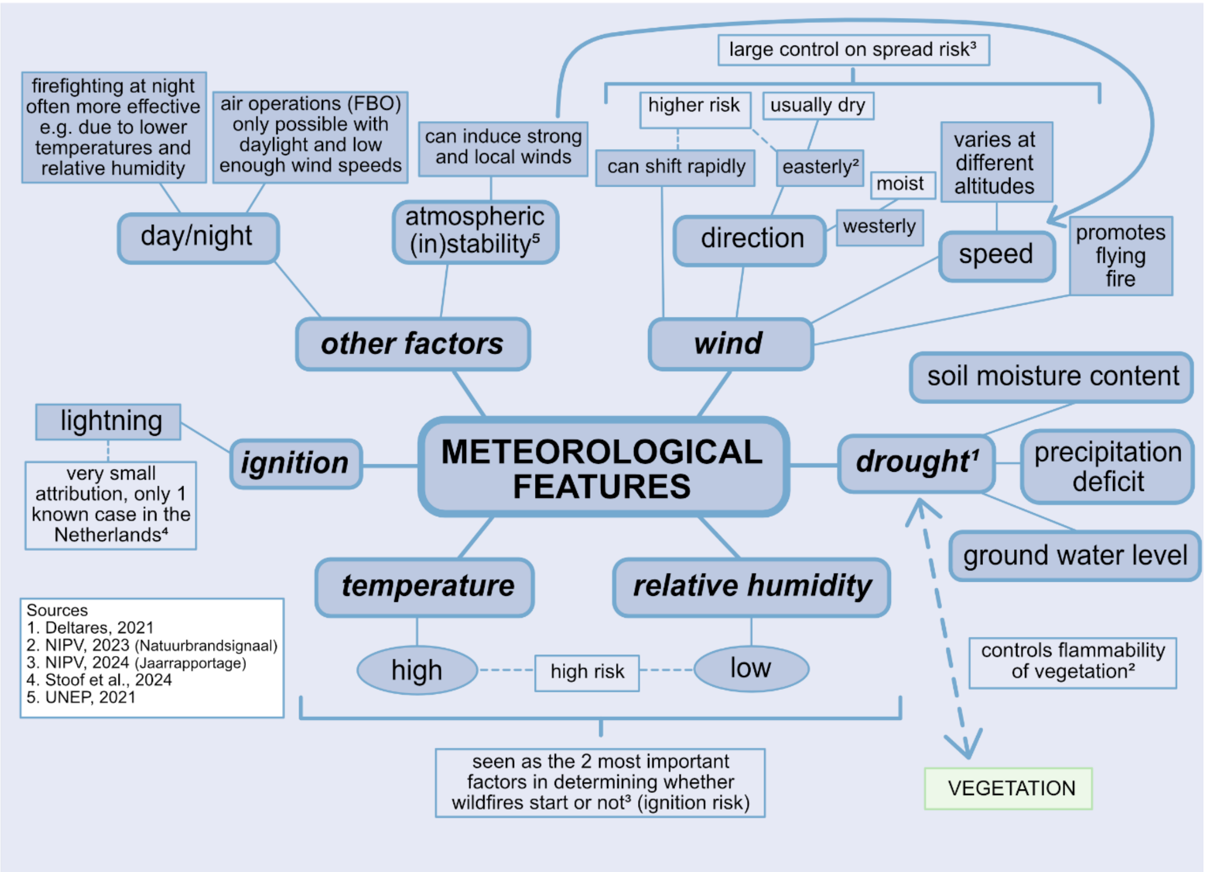

Figure 6d: Overview of factors related to ***meteorology*** *influencing wildfire risk*

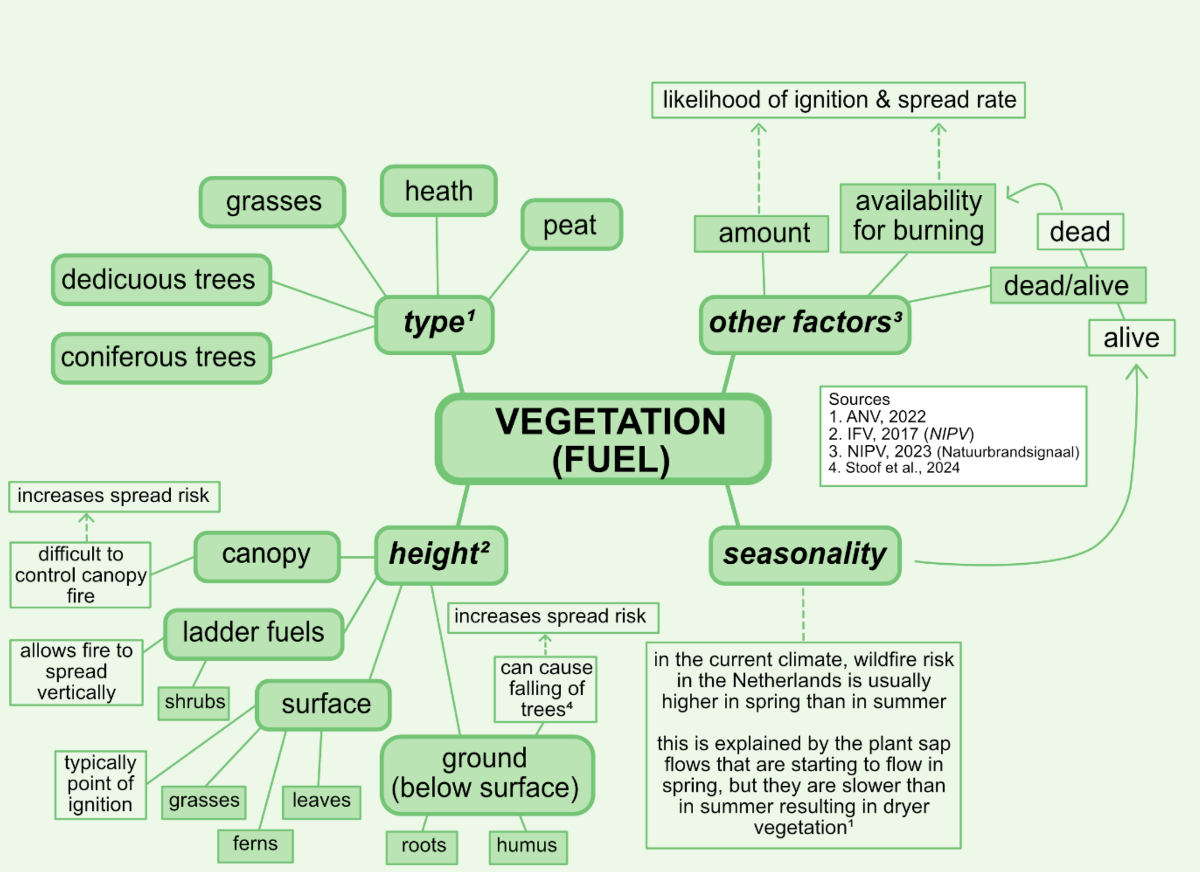

*Figure 6e: Overview of factors related to **vegetation** influencing wildfire risk*

4.2 Methods currently used in wildfire risk analysis

This theme comprises the different methods (i.e. fire indices and models) that are currently used by the wildfire specialists that were interviewed. The most remarkable note mentioned by multiple interviewees is that every wildfire analyst has their own ways of gathering information when analysing the risks in preparation as well as during an incident. Different websites for weather information and forecasts are used and this difference exists within and between all organizational layers in the operational services; between regional analysts from different safety regions, fire officers within the same region, national analysts, and specialists from other institutes.

One common source that is used daily during wildfire season by several wildfire specialists and analysts is the freely available EFFIS wildfire risk viewer from Copernicus. This is a website showing a map of Europe with daily updated values for the Canadian fire weather indices. NIPV specialists indicate they use this source as it is the only available model calculating the FWI for the Netherlands. However, they mention some disadvantages of using the EFFIS wildfire viewer: the indices are calculated for European scale so the resolution for the Netherlands is very coarse, barely giving detailed fire weather indications for specific areas; EFFIS uses the Canadian system of calculating fire weather, which often gives values that are an underestimation of the actual risk in the Netherlands due to differences in climate aspects, vegetation types, weather phenomena in (northern) Europe.

The M8-index is another index used in the Netherlands. As explained by VNOG fire officers during the workshop, it gives an indication of the chances of an uncontrollable wildfire starting. Technically, it is a drought index, fed by relative humidity based on stick weight from wood samples, air temperature, humidity and wind, and is located at 20 locations across the country. It has been used for example to determine whether aerial surveillance or a fire bucket helicopter would be deployed, when certain index thresholds are exceeded. Both VNOG and NIPV representatives indicated that the M8-index is becoming less significant as using stick weight is regarded as an outdated method, and because there have been events where the size and controllability of the wildfires that occurred did not correspond to the indicated M8-values. Whether the decrease in popularity and use of the M8-index is uniform over the different safety regions is unclear, but the NIPV specialists state that they prefer the use of the EFFIS wildfire viewer in combination with NIPV's wildfire spread model to analyse wildfires.

NIPV runs a wildfire spread model (NBVM, 'natuurbrandverspreidingsmodel') to analyse the propagation risk and get insights in any potential impacts of a wildfire. It contains several geospatial input-layers: meteorological data from KNMI's Harmonie weather model, fuel models based on satellite data on vegetation build-up and an automated impact-assessment based on a built environment dataset. This model is also used for research in wildfire case studies to test if the outcome generated by the spread model varies a lot from the actual wildfire spread that was observed. The application is only accessible by wildfire specialists, national wildfire advisors, action centres, safety regions and officers on duty, so it is not publicly available (NIPV, 2024). In comparison with the application FlamMap which is developed and used in the United States, the NIPV wildfire spread model does not incorporate data on risk of wildfire ignition (FlamMap, n.d.).

Key lessons

- There are no guidelines for fire personnel on what information sources to use during operations.
- The EFFIS wildfire viewer is a source often consulted by national wildfire analysts and specialists (i.e. from NIPV).
- NIPV owns a wildfire spread model and runs it to analyse propagation risks.
- The M8-index is a drought index based on stick weight that has been used nationally for analysing wildfire danger, but the index has been losing popularity in recent times.

4.3 Wildfire management approaches in the Netherlands: current situation and developments

This theme elaborates on the current situation and developments in wildfire management approaches that arose during the interviews. Various topics regarding this theme were touched upon, like what parties play a role and what collaborations are happening, as well as views on future developments such as the establishment of a national action centre for wildfires ('landelijk actiecentrum natuurbranden').

4.3.1 Current procedures and approaches

NIPV specialists explained that in the control rooms, emergency calls come in for police, fire brigades and the ambulance, and the main task of the centralists is to play a coordinating role during incidents. It is important to realize that control rooms of some safety regions are more proactive than others; some already use AI/machine learning approaches in their data analyses and incorporate weather forecasts in the control rooms. However, they did not expect that anyone at the safety regions would take early action if forecasts about the number of wildfires were to be communicated; this is because in wildfire management the Netherlands (as in most countries worldwide) is currently still reactive, meaning that actions are taken when an incident is reported. The specialists from NIPV as well as VRU stated they would like to see a shift from this reactive to a more proactive-based wildfire management. The VRU specialist says that the action chain of the preparatory phase is technically predetermined and that there are different steps (Fig. 7); wildfire risk is monitored during wildfire season by regional and national analysts, who issue an advice to different stakeholders. Based on this advice, decisions are made for example about scaling up to a different risk level. Safety regions work with four wildfire risk levels; low, normal, high and very high. For each level, separate action perspectives and measures that will be set in motion are predetermined. An example of this is the initial number of fire wagons that is sent to a wildfire after notification of the control room.

Fire officers from VNOG introduced the GRIP procedures during the workshop; it describes the scaling-up and down-scaling procedures during a large-scale incident. Each GRIP level has its own staffing and coordinators, and the procedure is the same for different safety regions so that cooperation runs smoothly and all different parties know how to act.

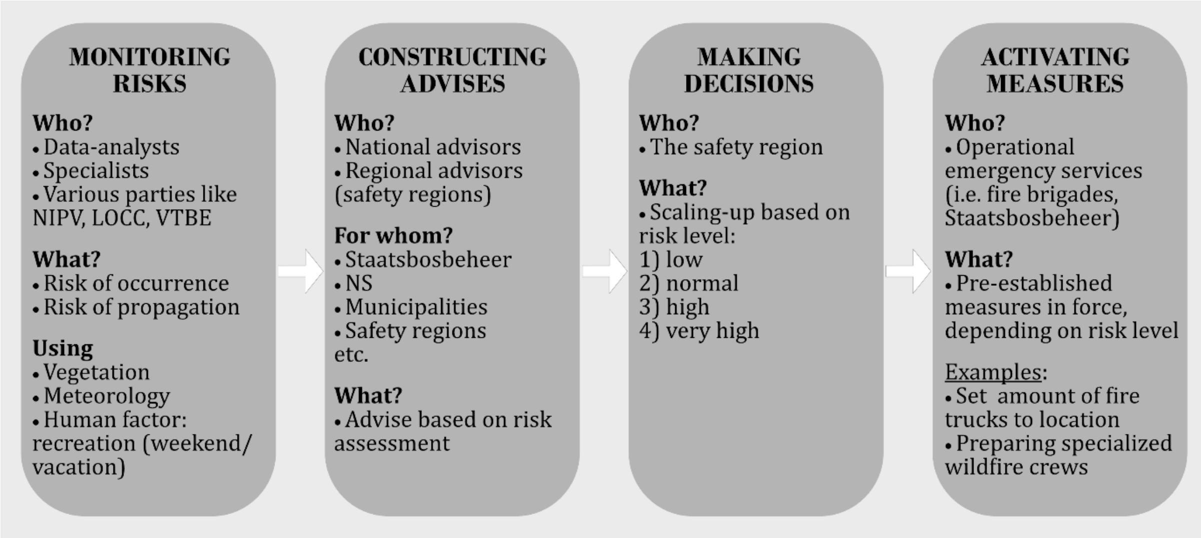

Figure 7: The action chain of the preparatory phase in wildfire management in the Netherlands

4.3.2 Reflections on wildfire risk management approaches

One topic that emerged in some of the interviews is the integration of meteorology at the fire brigades. The fire officers from VNOG that hosted the workshop appeared to have a lot of expertise and experience in fire weather as they spoke about many meteorological factors they take into account with their operations. On the other hand, a NIPV specialist mentioned how poorly meteorology is integrated in the fire and emergency services as well as in the control room, and how it is an underappreciated theme. The NIPV specialist demonstrated with some examples, 'some fire personnel is not even aware of the fact that relative humidity plays a big role in controllability of a (wild)fire, or that meteorological features can change throughout a day and differs a lot between night and day'. Another issue that was discussed during various interviews is the differences between organizational structure of the various safety regions; this can complicate trans-boundary operations, for example when coordinate systems of emergency services between regions do not connect or align. Also within KNMI, as explained by a colleague, the safety meteorologist has a lot more contact with employees of some safety regions than others. Some of the interviewees speculated that this might be related to a lack of awareness within operational forces; they might not know that it is free and advisable to contact KNMI's safety meteorologist for information and advice when a potentially dangerous weather-related incident might occur or has occurred. The VRU wildfire specialist indicates that, in his opinion, more uniformity between working approaches of the safety regions would be desirable. A last related point that emerged in various interviews is that there is room for improvement when it comes to getting the same vision and vocabulary between meteorologists and operational services. This was already concluded after a wildfire workshop held at KNMI in 2021, attended by NIPV representatives, safety region employees and KNMI meteorologists.

4.3.3 Involved parties and collaborations

From the interviews with representatives from Staatsbosbeheer, NIPV, WUR and KNMI it became clear which parties play a role in the wildfire issue and what collaborations are ongoing. Key players that emerged in the interviews are; LOCC, wildfire analysts of safety regions, KCR2, NIPV, VBNE, VIK teams and Universities. The exact roles of most of these organizations have been described in the background section of this report, so here I will focus on the collaborations. Since a few years, several parties meet weekly during wildfire season to make an analysis of the estimated wildfire risk for the upcoming days, based on meteorology, the state of vegetation, human activity (i.e. normal/holiday/weekend days) and the availability of capacity. Information of these factors from the past weeks as well as forecasts are taken into consideration. Currently these briefings are organized by LOCC, and the people involved are national wildfire analysts, some regional wildfire analysts (of high-risk regions with large natural areas), analysts from NIPV and a representative from VBNE. The risk analysis is then shared with several organizations like Staatsbosbeheer, other terrain managing parties and railway services who can then take actions such as early mowing of grass or increasing alertness of employees. Furthermore, a wildfire congress ('De Staat van Natuurbranden') is organized in November each year by NIPV, WUR, Staatsbosbeheer and one of the provinces. The purpose of the conference is to exchange knowledge by giving a stage to various parties working in the field to present developments and insights gained in recent times, and experts to share their experiences. An overview of organizations involved in wildfire control is presented in Figure 8, based on NIPV information presented at the wildfire congress 2024.

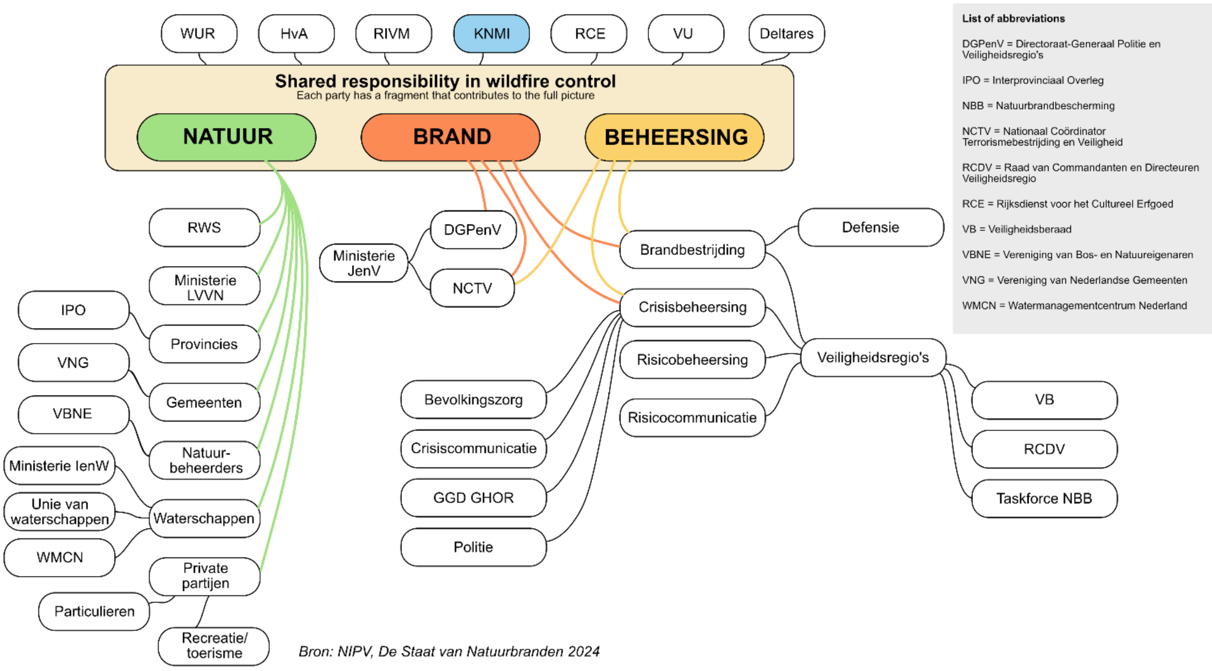

Figure 8: Overview of organizations involved in and branches of wildfire control (after an image shared by NIPV at De Staat van Natuurbranden 2024)

4.3.4 Development in the near future

Several interviewees referred to plans regarding the establishment of a national action centre for wildfires. NIPV specialists describe that the general aim of the action centre is to collect statistics and conduct research, make projections and analyses, and to gather knowledge about wildfire prevention methods and control strategies. The intention of the centre is to be multi-disciplinary in order to improve coordination and information provision between different fields. Additionally, the centre will organize financial resources, clear tasks and roles nationally. Currently, the plans and strategies are being prepared. During a few interviews, the position of KNMI with respect to the centre was also briefly discussed. These points are shared in Section 4.4.2.

Key lessons

- Wildfire management in the Netherlands is reactive, but specialists plead for a shift to proactive management to better regulate increasing wildfire risks.
- There is a need for better integration of knowledge on meteorology in operational services, especially in some regions of the Netherlands.
- Consistency in working approaches between safety regions need to be improved to facilitate better coordination.
- Gaining uniformity in vocabulary between researchers/meteorologists and operational services is an important step towards improved collaboration.
- A weekly wildfire briefing with various specialists and representatives from involved parties is held during wildfire season to analyse wildfire risk.
- A national action centre for wildfires is currently being established. The intention is to gather information, research and coordination on all wildfire related topics in a multi-disciplinary knowledge hub.

4.4 The role of KNMI in wildfire risk management

This theme illustrates the current position of KNMI in wildfire risk management, highlighting ongoing projects and research as well as the different ideas that exist around potential future contributions based on suggestions and requests from interviewees. Perception of stakeholders on KNMI's current and future role are discussed.

4.4.1 Developments

KNMI has been formally collaborating with NIPV on the wildfire issue for several years. This collaboration consisted of explorations on the topic of wildfire monitoring, visits for workshops to exchange knowledge and expertise, and an explorative simulation exercise in 2021. More recently, NIPV shared access to their wildfire notification database with KNMI researchers in a new research project within the Research and Development department; the development of wildfire QIF, which is strictly a research-only project. This is one of the ongoing projects regarding wildfires at KNMI, along with the computation of FWI for the Netherlands, the development of a wildfire analyst dashboard as a potential future operational service and the construction of a chapter devoted to wildfires as part of an extreme weather report. Here follows a concise description of each of these projects, based on explanations from KNMI colleagues who are working on the different projects.

Wildfire Quantitative Impact Forecasting

A random-forest algorithm was developed and trained with the NIPV wildfire notification dataset and historic weather features, to recognise patterns and allow for the generation of an impact-forecast using the weather forecast. The feature that is currently used as impact is 'number of wildfires per day', input on this feature is extracted from the NIPV wildfire database, and the model is still in the test-phase. Preliminary results show that there are many weather and non-weather (i.e. day of the week) features influencing the number of wildfire notifications that might occur on a day and that this can be forecasted. Currently, explorations on how to potentially use these types of forecasts operationally are ongoing. The preliminary results have been presented to NIPV representatives, and they have agreed on continuing the collaborations on improving the model.

Fire Weather Index computed for The Netherlands

A python code has been developed to calculate the six components of the Canadian FWI. This can be applied to individual KNMI weather stations and for gridded maps. Historic weather data has been available since 1901 for the station 'De Bilt' and over time more locations became available which gives a long historic perspective for the weather station maps. The current status of the project is that historic FWI values for all six components can be plotted on a map of the Netherlands for each date since the start of the measurements. In addition, high spatial resolution maps of the FWI can be created using multi-fidelity spatial regression techniques and second- and third-party data (like in De Baar et al., 2023). However, this type of second- and third-party data has only been collected over the past few years, so these types of maps can only provide a historical of a few years. The code has been completed and is running but steps are required before this can become an operational product.

Dashboard for wildfire analysts

A concept version of a dashboard is currently being constructed with the aim to support wildfire specialists from NIPV and KNMI. The added value of having one dashboard is that all relevant and updated meteorological information is gathered in one place, facilitating easier analysis and potentially allowing for more proactive fire management. The dashboard will contain features like temperature, wind speed and direction, relative humidity and drought (SPI index). As it is still in development, the project leaders are open to considering adding other features to the dashboard like QIF or FWI. Currently, the target group is small (KNMI and NIPV wildfire specialists), but in the future the dashboard could become a platform or service for a bigger target group. This collaboration also encompasses explorations in NIPV and KNMI specialists make exchange visits to give workshops with the purpose of improving mutual understanding of wildfire vocabulary.

Report on unseen extreme weather events

This is a broader project on unseen hazardous and extreme weather events within our current climate, and one chapter in the report is devoted to a potential wildfire event. The target group for the report is policy makers and companies. The aim is to map out a realistic wildfire scenario with a return period of 1 in 100 to 200 years that could occur in the Netherlands, using ensemble meteorological data in combination with RACMO climate data and computed FWI indices. Additionally, the potential impacts of an event of this size will be illustrated in collaboration with NIPV.

In the interviews with KNMI colleagues, some other ideas on future projects were mentioned:

- In collaboration with VRU, NIPV and KNMI's EWC, an initiative is being set up to place measuring stations at multiple locations on the Utrechtse Heuvelrug. KNMI is developing high-resolution weather maps using 2nd party data from other professional organisations and 3rd party data from citizens in combination with the existing and highly accurate KNMI weather stations (De Baar et al., 2023). As citizens are underrepresented in natural areas, there is a lack of sampling data which results in increased uncertainty on the maps in areas like the Veluwe and the Utrechtse Heuvelrug. Therefore, it is essential to place additional measuring stations in these areas to get more detailed maps of the meteorological conditions in the areas with reduced uncertainty. Eventually this will also help gain a more detailed view on dangerous wildfire weather, potentially using these maps to help create detailed FWI maps for the Netherlands.
- As proposed by WUR and Staatsbosbeheer, an idea exists for KNMI to get involved in either presenting at the yearly wildfire congress.
- Recently (January 2025), a KNMI representative became part of the consortium that works on the establishment of the national action centre for wildfires.

4.4.2 View on KNMI's role

All the interviewees agree that the KNMI is an important player in the field. Specialists stress that KNMI's knowledge and expertise in meteorology, climate and data-driven research and technology holds a great potential for valuable contributions to the wildfire issue. Interviewees from KNMI, Staatsbosbeheer and NIPV emphasize the value of KNMI's independency and objectivity as a governmental institution. Some mention that they value KNMI's efforts to share data openly (on KNMI Data Platform).

Some recommendations regarding KNMI's role and research opportunities were made in various interviews. NIPV specialists recommend combining the Harmonie weather model with EFFIS output to get more localized and tailored values for the fire weather indices; they believe this can be a quick win that will really help support wildfire analysts. A WUR researcher calls for adding relative humidity to the daily weather forecasts, as this is very relevant information for fire operations. Staatsbosbeheer representatives mention that to some parties working on wildfires it is often unclear what role KNMI exactly play. As a solution, they propose KNMI present at one of the next wildfire congresses to make this clear to all other players in the field. Unrelated to wildfires specifically, but more generally for all extreme and dangerous weather types, VNOG fire officers see a role for KNMI to issue more local warnings. This would help safety regions avoid unnecessary scale-up and consequential extra costs.

In various interviews with KNMI colleagues, some relevant matters were mentioned. One colleague said that the wildfire issue at KNMI currently falls under the 'heat issue' and is organized by the same program manager. Another colleague, a former safety-meteorologist, mentioned that by law, KNMI is only allowed to communicate through safety regions with regional warning codes. In his opinion, the inability to contact i.e. event organizations with upcoming dangerous weather can result in unsafe situations. Currently, there is a law case running on this specific topic. Furthermore, as mentioned before, KNMI does not get contacted by each safety region frequently as often. Still, KNMI is in contact with safety regions regularly, during the weather briefing from the weather room which is held twice a week and where all safety regions are present.

4.4.3 Wildfire QIF: developments and opportunities

NIPV specialists discussed future research possibilities for the wildfire QIF, as they emphasized the potential value of these types of forecasts for operational services and improving wildfire risk analyses. Some ideas that were proposed to help improve the QIF model skill include: adding a seasonal effect to the model as spring fires spread faster while summer fires show more intense fire behaviour; filtering out days with low amount of wildfire notifications (i.e. less than five) from the input data; extending the wildfire database with wildfire statistics from terrain management agencies who collected data from 1922-1994. Another suggestion was to operationally test the impact forecasts during the upcoming wildfire season in collaborative efforts between KNMI researchers, the KNMI weather room meteorologists and NIPV specialists. The testing methods still need to be further discussed in more detail, but will consist of running the model and evaluating the skill by comparing the models forecasts to monitored wildfire notifications. This way of testing the QIF on a national level corresponds to a recommendation that was made by a VRU wildfire specialist, who discouraged the proposed idea of testing QIF with regional fire personnel. Additional suggestions were made by Staatsbosbeheer and VRU representatives; they advised adding meteorological information on the past week alongside the QIF. According to them, this would allow for easier interpretation of the forecasts and better risk analysis. Lastly, ideas on the added value of the QIF in the national action centre, as well as potentially displaying it on the wildfire dashboard, have been briefly discussed in various interviews.

Key lessons

- KNMI has a contractual collaboration with NIPV on wildfire research.
- Current wildfire-related developments at KNMI are: 1) developing wildfire QIF using the NIPV wildfire notification database, 2) modelling the Canadian FWI for the Netherlands, 3) constructing a dashboard for wildfire specialists and 4) a report on unseen extreme weather events including a chapter on wildfires.
- Stakeholders' perceptions on the value of KNMI in wildfire risk management encompass expertise in climate and meteorology, data-driven research and technological developments, independency and objectivity, and open data sharing.
- Recommendations on potential future contributions from KNMI are:
    - Combining the EFFIS wildfire viewer with the Harmonie model for more accurate FWI values
    - More clear communication on wildfire developments and KNMI's role to other stakeholders
    - Issuing more local warnings
    - Improving QIF model skill and operationally testing in collaboration with NIPV

5. Discussions and conclusions

In this chapter, a short summary per research objective is provided, followed by a reflection on a selection of the emerging themes from the results. In the last section, recommendations and suggestions for research opportunities for KNMI are summarized to give an answer to the research question “How can KNMI enhance its role in wildfire risk management in the Netherlands, considering stakeholder insights and its position in the organizational wildfire landscape?"

5.1 Research objectives

5.1.1 *Objective 1: to assess current and projected wildfire risk and impacts*

Question 1.1: What key factors drive wildfire risk in the Netherlands?

Wildfire risk (ignition risk and propagation risk) in the Netherlands is driven by a combination of many human and natural factors, illustrating the complexity of identifying and defining wildfire risk. Identified key factors are of human and natural origin and contribute to wildfire ignition and propagation risk in various degrees. Key factors in ignition risk include civilian activity in combination with meteorological features (i.e. persistent drought) and fuel available for burning (i.e. abundant and fine vegetation at ground level). Key factors in propagation risk are wind speed and direction, rapid and unexpected changes in wind, and effectiveness of control efforts.

Question 1.2: What considerations need to be made when defining and assessing wildfire impact in the Netherlands?

Both ignition risk and propagation risk need to be assessed when evaluating the potential wildfire impact. An aspect that is crucial in wildfire impact is the timing and effectiveness of fire brigades control efforts; success during initial attack will highly reduce impact, but if a fire escapes initial attack and extended attack is needed, high impact on fire brigades can be expected. Exploring and implementing new strategies can help increase fire control effectiveness.

Question 1.3: How are wildfire risk and impact projected to evolve with climate change?

Wildfire risks and impacts are expected to increase in the Netherlands. This is a result from anticipated longer periods of sustained dry conditions in summer and spring, amplified by a general trend towards more sunny conditions, and overall wetter conditions in winter. During the warm season, precipitation is expected to occur more frequently but with short, intense showers. More precipitation in winter will lead to favourable growing conditions in early spring, increasing fuel amounts, and higher risks of wildfires due to the generally drier and hotter warm seasons. If more wildfires occur synchronously, fire brigades will experience higher pressure and impacts. This raises questions about preparedness of the current Dutch wildfire management system.

5.1.2 *Objective 2: to map the organizational landscape of wildfire management in the Netherlands and identify key stakeholders*

Question 2.1: Which organizations play a role in wildfire management and the safety chain in the Netherlands, and what responsibilities do they have?

Responsibilities in the wildfire management organizational landscape can be divided into the following branches: crisis management and operational efforts, the safety regions and NIPV fulfil this task; preventive management, VBNE (i.e. Staatsbosbeheer), NIPV and others (like railway services) carry this out; wildfire research and development, this task is executed by universities (including WUR and VU) as well as institutes (Deltares, KNMI, NIPV). Additional organizations that play a part in wildfire management are KCR 2, LOCC and VIK-teams.

Question 2.2: What collaborations exist between key players in wildfire management, and where do gaps or challenges in coordination appear?

A weekly wildfire briefing is a collaborative effort from several organizations where national and regional wildfire analysts and specialists from safety regions, NIPV, VBNE, LOCC gather during wildfire season, to analyse risks based on meteorology, state of vegetation, civilian activity and available resources. The following gaps and challenges in wildfire management and coordination were identified:

- Vocabulary differences between researchers and operational services can lead to misunderstanding and potential inefficiency in coordination and cooperation.
- No guidelines exist for analysts and fire service personnel on what information sources to use, which can lead to inefficient coordination between safety regions.
- FWI is not designed/calculated for the Netherlands specifically; the EFFIS wildfire viewer by Copernicus is often used by wildfire specialists but it is calculated for Europe and therefore lacks precision due to the coarse resolution.

5.1.3 *Objective 3: to evaluate KNMI's current role and responsibilities and potential future opportunities in wildfire risk management*

Question 3.1: Where does KNMI currently stand in the organizational landscape?

Currently, KNMI does not provide any services and warnings for dangerous wildfire weather. There is regular contact with safety regions during the weather room updates twice a week, but these briefings cover general dangerous weather forecasts and not wildfire weather specifically. A formal collaboration exists between NIPV and KNMI which consists of explorations in supporting each other in wildfire research and developments. Within KNMI, the wildfire theme is part of the heat theme within the Early Warning Centre, and various research projects about wildfires are ongoing; development of wildfire QIF, computing FWI for the Netherlands, development of a wildfire analyst dashboard, wildfires as a chapter of a report on unseen extreme weather events and impacts.

Question 3.2: What are the key challenges and requirements regarding wildfire management in the Netherlands according to stakeholders?

- Wildfire management in the Netherlands is reactive, while a proactive-based management would be preferred to help cope with increasing risks.
- An integrated fire management is necessary to better coordinate projects, research and responsibilities. A proposed framework for this is currently being established; a national action centre for wildfires.
- Better integrating knowledge on meteorology into operational services, specifically of some safety regions.

Question 3.3: How do stakeholders perceive KNMI's role and responsibilities?

Stakeholders express that they value KNMI's expertise in climate and meteorology, data-driven research and technological developments, open data-sharing and independency. Occurrence and behaviour of wildfires are closely linked to meteorological conditions. Therefore, KNMI's perceived role is to carry out weather- and climate-related research and develop services with the responsibility to limit wildfire impact on society. Various stakeholders see a role for KNMI wildfire products that are currently being developed in the national action centre for wildfires.

Question 3.4: What concrete recommendations emerge from stakeholders insights regarding wildfire research opportunities?

- Further developing and improving wildfire QIF in continued collaboration with NIPV to allow for better analysis of dangerous fire weather and potentially develop this application into an operational service.
- Developing a model that computes a combination of ignition risk (i.e. based on the wildfire notification database) and propagation risk (i.e. based on the wildfire spread model that NIPV operates).
- Combining the Harmonie weather model with EFFIS output to generate more localized and tailored values for the fire weather indices.

5.2 Key challenges in wildfire management

The results of this research highlight several challenges and gaps in wildfire management in the Netherlands. Due to climate change, occurrence of dangerous fire weather is projected to increase globally as well as in the Netherlands, resulting in increasing frequency and intensity of wildfires. In combination with a growing population, wildfire impacts are expected to worsen in the coming years (ANV, 2022; Verhoeven et al., 2023). There are concerns amongst specialists about current wildfire management strategies: those are predominantly reactive and suppression-based and are likely not sufficient to cope with the increasing risks. Fire suppression strategies become decreasingly effective with increasing fire behaviour, potentially threatening firefighter safety (UNEP, 2021). Proactive fire management is aimed at better mitigating wildfire risks in the preparatory phase (Pandey et al., 2023). Dutch specialists stress the need for a transition from reactive to proactive fire management, in order to efficiently deal with the projected higher frequency and intensity of incidents with the same resources and capacity. This transition will require a cultural shift within operational services and is a long-term, gradual process. It involves accepting that not all fires can be extinguished, but rather asking questions like 'What fires are acceptable? How do we want them to burn? What does that mean for landscape planning?' (Lambrechts et al., 2023). An example of a country that has undergone this transition is Portugal, provoked by catastrophic wildfire events in 2017. Focus in wildfire management shifted from the strong suppression policies that were in place to improved prevention measures and protection of people and properties, aiming for a more sustainable fire management (Pandey et al., 2023).

From the sessions with stakeholders, it appeared that this shift in the Netherlands has already started with a growing awareness amongst specialists that this transition is necessary. A concrete example of a first step towards more proactive wildfire management is *the weekly wildfire briefing* where specialists gather and analyse wildfire risk during the wildfire season, allowing for better analysis of when dangerous fire situations are expected and whether protective actions should be taken. A suggestion of another approach that can help stimulate the shift towards a more proactive-based wildfire management is *closer and more frequent collaborations* between parties from different branches of wildfire management (i.e. operational, research, prevention). Strengthened connections and close interactions between disciplines will help improve common understanding in how different actors can better support each other, both during wildfire incidents and in the preparatory phase. The need for an interdisciplinary approach in wildfire management, especially strengthening the link between scientific and operational experts, is also underlined by Stoof and Kettridge (2022). More frequent collaborations, for example between meteorologists and the fire brigades, can also help bridge the vocabulary gap that has been mentioned in several of the stakeholder sessions.

5.3 KNMI's role

KNMI is responsible for protecting the Dutch society from weather, climate and seismology-related hazards, and this is done by providing data-driven advice and issuing warnings about dangerous weather. This warning responsibility is established by law. A part of KNMI's role is carrying out research and exploring future risks related to climate change, as well as developing new products to continuously meet these responsibilities and for services to remain relevant (KNMI, 2024). With respect to increasing wildfire risks in the Netherlands, urgency at KNMI is felt to enhance its contribution in wildfire management by promoting wildfire research and development. The current wildfire projects (described in section 4.4.1) emerged from this urge to contribute. However, KNMI is officially not responsible for issuing warnings on dangerous wildfire weather, and no concrete wildfire services are offered. This can be explained by the fact that rising concerns about increasing wildfire risks is a relatively recent development in the Netherlands. Within the current organizational structure of wildfire management in the Netherlands, the fire brigades of the safety regions are responsible for regionally warning about wildfire danger. As mentioned by stakeholders, KNMI is valued for its expertise and knowledge on meteorology and climatology, as well as open data-sourcing and independence. Additionally, KNMI is currently transitioning from a traditional warning institute to an Early Warning Centre. The purpose of this transition is to issue earlier and more tailored warnings in collaboration with stakeholders in order to limit impacts of dangerous weather. Adopting the task of issuing wildfire weather warnings would align with these ambitions expressed by KNMI.

Meteorological offices of numerous countries globally are responsible for issuing wildfire warnings and other wildfire-related services, informing the public as well as stakeholder organizations on wildfire danger. A few examples include; NWS (National Weather Services) for the United States (Jacks and Hockenberry, 2013), BoM (Bureau of Meteorology) for Australia, DWD (Deutscher Wetterdienst) for Germany and the Met Office for England and Wales. Services encompass providing up-to-date information on dangerous fire weather, fire weather index maps of the country, and issuing red-flag warnings. Fire weather danger maps are often tailored to the country, providing daily or monthly fire index values (i.e. https://www.usgs.gov/fire-danger-forecast for USA, http://www.bom.gov.au/climate/maps/averages/ffdi/ for Australia). Developing such region-specific index values would be an interesting opportunity to help enhance KNMI's contribution to wildfire risk analysis in the Netherlands. Canadian FWI codes have already been developed for computing historic values and explorations on computing forecastable indices have been carried out at KNMI. Examining options in developing operational fire weather index maps as a service would be a great next step in this process.

In the hazard management cycle, generating and communicating early warnings is regarded as one of the crucial approaches to enhance preparedness, and over the past decades it has been increasingly applied in disaster risk reduction strategies. Provided proper design and augmentation, early warning systems can reduce disaster risks and promote early action (IPCC, 2012; Šakić Trogrlić et al., 2022). Early action can help mitigate risks proactively and therefore minimize impacts of extreme weather events (WMO, 2021). For the generation of early warning services, products and applications need to be developed. Examples of products like wildfire QIF and a wildfire analyst dashboard are currently in development at KNMI in collaboration with NIPV. Early warnings should be tailored to the user (i.e. citizens, emergency service personnel), aiming to support decision-making processes. However, as elaborated in section 5.3, the wildfire management system in the Netherlands is designed to operate reaction-based, and as a consequence the system does not encourage taking early action. This raises questions regarding operationalisation of such applications; how would operational services exploit early warnings or impact forecasts on wildfires, if the system is not designed for proactive decision-making? Explorations between KNMI and stakeholders are ongoing on how the implementation of new wildfire products and services can become operational, or gain a role in the national action centre for wildfires that is being established. It is important to make an inventory of how these products and services can help support the required shift from reactive to proactive wildfire management in the Netherlands, also early in the development phase.

Currently, a detailed and written strategy on KNMI's role in wildfire management and research does not exist. The wildfire theme is part of the heat theme, therefore there is no separate description of KNMI's exact role and ambitions regarding wildfires. Establishing such a strategy can help clarify what responsibilities and jobs exist within the organisation, and it can help create a clear view on KNMI's role for other parties. Appointing a project manager that will become responsible for the wildfire theme within KNMI can help to create structure in setting up a strategy.

5.4 Benefits and considerations of quantitative impact-forecasting

Impact forecasting is a relatively novel approach in hazard and risk reduction, aiming to reduce impacts of extreme weather and natural hazards (WMO, 2021). Developing quantitative wildfire impact forecasts has hardly been done anywhere in the world, and also at KNMI the development of these types of forecasts are still in the early stages. Despite the infancy of this work, it is considered to have a great potential, provided that required steps are taken in the advancements towards an operational product or service. The added value of QIF is that it provides earlier and more detailed indications of potential impacts that wildfires can have, thus offering guidance in decision-making processes and taking data-driven early action. Early action measures include a broad variety of activities to anticipate the impacts of a wildfire (e.g. strategic evacuation planning, resilient landscape design) (Tersmette et al., 2023).

There are ethical aspects that need to be considered when developing and deploying impact forecasts (Potter et al., 2025). For example, if technology and algorithms get the upper hand in critical decision- making processes without using a person’s own observational and intellectual capacities, there is a chance that the decisions that are made overlook local context, which can lead to social injustice. Another concern is (un)fairness of predictions: when there are systematic biases in the historic impact training data, algorithms can magnify or diminish certain impacts in a forecast, resulting in inequality and reduced trust in such models. Krumina (2023) elaborates on these and many more considerations that should be reflected on when developing and mobilizing impact forecasts, and suggests principles that can applied to minimize potentially negative implications of IBF. In order to maximize KNMI's wildfire QIF and stimulate interoperability, implementation needs to be done in close collaboration with NIPV. This will secure both specialist knowledge and required data and technology (Potter et al., 2025). Arrangements with NIPV are currently being made for operationally testing the wildfire QIF during the upcoming wildfire season, and exploring how it can be used in the weekly wildfire briefings along with already existing analyses techniques. Deploying wildfire QIF responsibly and efficiently is a valuable first step towards increasing KNMI's contribution to wildfire management and better meeting its responsibility in protecting people.

5.5 Conclusions: suggestions, requirements and opportunities for KNMI

From sessions with stakeholders and literature reviews, it appears that KNMI's transition to an early warning centre coincides with the required shift from reactive to proactive wildfire management that is being stressed by Dutch wildfire specialists. The following suggestions and requirements for KNMI to enhance its role in wildfire management in the Netherlands are identified:

- To enhance KNMI's role in wildfire research, ***close collaborations*** with stakeholders and specialists from operational disciplines are required.
- Regarding KNMI's expertise in weather and climate research and development, as well as KNMI’s responsibility to protect society from weather-related hazards, KNMI should ***offer wildfire services and issue wildfire weather warnings*** to help enhance its role in wildfire management.
- Making clear inventories in collaboration with people from the operational branch of what wildfire services are needed and by whom, must happen throughout the entire process as well as ***in the earliest stages of development***.
- A suggestion for a wildfire-related service that KNMI could produce is developing an application with a map of the Netherlands that provides daily up-to-date FWI values.
- Suggestions for improving wildfire QIF are: adding a seasonal effect and only testing the model for days with a high number of wildfire notifications to try to enhance model skill, and presenting the QIF alongside traditional weather information to assist interpretation of the forecasts.
- Suggestions for implementing wildfire QIF are: continued close collaboration with NIPV and operationally testing the application at the weekly wildfire briefing.
- Describing KNMI's exact role and ambitions in wildfire research and management is recommended to help enhance transparency around responsibilities both within and outside of the organization.
- A concrete recommendation to help clarify KNMI's role in wildfire management to other actors in the field is to present at the yearly wildfire conference (*‘De Staat van Natuurbranden’*).

In summary, this report highlights the many opportunities for KNMI to enhance and establish its role in wildfire management in the Netherlands. KNMI can act as a supporting party in the shift to more proactive wildfire management, by issuing (early) wildfire warnings and developing new products and applications, facilitating preparedness of the operational services.

6. Other internship activities

In this chapter, the internship activities that do not fall within the scope of the research objective to explore the opportunities for KNMI to enhance its role in wildfire risk management in the Netherlands, are described briefly. The internship project encompassed a broad range of activities additional to the literature review and sessions with stakeholders: 1) attending events; 2) testing the QIF model by adding FWI values to the input data; 3) exploring possibilities to test wildfire QIF with decision-makers; 4) collaborating with UU to explore ethical implications of QIF.

6.1 Events

Two events were attended to gather more knowledge on wildfire control and management in the Netherlands:

1) A wildfire workshop at VNOG designed for representatives of the KNMI, to learn about the basics of wildfire control and recent developments in the field. A few lessons from this workshop are also part of the research results presented above.
2) "De Staat van Natuurbranden '24 - *samen voorwaards*". This is the yearly wildfire congress organized by WUR, NIPV, Staatsbosbeheer and one of the provinces. Attending the congress was a good opportunity to network and speak with several people with a broad variety in backgrounds related to the wildfire theme.

6.2 Testing the QIF model skill

This activity refers to an experiment regarding two of the wildfire developments at KNMI described in Section 4.1.1; the algorithm that was developed to generate wildfire QIF and the FWI that was computed for the Netherlands. The intention was to add four of the calculated fire weather indices (FWI, FFMC, ISI and BUI) to the weather input of the model, to iteratively test their effect on the model skill. The research objective was to analyse which fire weather indices and combinations would result in the best model skill, and whether this skill would be better than using solely weather features as input. The outcome of the various tests showed that adding FWI to the input for the QIF did not significantly improve the model skill. A KNMI colleague will be publishing a paper on these explorations and findings, in collaboration with NIPV, who provided the wildfire notification database that was used as impact-database in the model.

6.3 Testing the wildfire QIF with decision-makers

A draft for an explorative experiment was set up, with the aim to test the usability and potential of the wildfire QIF that is being developed. The concept of the experiment was to organize a workshop with decision makers (i.e. fire officers), and test with a choice experiment on a hypothetical wildfire scenario how the participants would use of the QIF, and to what extent it would influence their decisions. The research question was: "*How can impact-forecasts (i.e. probability forecasts of the amount of wildfire notifications) support the fire brigades in more effective decision-making in the preparatory phase?".* The choice experiment was created in Formdesk and consisted of an online questionnaire covering questions about taking early actions like scaling up or collaborating. The simulation exercise would be held twice, once providing only normal weather information and no QIF, once providing QIF as an addition to the normal weather information. Differences between results from the two simulation rounds would be analysed to explore the research objective.

However, after receiving constructive feedback on the experiment set-up from a VRU wildfire specialist during an interview, it was clear that testing in the suggested format was impractical and the experiment could not be continued. The most important reason for this was that, in the specialists' opinion, we would be testing the product too soon in the development process, and more steps and additional explorations (such as collaborations with partners on the operational side) are needed before being able to conduct a realistic experiment with the QIF. Another important comment from the VRU specialist was that our proposed target group for the workshop (fire officers) is not the right group for testing decision-making, as decision-making is not part of their work activities. This is because the wildfire management in the Netherlands is reactive, rather than proactive.

6.4 Ethical implications QIF

Recently, a new collaboration with the Humanity Faculty of Utrecht University (UU) was initiated. The aim of collaborating with social scientists is to explore what potential negative implications of quantitative impact-forecasting need to be considered when developing such forecasts. At the end of an introductory meeting with three UU professors, the idea for a first collaboration project was proposed to investigate the ethical implications of QIF in a master student project. The intentions and expectations are to further continue collaborations with UU Humanity Faculty in the future.

This project was set up as follows: four students from the masters Applied Ethics were asked to write a report for the KNMI. The research question assigned to the students was formulated "*What could be ethical limitations of regular, locally precise impact forecasting with inherent uncertainty, especially with respect to increasing risks related to climate change?".* Two meetings with the students were held to explain context and backgrounds on the topic of impact-forecasting and any related concerns, and to further discuss details and any questions they had. After finishing the report, the students presented their findings at KNMI.

In their report, the students discuss four topics and describe practical implications to help support KNMI in further development and use of QIF: organizational structure, moral responsibility, dealing with uncertainty and technical risks. Some main action points for KNMI suggested in the report are:

- Being aware of the vulnerabilities that come with interdependency when collaborating on issues with stakeholders, this needs to be managed proactively.
- Reflecting on issues like responsibility gaps and void, i.e. when it becomes impossible to track who can be held responsible when (a link in) the system fails, and actively working to avoid them. Impact-forecasting is a collective responsibility between different people within KNMI and outside KNMI, so responsibilities need to be mapped out to avoid responsibility gaps and voids.
- To deal with uncertainty, KNMI should define what risks are tolerable and (un)acceptable. Doing this will enable KNMI to substantiate their course of actions.

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