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Assessing fire hazard in coastal heathlands

Predicted impacts of weather, land use and management

TALL SOM FORTELLER

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DISCUSSION PAPERS

1011

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Abstract

Unmanaged and overgrown coastal heathlands represent a substantial fire hazard. We analyse how this hazard in Norwegian coastal heathlands is influenced by weather conditions, land management, and usage. Our analysis integrates vegetation, maintenance, and management data with emergency response records from fire departments and weather data. Using panel data regressions, we assess the risk of fire in response to these variables. A key finding is that increased coastal heathland management significantly reduces fire risk, particularly during droughts, warm weather, and periods with strong winds. The reason is that well-maintained coastal heathlands having reduced levels of dry vegetation, making them less susceptible to ignition even during conditions when the overall fire hazard is increased.

Keywords: Land use; Landscape maintenance; Costal heathlands; Fire hazard; Panel data

JEL classification: C23, Q15, Q54, Q57

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Sammendrag

Uskjøttet og delvis gjengrodd kystlynghei utgjør en betydelig brannfare, noe som ble tydeliggjort gjennom flere store branner på Frøya og Flatanger vinteren 2014, flere branner sommeren 2018, og i storbrannen på Sotra i begynnelsen av juni 2021. Dette skyldes en kombinasjon av tørt gress, gammel lyng, einer og skog, som er lett antennelig og brenner voldsomt. Effektiv skjøtsel av kystlyngheiene reduserer opphopning av brennbart materiale, noe som kan redusere samfunnets kostnader knyttet til brannslukking, samt tap av eiendom, biologisk mangfold og produksjonsverdi i brannsituasjoner.

Denne analysen ser nærmere på brannfaren i norske kystlyngheier og hvordan den varierer med værforhold, skjøtsel og bruk av disse områdene. Vi har koblet kartdata for vegetasjon, vedlikehold og gjengroing av kystlyngheier med værdata fra ulike værstasjoner og data for brannutrykninger til både gress- og krattbranner og skog- og utmarksbranner. Ved å analysere disse datasettene i sammenheng ved bruk av en paneldatamodell, finner vi ut hvordan brannfaren, målt i antall brannutrykninger i inn- og utmark, varierer med været, skjøtselen og bruken av kystlyngheiene.

Vi finner at værforholdene er den mest betydningsfulle faktoren for branner i inn- og utmark, spesielt når det er mangel på nedbør over en lenger periode i kombinasjon med høye temperaturer og sterk vind. Det er spesielt mange brannutrykninger knyttet til kystlyngheier som naturtype, og antall brannutrykninger øker med redusert skjøtsel og påfølgende gjengroing av lyngheiene. Bruken av kystlyngheiene til friluftslivsaktiviteter øker også antallet brannutrykninger. Det er også en klar sammenheng mellom antall brannutrykninger til gress- og krattbranner og utrykninger til skog- og utmarksbranner, noe som indikerer at gress- og krattbranner raskt kan spre seg til omkringliggende områder.

En hovedkonklusjon er at økt skjøtsel av kystlyngheier markant reduserer brannfaren, spesielt i perioder med tørke, høy temperatur og sterk vind. Dette skyldes at velskjøttede kystlyngheier inneholder minimalt med brennbart materiale og er derfor lite brannfarlige, selv når den generelle brannfaren er høy.

1. Background and introduction

Norwegian coastal heaths form a part of the broader European coastal landscape that spans from Portugal to the Lofoten area in the northern reaches of Norway. These heathlands are limited to the outermost coastal regions and are the product of approximately five millennia of resource utilization by coastal communities. However, these human-influenced coastal heathlands are presently vanishing and have been classified as critically endangered in the Norwegian Red List of Habitats since 2011. It is estimated that over 80 percent of these open coastal heathlands have already been lost (Miljødirektoratet, 2013).

The absence of proper management in coastal heathlands not only results in the loss of valuable cultural landscapes and agricultural productivity but also poses a significant fire hazard (Log et al., 2017; Kvamme and Kaland, 2009). This heightened fire risk is attributed to a combination of factors, including the presence of aged, dead heather alongside the growth of highly flammable species like Sitka spruce and juniper, known to burn with high intensity (Diotte and Bergeron, 1989). Effective management of coastal heathlands is pivotal in mitigating the fire hazard, primarily because young, low-lying heather is notably less susceptible to combustion. This resilience can be attributed, in part, to the higher moisture content found in young heather as compared to the dry, aged heather. This higher moisture content makes the young heather more resistant to drought conditions (Log et al., 2017, Log, 2020). Furthermore, well-managed heathlands exhibit a diminished presence of highly flammable materials, such as aged dead heather, Sitka spruce and juniper, further contributing to reduced fire risk.

The flammability of these coastal heathlands became evident during the winter of 2014, marked by two substantial wildfires – one in Flatanger on January 27th and another on Frøya on January 29th, following an exceptionally dry January. Both fires quickly spread across the landscape, and their containment was impeded by strong winds. In early June 2021, a large fire outbreak occurred on Sotra, resulting in multiple injuries, evacuations, and the destruction of numerous cabins and houses. The dry and hot summer of 2018 marked one of the most devastating years for wildfires in Norway in recent memory, characterized by a twofold increase in wildfire incidents when compared to previous years.

The financial implications of such extensive wildfires are significant, given the substantial allocation of resources, including equipment, manpower, and helicopters, for firefighting efforts. Moreover, these incidents result in the loss of biodiversity, recreational opportunities, property values, and buildings. In many instances, the affected population necessitates evacuation from high-risk areas.

Various studies have underlined the importance of effective maintenance in improving the value of the heathlands (Strange et al., 2007) and reducing heather flammability (Log et al., 2017; Diotte and Bergeron, 1989; Kvamme and Kaland, 2009), including the introduction of grazing animals (Hobbs and Gimingham, 1987). These studies emphasize the significance of regular controlled burning and animal grazing for effective maintenance. Also, Gutierre et al. (2021) discuss how the fire hazard of wildfires is affected by temperature variations. Apt et al. (2023) estimate the effects of weather conditions on forest fires in California applying annual data. However, as far as we are aware, previous studies have not attempted to measure the wildfire risk, identify its factors, and assess the impact of landscape maintenance in reducing this risk simultaneously using regression analysis applying high frequency data. While several previous studies have emphasized the importance of proper heathland maintenance in mitigating fire hazards, the extent of this risk reduction and the number of preventable annual wildfires resulting from enhanced maintenance practices remain unknown. This information is vital for effectively communicating to the public the need for policy measures aimed at enhancing initiatives in this field. Furthermore, it increases the likelihood of securing political support for such policy measures.

In this paper, our primary objective is to quantitatively assess the impact of maintenance levels on the risk of wildfires in coastal heathlands, while accounting for variations in weather conditions and the utilization of these areas for recreational purposes. The rationale behind considering these additional factors is that effective maintenance plays a crucial role in reducing the fire hazard in heathlands frequently used for recreational activities, especially during unfavourable weather conditions. Our objective is to measure the extent of these impacts to evaluate the benefits of intensifying management efforts to decrease the occurrence of wildfires in this type of landscape.

An important aspect of this analysis is the combination of map data with information from both governmental and private sources, allowing for a comprehensive and in-depth exploration of the factors that influence the likelihood of wildfires. Our focus is on fire incidents occurring in grass- and shrublands, which encompass coastal heathland fires, as well as forest fires. We utilise information from maps delineating landscape types and their maintenance status and the patterns of land utilization for recreational activities, in combination with daily records of emergency responses to wildfires, and weather data spanning the period from 2016 to 2018. We combine and analyse these different data sources by using regression analysis, specifically employing the random effects Poisson-distributed panel data specification. This enables us to estimate the influence of multiple factors, such as weather conditions, land use, maintenance and the use of coastal heathlands for agricultural and recreational purposes, on the number of wildfire emergencies attended to by the fire department.

In Section 2, we provide an overview of the data sources used, explaining how they are combined, and offer descriptive statistics for the primary variables employed in our analysis. Section 3 details how these data are employed in the statistical panel data model to quantify the impact of various factors on wildfire risk. The empirical results are presented in Section 4. In this section, we illustrate how weather conditions and maintenance influence the fire hazard, and how the effects of maintenance change with shifting weather conditions. Section 5 includes the creation of scenarios for improved maintenance and calculating the annual reduction in the number of wildfires. Finally, the last section presents concluding remarks, summarizing the findings and insights derived from this analysis.

2. The data

For our analyses, we combine several publicly available data sources. Data regarding the distribution and attributes of Norwegian coastal heathlands were obtained from the map database for key habitats maintained by the Norwegian Environment Agency, referred to as 'Naturbase.' This extensive map database categorises different habitat types within the landscape, including the identification of coastal heaths as one of these specific habitat types. Moreover, 'Naturbase' offers valuable insights into the maintenance status of individual heather moors, alongside details regarding the existence of maintenance plans and management agreements at the time of data registration. We also collected maps containing information about areas prone to overgrowth and locations with grazing animals from the map database of the Norwegian Institute of Bioeconomy Research (NIBIO). These maps were then combined with map layers from 'Naturbase' that feature areas with coastal heathlands. This combination of data allowed us to calculate the total area undergoing overgrowth within coastal heathlands and to identify the specific locations where animals graze within these areas. Subsequently, this information was layered upon maps of Norwegian municipalities and aggregated at the municipality level. This map information data were then merged with other datasets accessible at the municipality level.

Data regarding emergency responses to wildfires have been sourced from the Norwegian Directorate for Civil Protection (DSB)'s fire statistics database known as BRIS. The dataset from BRIS utilized for this analysis covers information related to the daily number of emergency calls per municipality concerning wildfires during the period spanning from January 1st 2016 to December 31st 2018. BRIS provides comprehensive data, including the classification of the fire emergency type. This analysis is primarily focused on two specific categories of fires: grass- and shrubland fires, as well as forest fires. Notably, fires occurring in coastal heathlands are subsumed within the classification of grass- and shrubland fires. Given the potential for wildfires to rapidly spread across various terrains, our analysis also includes forest fires.

Weather data contain information regarding precipitation (measured in millimeters over the last 24 hours), temperature (measured in degrees Celsius), and wind conditions (measured in meters per second). These measurements are conducted three times daily at weather stations located across the country. This dataset is sourced from the Meteorological Institute's weather database. This weather data are linked to the corresponding municipality where the respective weather station is situated.

Data concerning human activity in coastal heathlands are sourced from multiple sources. Mapping data related to outdoor activities are recreational area maps from the Norwegian Environment Agency's map database. By overlapping these recreational area maps with map layers highlighting coastal heathland regions, we identify and isolate recreational zones that either intersect with or are situated within a 1-kilometer radius of coastal heathlands. The Norwegian Environment Agency's map database further contains details concerning user frequency, accessibility, and attributes specific to each recreational area. Information about marked paths and trails is obtained from the Norwegian Mapping Authority's map repository for hiking and outdoor routes. These data are then superimposed onto map layers from Naturbase of coastal heathlands, enabling us to calculate the total length (in meters) of marked hiking paths and trails that traverse through coastal heath areas. Finally, we used map information from Statistics Norway's Geodatabase of buildings (Matrikkelen) to quantify the number of structures and dwellings situated within or near coastal heathlands. These various map datasets are subsequently overlaid with maps representing Norwegian municipalities and the information is aggregated.

It is worth noting that all the data extracted from map layers are snapshot measurements, and their timeframes differ across different geographic regions. In this analysis, we have chosen to employ the municipality as the spatial dimension.[1] However, the majority of the information utilized in this study demonstrates both temporal and cross-sectional variation. Weather data, for instance, are collected three times daily, and data on fire emergencies include daily counts of emergency calls per municipality for the period spanning from 2016 to 2018. To create an organised panel dataset, we aggregate to a weekly format.[2] In practical terms, this involves aggregating variables, such as daily emergencies per municipality, into a weekly count for the three-year period between 2016 and 2018. Likewise, weather data, which are gathered at multiple weather stations across the country, are aggregated at multiple levels. First, the daily figures are averaged for all weather stations within a given municipality. Subsequently, these figures are combined across all weather stations within the municipality, culminating in weekly summaries. Precipitation data are aggregated over time, while temperature data are averaged. However, it is important to note that not all weather stations consistently record all three weather variables, and there are instances where measurements may be temporarily unavailable (due to maintenance or other reasons). Consequently, missing values for certain weather variables within specific municipalities during specific weeks are substituted with the respective county-wide average values. This procedure avoids reducing the number of observations

[1] Several municipal mergers occurred between 2016 and 2018. In our empirical analysis, we have structured the data based on the municipal classification in 2018, ensuring consistency throughout the entire time period.
[2] We opted to aggregate this data on a weekly, rather than a daily basis, due to limitations in the capacity of the statistics program used for conducting the regression analysis.

without biasing the estimation results. The combined weather data are subsequently matched with the wildfire emergency data, merging them by municipality, year, and week. The resultant panel data set is comprehensive with observations for 419 municipalities spanning 158 weeks.

Table 1 provides descriptive statistics for the number of weekly emergency incidents related to forest fires and grass and shrub fires, along with weather conditions, across all municipalities from 2016 to 2018. During this period, we find that, on average, there were approximately 0.04 emergency calls per week per municipality for grass and shrub fires and about 0.02 calls per week for forest fires. Note that for both categories of wildfires, most municipalities had no emergency incidents during a given week. To be specific, 97 percent of the municipalities reported no grass and shrubland fire emergencies, and 98 percent reported no forest fire emergencies. However, it is worth recognising that there is a significant variation in the number of fire incidents observed, largely due to the increased wildfire activity during the summer of 2018. Notably, for both types of fires, the highest number of emergency calls recorded for a municipality in a single week was 15. Furthermore, the standard deviation is large, ranging from six to ten times greater than the respective averages. This large variation is a result of differences in fire occurrences across regions and changes over time. Additionally, we have observed substantial weather fluctuations during this period. This variability enables us to study the impact of these weather-related factors on the likelihood of wildfires.

Tabell 1: Descriptive statistics for the dependent variables and weather variables included in the statistical analysis for all municipalities (N=419) over all weeks in the period 2016 to 2018 (T = 158)

	Mean	Std. dev.	Min	Max
Number of grass and shrub fires per week per municipality	0.04	0.26	0.00	15.00
Number of forest fires per week per municipality	0.02	0.21	0.00	15.00
Total precipitation (mm) across all weather stations in the municipality per month	101.04	84.90	0.00	796.45
Average temperature (°C) per month across all weather stations in the municipality	5.46	6.88	-18.69	25.88
Average wind (m/s) per month across all weather stations in the municipality	3.91	1.71	0.00	16.47
Total precipitation (mm) per week across all weather stations in the municipality	23.67	28.09	0.00	328.60
Number of days without precipitation per week across all weather stations in the municipality[a)]	1.81	1.80	0.00	16.33
Average temperature (°C) per week across all weather stations in the municipality	5.45	7.27	-25.83	25.05
Average wind (m/s) per week across all weather stations in the municipality per week	5.64	2.49	0.00	26.13

[a)] The number of days without precipitation are aggregated over all weather stations within the municipality. As a result, the maximum value may exceed 7.

3. Econometric specification

To examine how the number of emergency responses to wildfires relates to various factors influencing fire risk, we employ a panel data estimation method. This relationship can vary over time (weekly) due to factors like changing weather conditions, and it can also differ across municipalities because of variations in terrain, recreational activities, and climate. We use a two-way model that considers both these variations simultaneously and includes random municipality effects.

Additionally, it is crucial to account for the fact that wildfire emergencies are relatively infrequent. Most weeks have no recorded emergencies in a municipality. In fact, around 97 percent of observations for grass and shrub fires and 98 percent for forest fires are zeros. Moreover, the number of calls related to wildfires can only take integer values. Hence, the dependent variable in our regression model follows a Poisson distribution, as explained by Greene and Zhang (2019), Wooldridge (2010), chapter 19, and Boucher and Denuit (2015).

To consider all these aspects, we have chosen to estimate a Poisson panel data model with random effects (Green and Zhang, 2019; Wooldridge, 2010).[3] In this model, the parameters to be estimated (α, β) are included in the regression function as follows:

$$\ln(\lambda_{it}^{*}) = \alpha + \boldsymbol{\beta}\mathbf{x}_{\mathbf{it}} + \varepsilon_i, \tag{1}$$

where $\mathbf{x}_{it}$ is a vector of explanatory variables for the number of emergencies in municipality i in week t and variables that influence the variation in the relationship between different municipalities.[4] $\alpha + \varepsilon_i$ represents the random effects, where $\exp(\varepsilon_i)$ is a gamma-distributed error term with parameters (θ, θ), so that the expected error term, $\mathrm{E}(\exp(\varepsilon_i))$, has mean 1 and variance $1/_{\theta} = \alpha$. In this model, the conditional expectation for the number of emergencies per week per municipality (y_{it}) given $\mathbf{x}_{it}$, will be given by:

$$\mathrm{E}(y_{it}|\mathbf{x}_{it}) = \lambda_{it} \,. \tag{2}$$

This implies that $\ln(\lambda_{it}^{*}) = \ln\left(\lambda_{it} \exp(\varepsilon_i)\right)$, so that $\mathrm{E}(\ln(\lambda_{it}^{*})\,|\mathbf{x}_{it}) = \ln(\lambda_{it}) = \boldsymbol{\beta}\mathbf{x}_{\mathbf{it}} + \alpha$. If you derivate the expected number of emergencies in Equation (2) with respect to a change in one of the explanatory

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[3] We estimated both a fixed and a random effects specification of the Poisson and the Negative Binominal models. The random effects Poisson panel data model yielded the best results.

[4] See Tables 2 and 3 for a summary of the variables included in the estimations.

variables (x_{it}), e.g. precipitation, you will find an expression of how a change in this factor affects the expected number of callouts:

$$\frac{\partial E(y_{it}|\mathbf{x}_{it})}{\partial x_{kt}} = \beta_k \lambda_{it} = \beta_k \exp(\alpha + \boldsymbol{\beta}\mathbf{x}_{it}) \ . \qquad (3)$$

Due to the non-linear nature of the estimation model, the marginal effects of a change in one of the explanatory variables on the dependent variable is a function of the estimated parameter for the variable that has changed multiplied by the expected value of the dependent variable at a particular point of observation for all explanatory variables. This means that the impact of a factor, like reduced precipitation on fire hazard, is contingent upon the observation of all variables, including costal heathland management. This can be seen, as the influence of a change in an explanatory factor, as outlined in Equation (3), is a function of the expected count of emergencies, as specified in Equation (2). Furthermore, the count of emergencies is influenced by the levels of all explanatory factors as defined in Equation (1). As a result, an estimated regression coefficient represents the effect on the logarithm of the expected weekly count of wildfire emergencies per municipality caused by changes in a specific explanatory variable while holding all other explanatory variables in the model constant (ceteris paribus).

4. Factors Influencing the Fire Risk

Numerous factors influence of fire hazard, either independently or in conjunction with other factors. Specifically, we anticipate that weather conditions play a significant role, and we expect this role to change depending on the level of maintenance. The key question is the magnitude of these effects and how their combined impact shapes the fire hazard. First, we present our estimation results and illustrate the nonlinear relationship between weather conditions and fire hazard. Then, we investigate the combined effects of maintenance measures and weather conditions. These findings are subsequently applied in Section 5 to forecast the reduction in the annual count of fire incidents under different scenarios involving increased maintenance.

4.1. Estimation results

The factors denoted as $\mathbf{x}_{\mathrm{it}}$ in the regression encompass a variety of explanatory variables. These explanatory variables are categorized into four subgroups: Group i) comprises variables that describe weather conditions. Here, we include both weekly and monthly variables, as prolonged periods of certain weather conditions may accelerate the increase in fire hazard. Group ii) encompasses variables characterising the features of the municipality's coastal heathlands. Group iii) consists of variables detailing human activity in coastal heathlands. Finally, group iv) provides insights into the potential for fire spread across different types of wildfires. Variables in groups i) and iv) exhibit spatial (municipality) and temporal (weekly) variation, while those in groups ii) and iii) vary solely among municipalities. Note that only statistically significant explanatory variables in groups iii) and iv) are included in the estimation.

Our regression model approximates the logarithm of the expected number of emergency calls related to wildfires through a linear function, as described by Equations (1) and (2).[5] In our analysis, the dependent variables, i.e., the variables being explained, are the count of emergency calls for a) grass and shrubland fires and b) forest fires on a per-week basis for each municipality. The estimation results from these regressions are presented in Tables 2 and 3, respectively. In these tables, the second column presents the estimated regression coefficients, while the third column provides the p-values associated with these coefficient estimates.

Regarding the weekly count of emergency incidents related to grass and shrubland fires in each municipality, the findings in Table 2 reveal the significance of all the weather condition variables. This

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[5] We conducted the regression analysis using the LIMDEP® 9.0 software. See Greene (2007), pp. E 26–17 for more information.

implies that, even when we account for the number of days without precipitation during a given week, the quantity of precipitation remains a crucial factor influencing the fire risk, and vice versa. Moreover, the results suggest that higher mean temperatures and increased wind speeds during the current week are associated with an elevated fire hazard. The only estimated coefficient displaying a somewhat unexpected direction of influence is the effect of mean wind speeds throughout the current month, which unexpectedly reduces the risk of grass and shrub fires. One explanation for this outcome is that longer-lasting, more extensive storm systems characterised by sustained strong winds (sufficient to impact the average wind speeds over an entire month) often carry moisture-laden air with them that reduces the flammability of overgrown heaths. In such cases, this variable might encapsulate correlations arising from the interplay of humidity and precipitation, common in such extended storm systems.

Table 2: Poisson panel data estimation with random effects of the number of calls to grass- and shrubland fires per week per municipality in the period from 1st January 2016 to 31st December 2018a)

Explanatory variables	**Coefficient**	***p*-value**
($\boldsymbol{\alpha}$)	1.055	0.0000
Effects of explanatory variables ($\boldsymbol{\beta}$)		
Constant (β_0)	-3.611	0.0000
i) Weather conditions		
Total precipitation this month (mm)	-0.005	0.0000
Average wind speed during the month (m/s)	-0.171	0.0000
Number of days without precipitation this week	0.146	0.0000
Total precipitation this week (mm)	-0.031	0.0000
Average temperature this week (ºC)	0.057	0.0000
Average wind speeds this week (m/s)	0.162	0.0000
ii) Properties of the costal heathlands		
Number of areas with costal heathlands in the municipality	0.134	0.0000
Total areal of costal heathlands within a municipality (hectare)	0.002	0.0416
Average maintenance status on the costal heaths within a municipality (1 = Good status, 2=Weak status, 3=No maintenance, 4=Moderately to heavily overgrown, 5=Poor status)	0.552	0.0000
Share of the costal heathland area that are growing over	1.057	0.0000
Number of costal heathland areas in the municipality with a maintenance/management plan	-0.160	0.0000
Number of costal heathlands in the municipality with grazing animals	-0.104	0.0166
iii) Human activities		
Number of registered recreational areas in and near costal heathlands (1 km circumference) with good accessibility	0.573	0.0000
Number of costal heathlands in a municipality with marked trails	0.346	0.0015
User frequency for registered recreational areas in or near costal heathlands in a municipality (1 = Much use, 2 = Some use, 3 = Little use) [b)]	-0.060	0.0017
Number of houses localised within a costal heathland area	0.359	0.0020
iv) Risk of spread		
Number of forest fires in the municipality the same week	0.225	0.0000

[a)] In this dataset, we have observations for 419 municipalities over 158 weeks.
[b)] Note that the user frequency variable is encoded so that the high number means that the recreational area is little used.

Moreover, Table 2 sheds light on several attributes of coastal heathlands that contribute to our understanding of the frequency of emergency calls related to grass and shrub fires. The findings suggest that, on average, coastal heathlands exhibit a greater fire hazard in comparison to other habitats where similar fires may occur. This increased susceptibility can be attributed, in part, to the presence of aged, dry, and deceased heather covering the heathlands. Furthermore, the presence of highly flammable vegetation, such as juniper and Sitka fir, increases as coastal heathlands become overgrown. The fire risk rises with the size of coastal heathlands in a municipality, the proportion of these areas that are overgrown, and the extent of overgrowth they display. Furthermore, our regression analysis highlights that the presence of grazing animals in coastal heathland areas mitigates the fire risk. This finding underscores that having grazing animals on coastal heathlands yields an additional, favorable effect on fire hazard beyond good maintenance practices. This is because coastal heathlands require a high degree of maintenance for animals to graze because the animals need to graze on plants like herbs, grass, and young heather. If the heather is old and the heathlands are not adequately maintained, the grazing value is significantly reduced (Miljødirektoratet, 2013; NIBIO, 2017). The act of grazing itself also plays a role in suppressing fire risk by controlling vegetation growth and preventing overgrowth. Additionally, the results demonstrate that municipalities with established maintenance and management plans for their coastal heathlands experience a significant reduction in fire risk.

The estimation results reveal that human activity in, and around coastal heathlands increases the fire risk. There are three variables that measure the degree of human involvement in these areas, and each of them contributes to an increase in fire risk: The number of registered recreational areas in and near (1 km) coastal heathland with good accessibility,[6] the average user frequency of recreational areas that overlap or are located in the 1 km perimeter of a coastal heathland,[7] and the number of coastal heaths in the municipality that has a marked hiking trail that passes through the area. Our analysis also indicates that the existence of homes within these heathlands heightens the risk of grass and shrub fires. This heightened risk can also be partially ascribed to the possibility of fires spreading from structures to the surrounding landscape. However, our data lack the necessary information on house fires required to isolate this effect.

[6] The level of accessibility to a designated recreational area is influenced by various factors, including rights of access, physical infrastructure, transportation, and information availability. The assessment of an area's accessibility is rated on a scale of 1 to 5, and this information is included in the map layer. In this context, good accessibility refers to the average proportion of designated recreational areas in a municipality that either overlaps or is in close proximity (within 1 km) to coastal heathlands and has received the highest two scores on the accessibility scale.

[7]Note that a *high* value of the user frequency variable indicates a *low* user frequency.

Finally, we introduced the count of forest fires within the municipality during the current week. This variable is intended to capture the potential effects of fire spreading from forest to grass and shrubland. The findings indicate a significant correlation between these two categories of fires. It is important to note that this effect can work in both directions, as coastal heathlands might also impact the risk of forest fires by influencing the potential for fire to spread from heathlands to nearby wooded regions. Therefore, we performed a comparable regression analysis to determine the count of emergency incidents associated with forest fires for each municipality on a weekly basis. This analysis utilized a Poisson panel data model with random effects as well. The results derived from this analysis are presented in Table 3. In this estimation, we only include explanatory variables that had significant explanatory power at a 5 percent level in relation to fire risk.

Table 3: Estimation results for a Poisson panel data estimation with random effects for the number of emergencies to forest fires per week per municipality in the period from 1st January) 2016 to 31st December 2018[a)]

	Coefficient	*p*-value
(**α**)	0.867	0.0000
Effects of explanatory variables (**β**)		
Constant (β_0)	-4.605	0.0000
Total precipitation this month (mm)	-0.012	0.0000
Average temperature during the month (ºC)	0.093	0.0000
Number of days without precipitation this week	0.100	0.0000
Total precipitation this week (mm)	-0.012	0.0000
Average temperature this week (ºC)	0.065	0.0000
Number of registered recreational areas in and near costal heathlands (1 km circumference) with good accessibility	0.324	0.0001
User frequency for registered recreational areas in or near costal heathlands in a municipality (1 = Much use, 2 = Some use, 3 = Little use)[b)]	-0.102	0.0010
Number of costal heathlands in the municipality with frequent use	0.413	0.0171
Length of marked trail in the municipality going through costal heathlands (km)	0.582	0.0000
The existence of costal heaths in the municipality (0, 1)	0.608	0.0000
Number of grass and shrub fires in the municipality the same week	0.229	0.0000

[a)] In this dataset, we have observations for 419 municipalities over 158 weeks.
[b)] Note that the user frequency variable is encoded so that the high number means that the recreational area is little used.

The estimated coefficients of all meteorological variables display the anticipated signs. The two monthly variables; total precipitation and the average temperature for the current month, are also found to be statistically significant. While the average wind conditions for the month do not emerge as significant for forest fires, unlike grass and shrubland fires, the average temperature for the month remains statistically significant in this estimation. This divergence might be attributed to the regional differences in the occurrence of these fire types. Grass and shrub fires are more prevalent along the coast, which is frequently subjected to maritime storms. In contrast, the larger forested areas are typically located further inland, where the elevated summer temperatures contribute to vegetation drying.

Furthermore, Table 3 demonstrates that human activity in coastal heathlands has a significant impact on forest fires. This may be a result of the spreading effects that extend beyond what the variable accounting for the number of grass and shrubland fires captures, as well as the presence of coastal heathlands in the municipality, which likely captures a significant portion of the spread. It could also be due to the occurrence of certain activities in recreational areas that encompass both forest and heathlands. Notably, all the significant impacts of outdoor activities align with expectations regarding their influence on fire hazard.

It is worth noting that the presence of coastal heathlands in a municipality has a significant influence on the expected number of forest fires, distinct from the impact of grass and shrub fires within the same municipality during the same week. This observation indicates that the likelihood of fire spreading is more prominent in grass and shrub fires within coastal heathlands compared to fires in other types of grass and shrub habitats. This is likely due to the fact that coastal heathlands, on average, demonstrate higher levels of flammability and fire hazard compared to other natural environments where grass and shrub fires may take place, making fires in coastal heathlands more susceptible to spreading to adjacent forests.

4.2. The weather effects on fire risk

The results presented in Tables 2 and 3 provide insight into the direction and the statistical significance of the factors that account for the variations in the weekly number of emergency incidents related to grass and shrub fires and forest fires per municipality. Given that the regression functions are inherently non-linear, the impact, often referred to as the marginal effect, on the expected number of emergencies resulting from a change in an explanatory variable, depends on the levels of all the variables included within the estimated regression functions (as discussed in in section 3). To illustrate, consider the case of a temperature increase. The changes in the expected number of emergency calls are contingent on several factors, including whether the temperature was initially cold or hot, and the concurrent levels of all other explanatory variables such as precipitation, maintenance practices, and human activity in coastal heathlands.

We have calculated the marginal effect of each explanatory variable, which varies across both location and time (e.g., weather conditions), on the expected number of emergency incidents related to grass and shrubland fires. Additionally, we have explored how this influence changes in relation to the values of other variables, including maintenance indicators. These calculations are made possible by utilising Equations (1) - (3), the estimated regression coefficients, and the mean values of the explanatory variables used in the estimation.

In the following sections, we will visually illustrate the impact of alterations in different explanatory variables on the expected number of emergency calls. These visual representations will primarily focus on incidents involving grass- and shrubland fires, as our main objective is to investigate the impact of coastal heathland management on wildfire risk.

Figure 1: Expected number of emergencies to grass- and shrubland fires per municipality per week as a function of changes in mean temperature

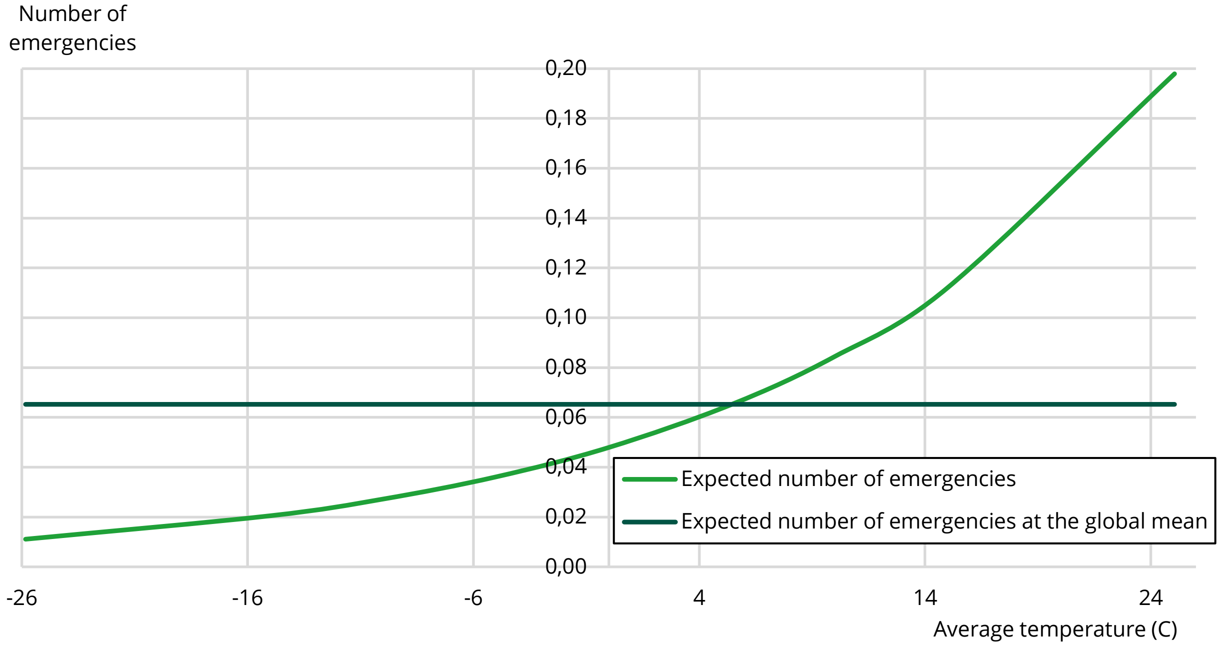
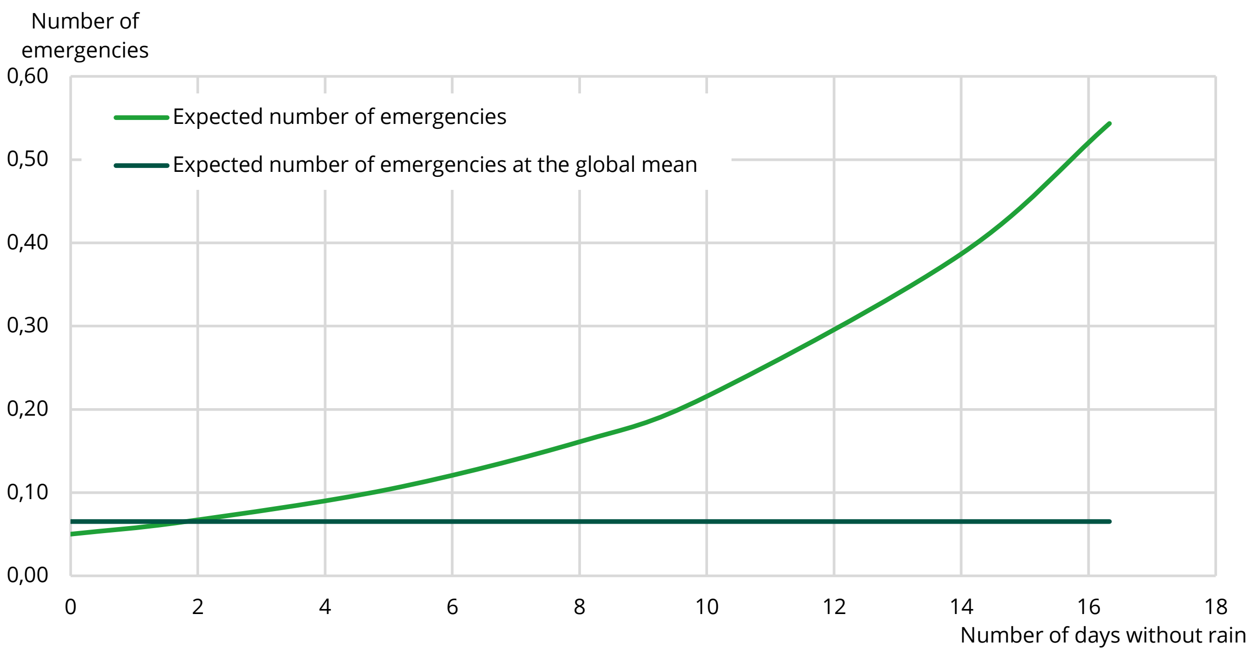


Figure 1 depicts how the expected number of emergencies related to grass- and shrubland fires varies with the average temperature recorded across all weather stations within a municipality during a given week. In Figure 1, the expected value (indicated by the green line) is calculated by evaluating all explanatory variables, except the average temperature, at their mean values for all municipalities and weeks. The curve begins at the minimum value of the variable and extends to the maximum value. The black line represents the expected number of grass- and shrubland fire emergencies at the mean for all variables, including the average temperature during the current week (referred to as the global mean). Note that the black line intersects with the green line precisely at the point corresponding to the average temperature across all observations. This black line, capturing the expected number of emergencies at the global mean, serves as a reference point for scale in comparisons across figures. The figure shows that the expected number of emergencies is lower during colder periods compared to warmer ones. We also see from Figure 1 that, at lower temperatures, an increase in the mean temperature does not increase the fire risk very much. However, once the average temperature surpasses 10-15°C, any further temperature increases lead to a progressively greater rise in the risk of wildfires.

The results of the estimations, given in Table 2, highlight the significant role of precipitation in accounting for the variation in the number of emergency incidents associated with grass- and shrubland fires. In Figure 2, we visualise how the expected number of grass- and shrubland fires per municipality per week fluctuates with the total number of days without precipitation during the current week, considering all weather stations within the municipality.[8] In this figure, the green line depicts the relationship between the expected number of fires and the number of days without precipitation for the mean municipality for the mean week. Meanwhile, the black line serves as a reference point, signifying the global mean, as shown in Figure 1.

Figure 2: Expected number of emergencies to grass- and shrubland fires per municipality per week as a function of the number of days without precipitation (summed up over all weather stations per municipality per week)

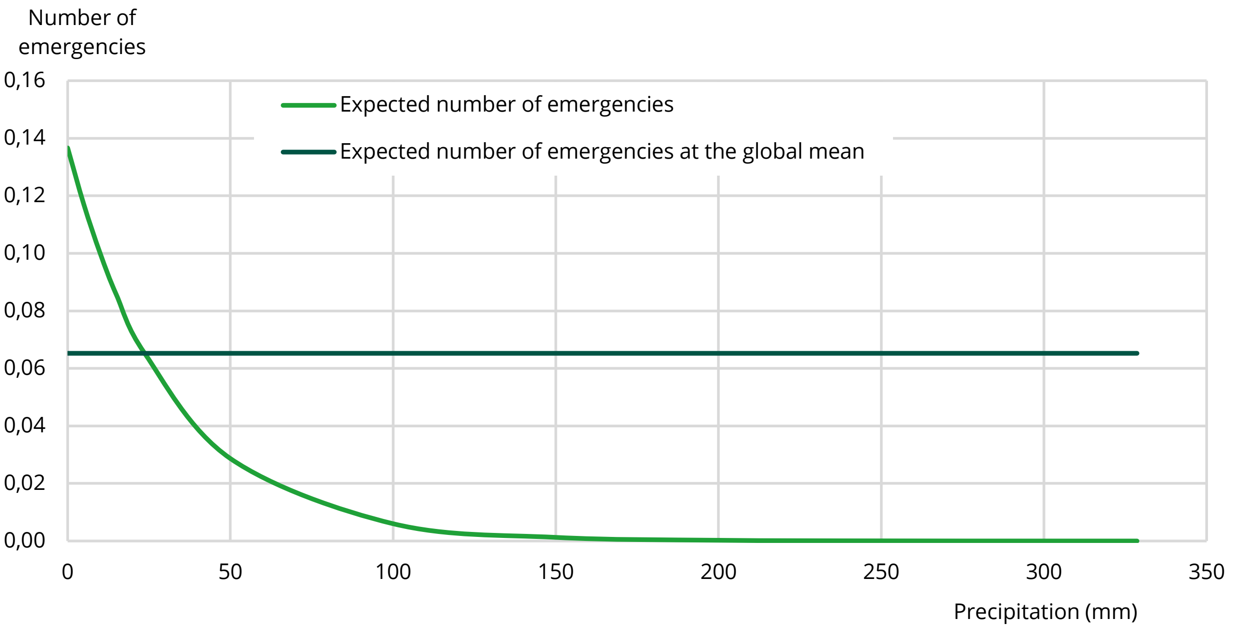


The figure illustrates that the expected fire hazard exhibits a broader range of outcomes compared to the effects of average temperatures (compare Figures 1 and 2). It implies that an extended period of drought, with little or no precipitation, has a more pronounced impact on the risk of wildfires in grass- and shrubland areas than the average temperature. The longer one goes without precipitation, the more pronounced the increase in the number of expected wildfire incidents for each additional day without rainfall.

[8] The number of days without precipitation are aggregated over all weather stations within the municipality. As a result, the maximum value may exceed 7.

The frequency of emergencies related to grass- and shrubland fires per week is also influenced by the amount of precipitation during that week. Figure 3 illustrates this relationship. The figure reveals a significant decline in fire risk, approaching zero when precipitation levels are sufficiently high. It is worth noting that the scale in this graph is much lower than that for the number of days without precipitation. This is because this variable captures supplementary factors associated with precipitation levels, which are separate from drought conditions, already accounted for by the number of days without precipitation. It is important to understand that the smaller scale does not diminish the significance of precipitation; rather, it signifies that a substantial portion of the impact of reduced precipitation on fire hazard is accounted for by the drought effect, as measured by the number of days without precipitation.

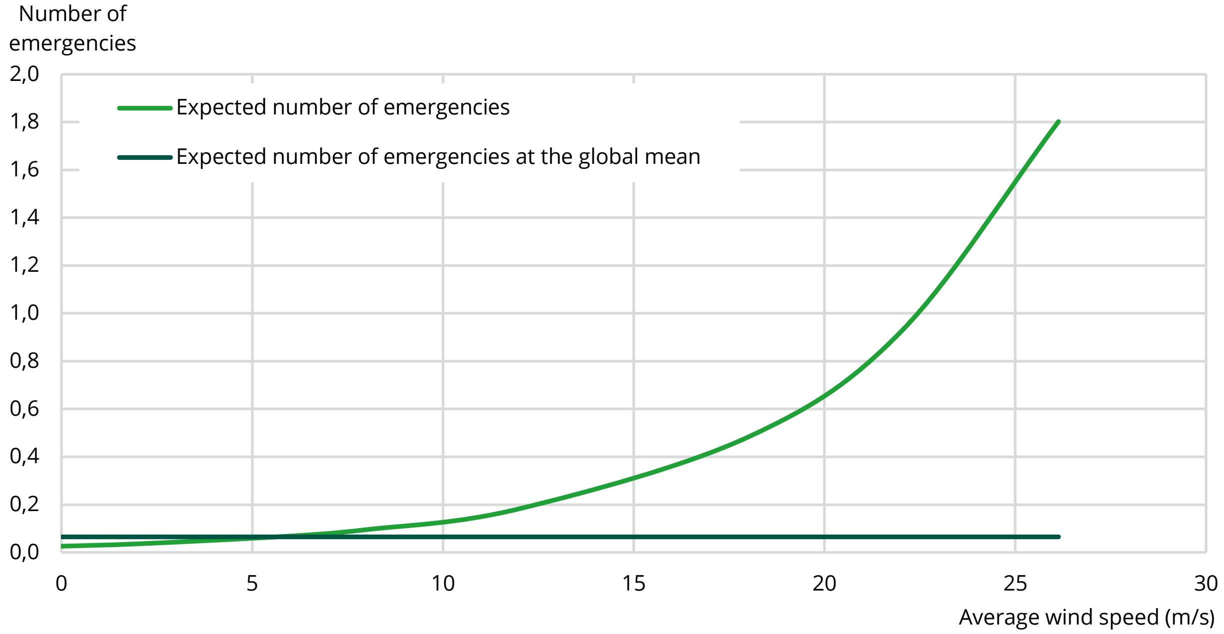
Figure 3: Expected number of grass- and shrubland fires per municipality per week as a function of the amount of precipitation per week as a function of total precipitation for all weather stations per municipality per week



We see that the decline in the frequency of emergency incidents related to grass- and shrubland fires approaches zero as the volume of precipitation increases. This suggests that the risk reduction due to increased precipitation is less significant during weeks with substantial rainfall. Conversely, in dry conditions, increased precipitation can significantly reduce the risk of grass- and shrubland fires. These effects should be interpreted as complementary to the indicator for drought periods, as measured by the number of days without precipitation presented in Figure 2. Increased precipitation not only helps alleviate drought conditions but also contributes to a further reduction in fire risk. This effect is particularly large in cases when precipitation is low, as additional precipitation has a more pronounced impact on the fire hazard in such periods compared to periods with abundant rainfall.

Wind speed also plays a crucial role in heightening the risk of grass- and shrubland fires. Increased wind speeds contribute to the drying of vegetation during periods characterised by limited or no precipitation and high temperatures. Moreover, strong winds increase the risk of flare-ups and facilitate the rapid spread of fires. Figure 4 visually illustrates the impact of wind conditions on the occurrence of emergency incidents related to grass- and shrubland fires. The green line in the figure shows that the fire risk increases notably with an increase in the average wind speed (measured in meters per second). Note that the scale depicted here, represented by the black line, is considerably larger than what is observed in some other weather conditions (see Figures 1, 2, and 3). This indicates that wind conditions during the same week as the fire outbreak have a substantial impact on the fire risk, especially when the average wind speed surpasses 12 meters per second. This suggests that wind supplies oxygen to the flames and promotes fire spread through spark dispersion, constituting the dominant factors captured by the coefficient of average wind speed.

Figure 4 **Expected number of grass- and shrubland fires per municipality per week as a function of average wind speed across all weather stations per municipality per week**



The figure shows that when there is not much wind, an increase in wind speed does not raise the fire hazard as much as when it is already windy. In this case, the impact of wind is much stronger than that of other weather factors, indicating that wind plays a crucial role in explaining the fire risk, assuming everything else remains constant.[9] Overall, it seems that a combination of an extended period without precipitation and strong winds substantially contributes to the risk of grass- and shrubland fires.

4.3. The effects of heathland management on fire risk

As mentioned in Section 4.1, our research shows that when coastal heathlands become overgrown and are not managed well, the risk of both grass- and shrubland fires and forest fires increases. This is because flammable materials build up, and fires spread quickly in such areas. When people use these heathlands for recreational activities, the risk goes up even more. On the other hand, if proper maintenance and management plans are in place, and if animals graze in these areas, the risk of fires is reduced. In this section, we will take a closer look at how maintenance affects fire risk and how this effect is influenced by the weather.

In our estimation, we use three variables to measure the impact of maintenance in the municipality's coastal heathlands: the proportion of coastal heathland areas in the municipality that are considered as being in the process of becoming overgrown, the number of coastal heathlands in the municipality with management and maintenance plans, and the number of coastal heathlands in the municipality with grazing animals.

We use the results from our estimation, along with Equations (1) – (3), to explore how the expected number of weekly emergency calls related to grass- and shrubland fires changes in response to efforts to maintain coastal heathlands within that municipality. To gain a better understanding of the significance of these other variables, we illustrate the impact of maintenance measures in relation to various weather conditions. This is because we anticipate that maintenance becomes particularly crucial during dry, warm, and windy conditions. Consequently, we calculate how the effects of three maintenance measures (grazing, reducing the area of regrowth, and the use of maintenance and management plans) vary concerning the number of days without precipitation, temperature, precipitation, and average wind speeds during the current week. Given that the expected number of weekly emergencies also relies on all other factors included in the model, we chose to set the values of these variables to their average levels for this analysis.

[9] Note that the predicted effects of an explanatory variable represent the net effects in the case where variables may be correlated. The difference in scale may thus be because wind conditions are exclusively captured by one variable, whereas drought and precipitation are highly correlated and captures the same effects.

We predict the number of emergencies based on three levels of maintenance measures: i) at the minimum values of these variables, ii) at the average value, and iii) at an upper level. The upper level is set to two standard deviations above the average values for the number of heathlands in the municipality with management and maintenance plans, and those with grazing animals, respectively.[10] For the proportion of coastal heathlands that are becoming overgrown, we assign a value of 1 as the upper level, indicating that all the heathlands in the municipality have completely become overgrown.

Since these measures are only applicable to municipalities that possess coastal heathlands (referred to as coastal heathland municipalities), our calculations are based on descriptive statistics specific to these coastal heathland municipalities. It is important to note that the results should be understood as the impact of maintenance measures designed for coastal heathlands in these coastal heathland municipalities only.

Grazing animals

Figure 5 illustrates how the presence of grazing animals in coastal heathlands reduces the fire risk and how this impact varies with the average temperature in a coastal heathland municipality. The black curve represents the calculated fire risk for a coastal heath municipality with an average number of grazing animals. The green curve indicates the predicted fire risk in a scenario where no grazing animals are present on any of the heathlands in the municipality. The blue curve shows the predicted fire risk when the number of coastal heathlands with grazing animals is set to the upper value for the prediction (two standard deviations above the mean). The figure clearly illustrates that the presence of grazing animals in coastal heathlands reduces the fire risk, with this reduction being particularly pronounced during periods of high average temperatures.[11]

Figures 6, 7, and 8 display comparable curves depicting how the presence of grazing animals in coastal heathlands mitigates the fire risk under different weather conditions, including periods of drought (measured by the number of days without precipitation), precipitation levels (mm), and average wind speeds (in meters per second). All three figures reveal that the presence of grazing animals in coastal heathlands significantly reduces the fire risk. This effect is particularly pronounced

[10] We do not include the maximum values of the variables in our calculations for management plans and grazing animals. This is because the empirical distribution of these variables has a long tail, causing the maximum value to differ significantly from the bulk of the data. Therefore, we have chosen to utilize an upper threshold that aligns better with the majority of observations. Notably, when we employed the observed maximum value in the analysis, it yielded the same conclusions, but with more pronounced effects.
[11] These figures will differ from the results shown in Figure 1 because they are calculated using the means specific to coastal heath municipalities, whereas Figure 1 is based on the mean values across all municipalities.

when adverse weather conditions intensify the fire hazard, such as during hot, dry, or windy conditions.

Figure 5: Estimated effects on the expected number of calls to grass- and shrubland fires in coastal heath municipalities per week as a function of average temperature across all weather stations per municipality per week

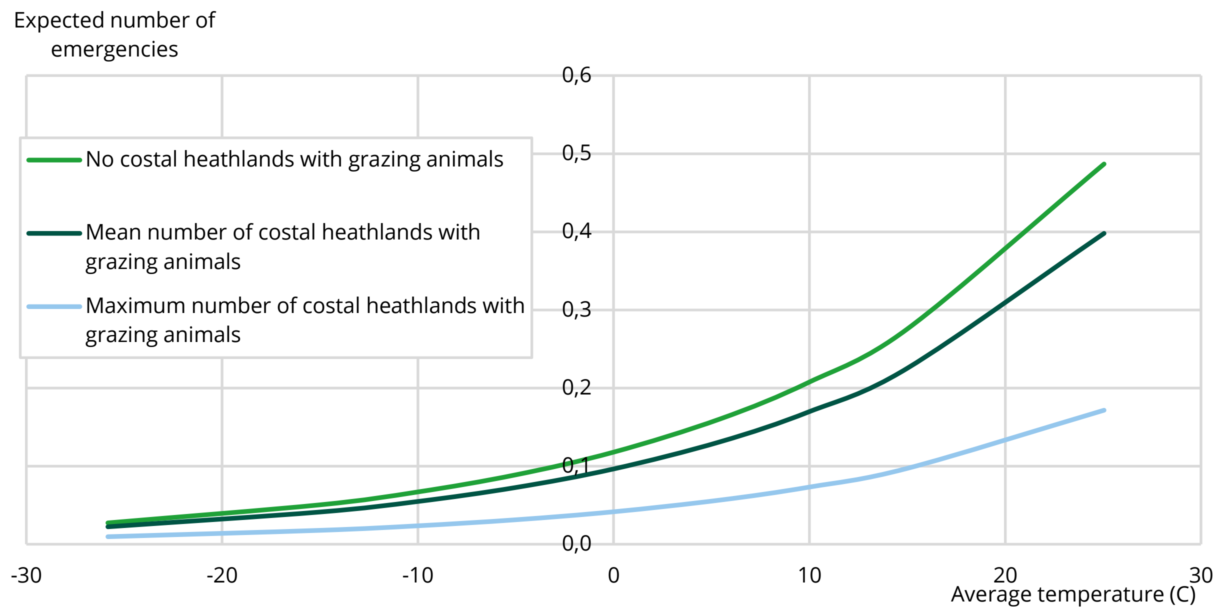
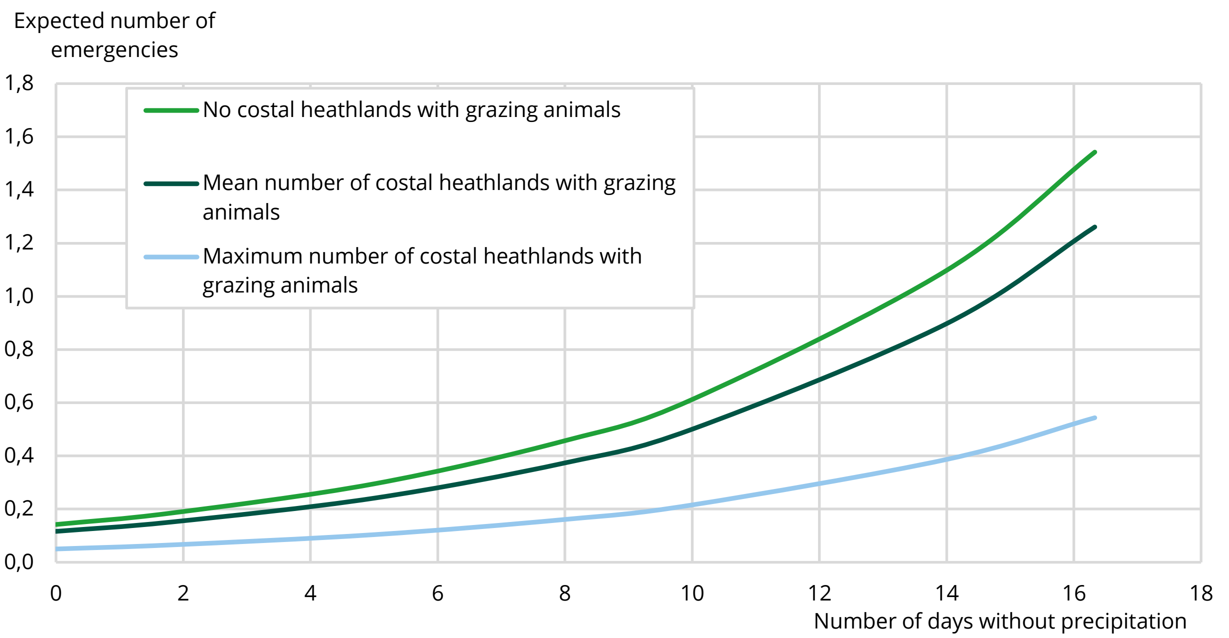


Figure 6: Estimated effects on the expected number of calls to grass- and shrubland fires in coastal heath municipalities per week as a function of the number of days without precipitation across all weather stations per municipality per week



Notice the variations in fire risk as we transition from average to extreme weather conditions. These variations become more noticeable when the weather is hot, dry, or windy. In an extreme situation where all these conditions are high, the reduction in fire risk due to the presence of grazing animals would be even more significant, as well-maintained heathlands with grazing animals tend to have a lower risk of fires, as these animals assist in managing the vegetation, preventing excessive growth.

Figure 7: **Estimated effects on the expected number of calls to grass- and shrubland fires in coastal heath municipalities per week as a function of mean precipitation across all weather stations per municipality per week**

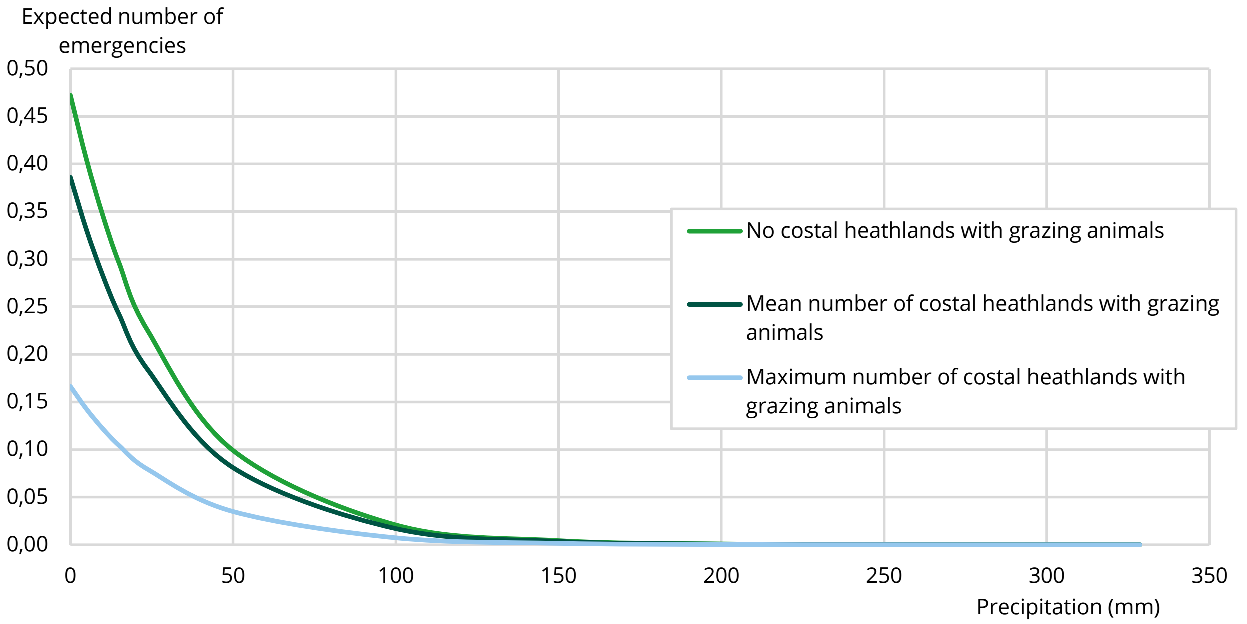
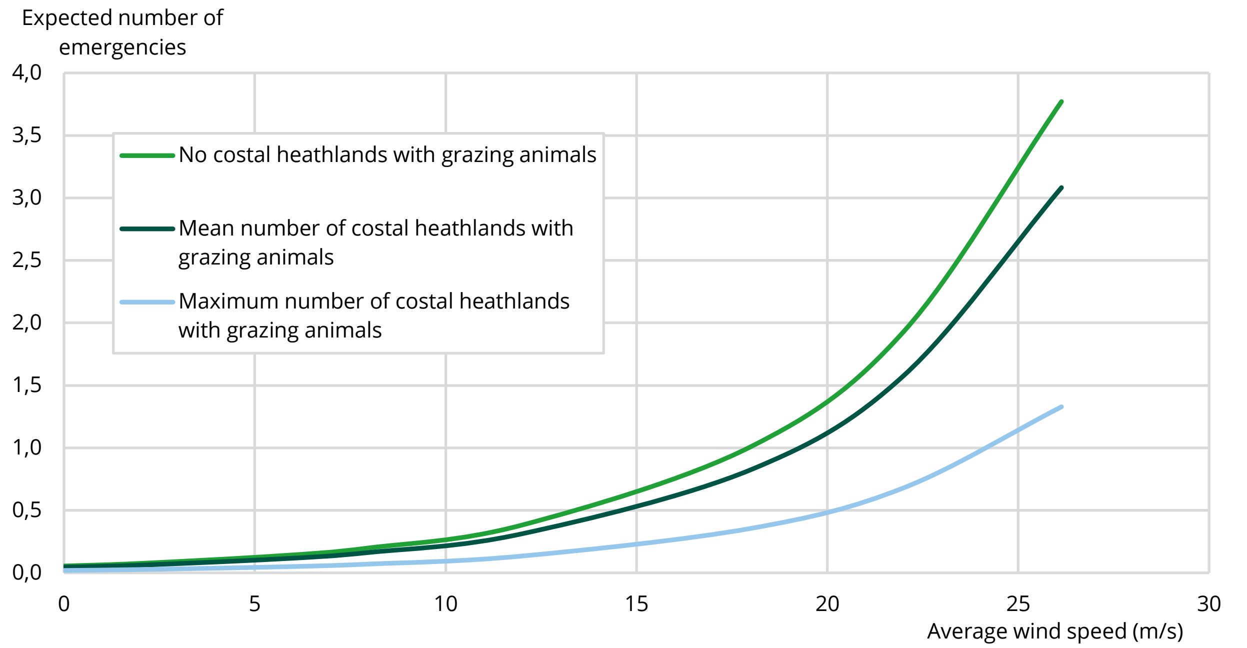


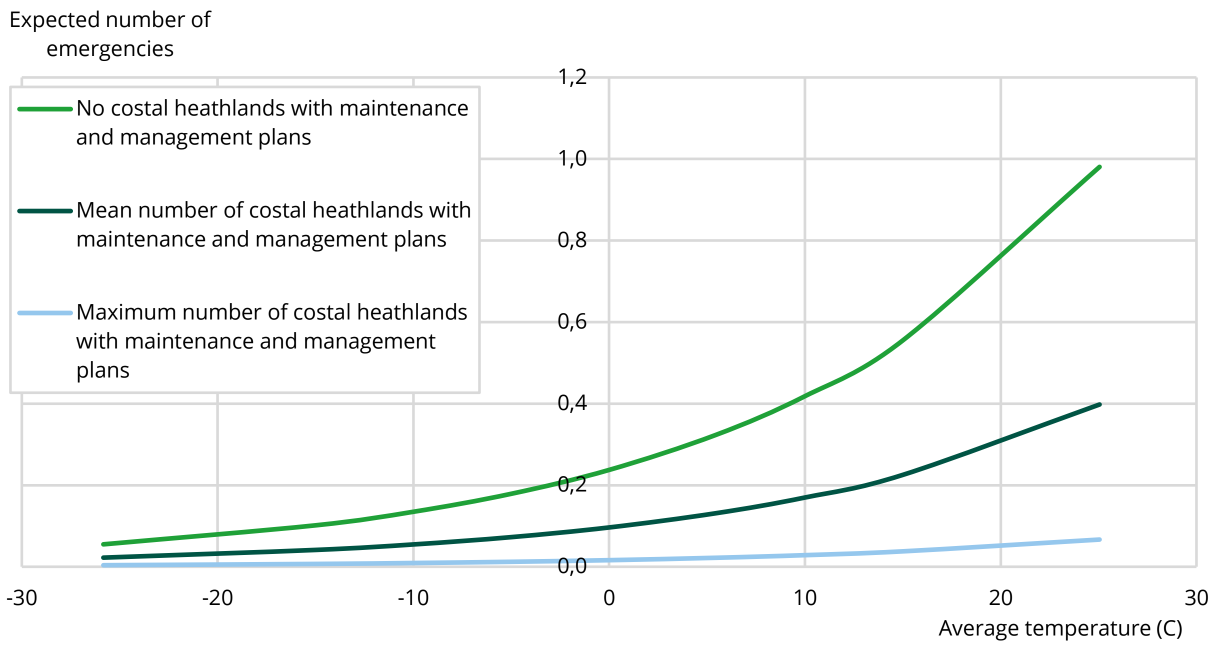
Figure 8: **Estimated effects on the expected number of calls to grass- and shrubland fires in coastal heath municipalities per week as a function of average winds speed across all weather stations per municipality per week**



Maintenance and management plans

The next aspect we are examining is the number of coastal heathlands in the municipality with management and maintenance plans. We are predicting the fire risk, as the expected number of calls related to grass- and shrubland fires considering three scenarios, when no heathlands have a plan (green line), when an average number of the heathlands have a plan (black line), and at the upper level for the prediction, when twice the standard deviation above the average have such plans (blue line). These predictions are made under various weather conditions, including temperature (Figure 9), days without precipitation (Figure 10), total precipitation (Figure 11), and average wind speeds during the current week (Figure 12).

Figure 9: Estimated effect of the number of coastal heathlands with maintenance and management plan on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of the average temperature over all weather stations per municipality per week



Similarly to the impact of grazing animals, maintenance and management plans for these areas significantly decrease the fire risk, especially under high-risk weather conditions. It is important to observe the magnitude of this effect. These plans have nearly twice the impact on the fire risk compared to grazing animals. This is likely because grazing animals complement already well-maintained coastal heathlands, while maintenance and management plans are put in place when the heathland is not adequately maintained.

Figure 10: Estimated effect of the number of coastal heathlands with maintenance and management plan on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of the total number of days without precipitation measured over all weather stations per municipality per week

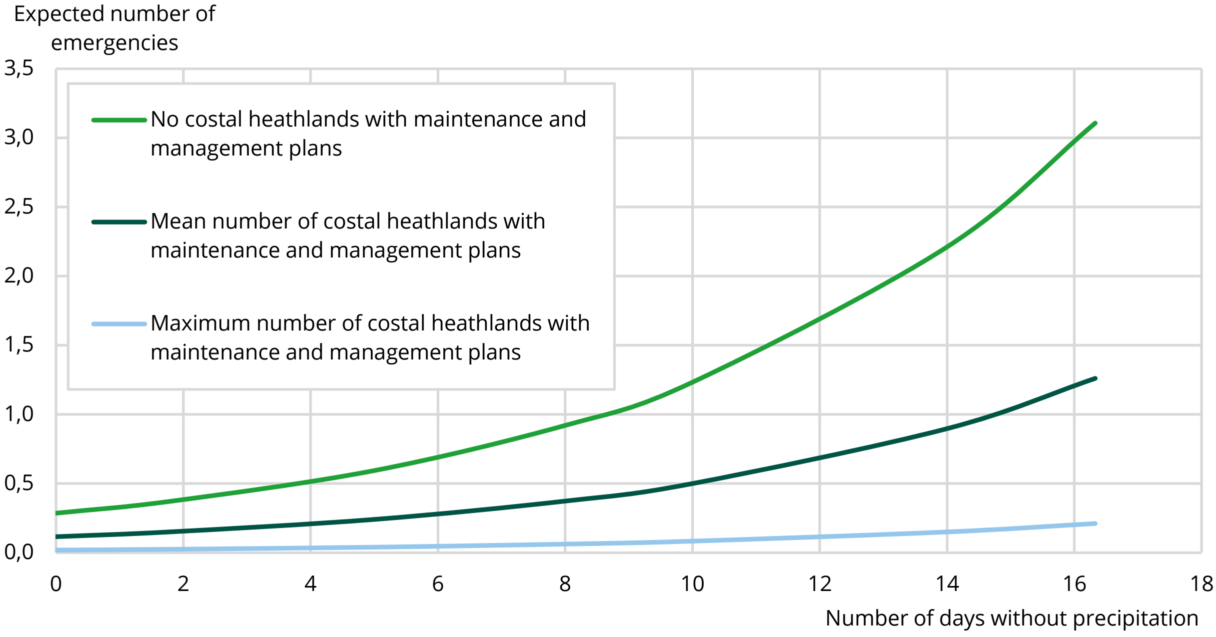


Figure 11: Estimated effect of the number of coastal heathlands with maintenance and management plan on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of total precipitation measured over all weather stations per municipality per week

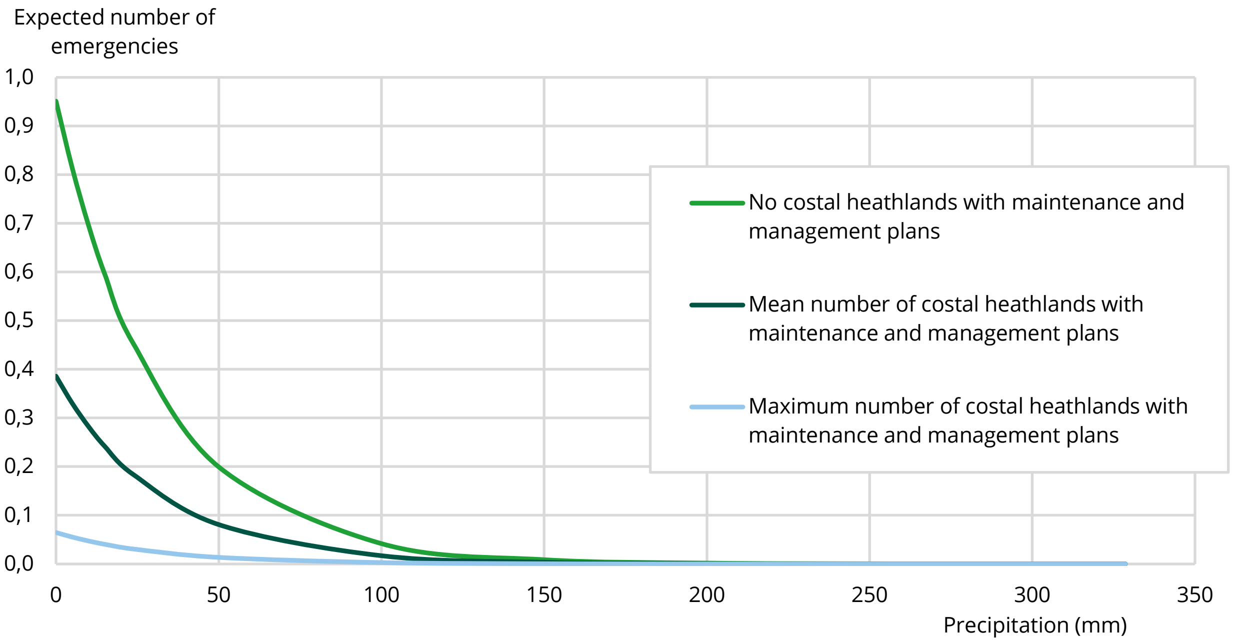
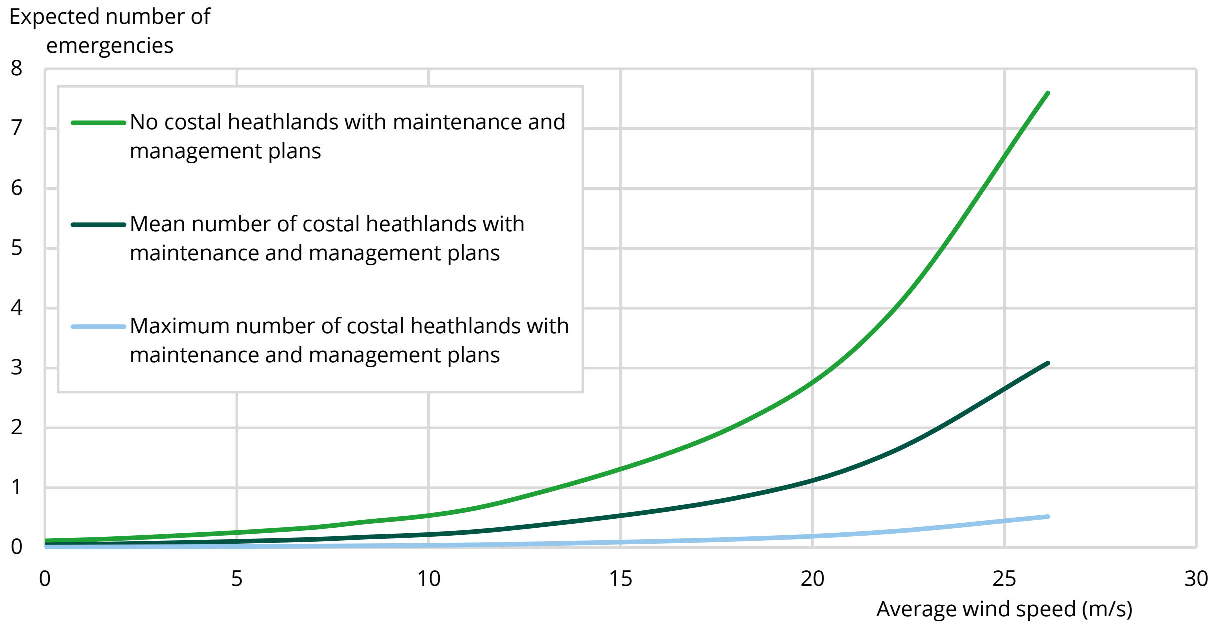


Figure 12: Estimated effect of the number of coastal heathlands with maintenance and management plan on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of average winds measured over all weather stations per municipality per week



Preventing regrowth

This section demonstrates the impact of reducing the extent of coastal heathland areas in the municipality that are growing over. The scenarios include no regrowth (green line), an average level of regrowth (black line), and full regrowth of all coastal heathlands in the municipality (blue line). We illustrate how these predictions change under various weather conditions, such as average temperatures (Figure 13), days without precipitation (Figure 14), total precipitation (Figure 15), and average wind speeds during the current week (Figure 16).

A reduction in regrowth may result from measures like clearing unwanted vegetation or controlled burning of old heather. It is important to understand that these predictions indicate the additional impact of overgrowth controlled for other measures, assuming all other factors remain constant (calculated at the average values of all other variables). In other words, the prediction shows how the fire hazard changes among municipalities with the same number of coastal heathlands, the same number of heathlands with maintenance and management plans, the same number of coastal heathlands with grazing animals, and similar levels of human activity, among other factors.

Figure 13: **Estimated effect of reducing regrowth of coastal heath on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of the average temperature over all weather stations per municipality per week**

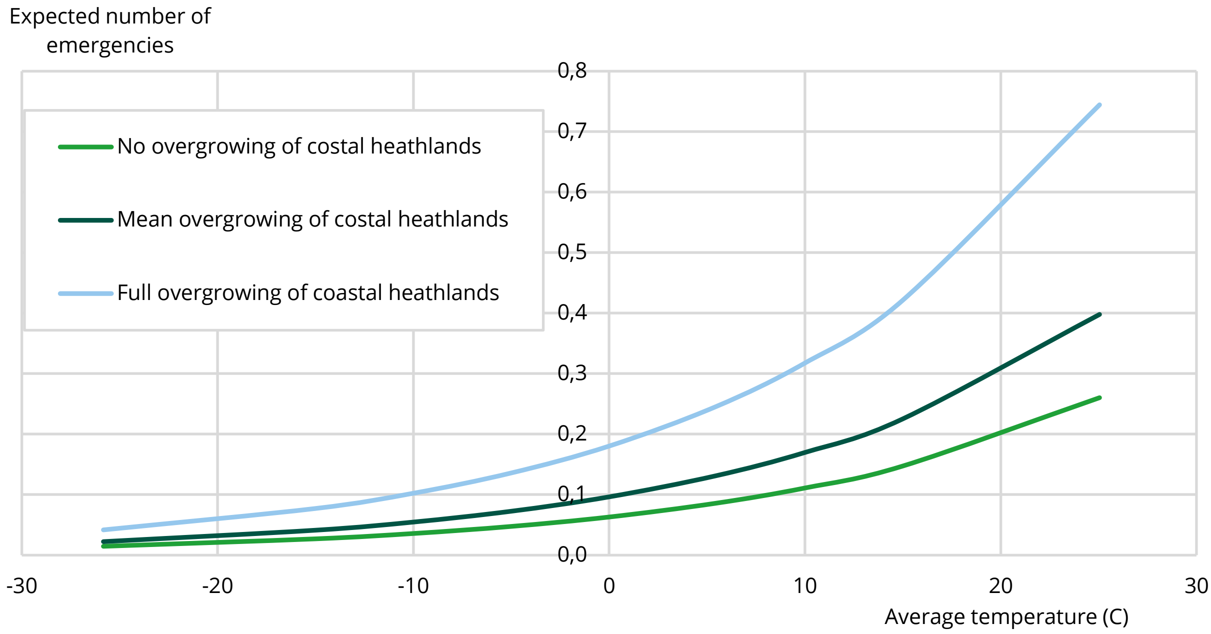


Figure 14: **Estimated effect of reducing regrowth of coastal heath on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of the total number of days without precipitation across all weather stations per municipality per week**

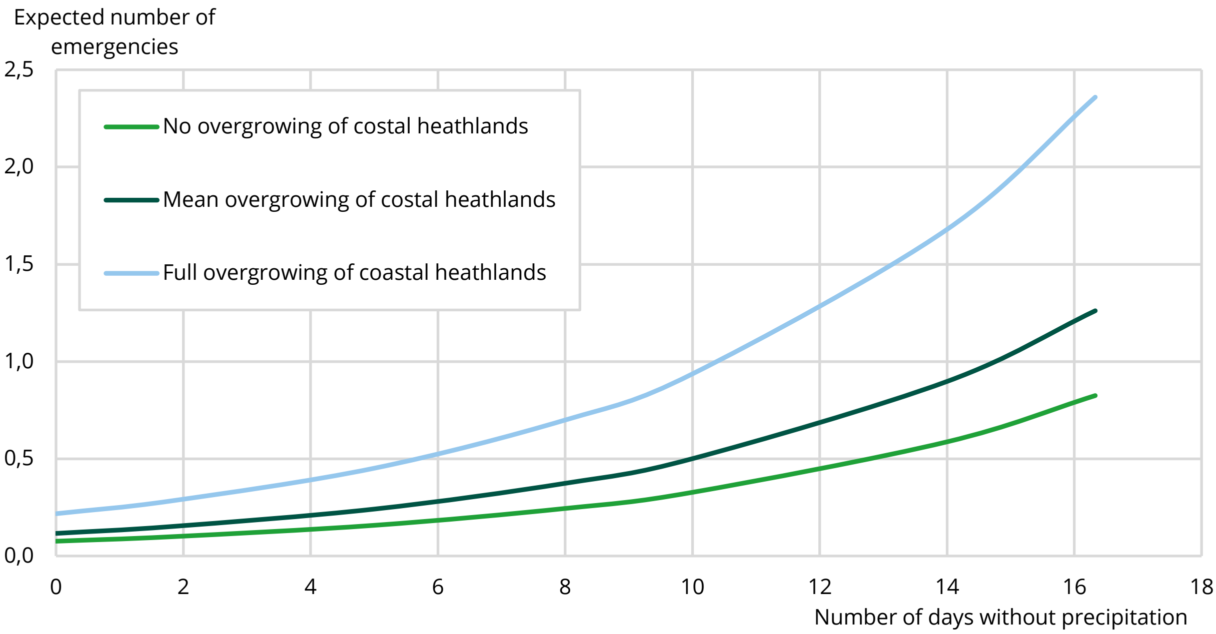


Figure 15: Estimated effect of reducing regrowth of coastal heath on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of total precipitation across all weather stations per municipality per week

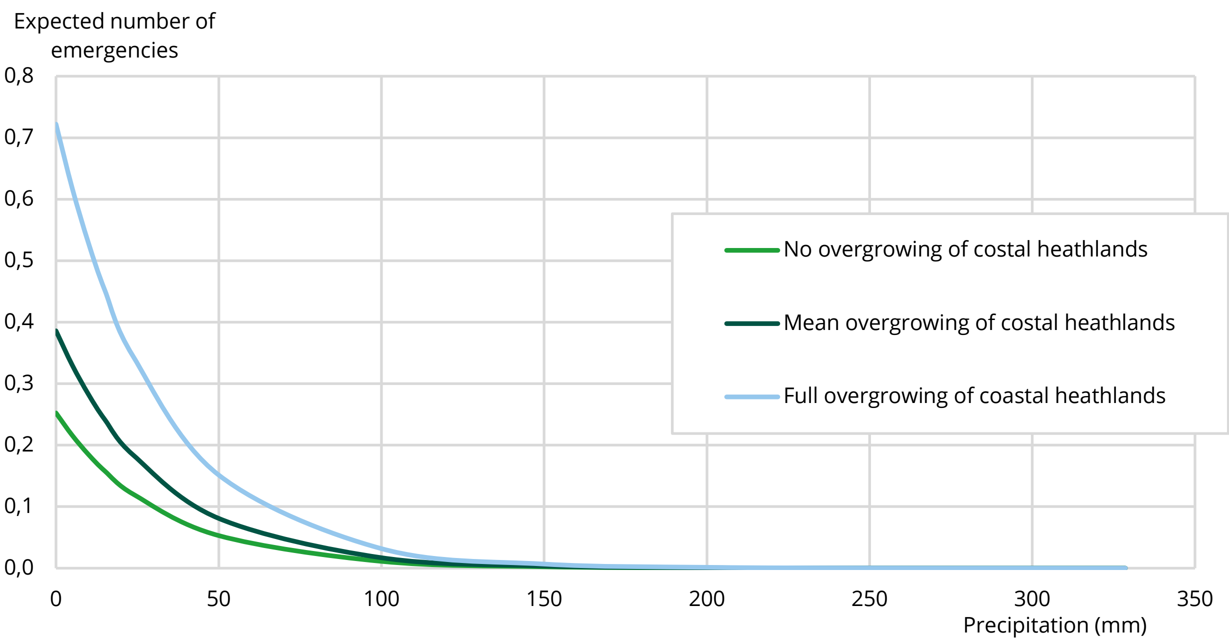
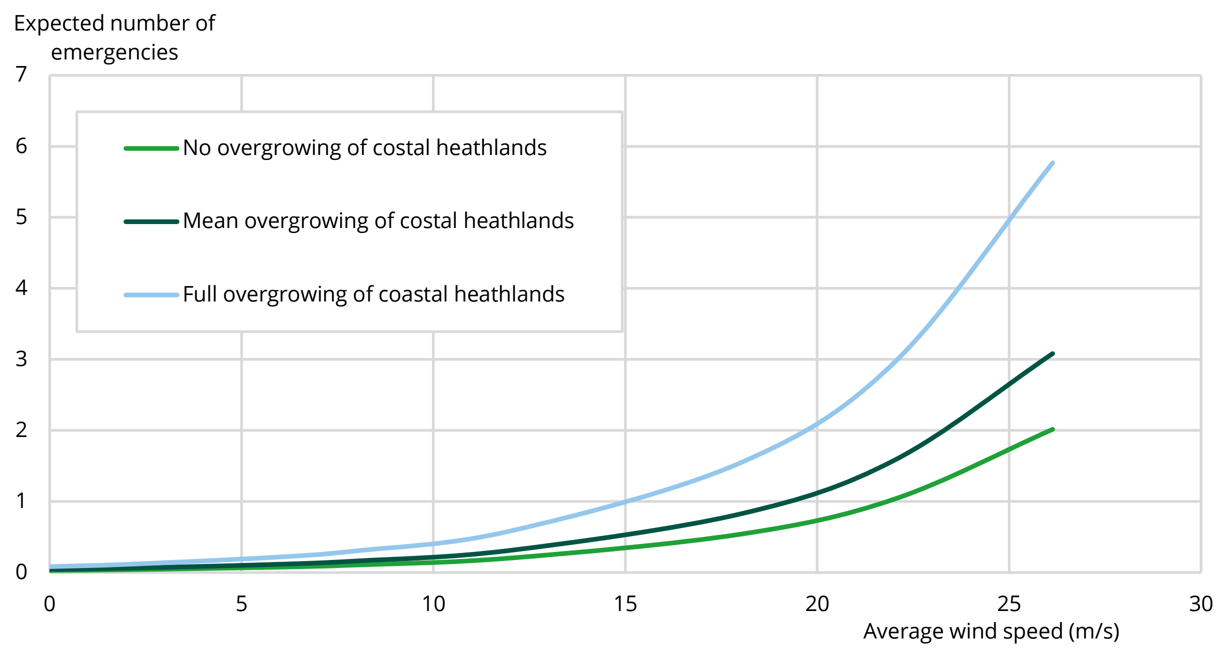


Figure 16: Estimated effect of reducing regrowth of coastal heath on the number of emergencies to grass- and shrubland fires per coastal heath municipality per week as a function of average winds across all weather stations per municipality per week



Like for other measures, we find that preventing overgrowth significantly reduces the risk of fire. In this case, the impact is nearly as substantial as that of management and maintenance plans and clearly more substantial than grazing animals. Interestingly, the most significant effect occurs when transitioning from full overgrowth to the average level, while the effect of going from the average level to no overgrowth is less pronounced. This pattern is also observed for the number of coastal heathlands with management and maintenance plans, although the effect is more pronounced for overgrowth prevention measures. The reason behind this could be that overgrowth prevention is typically targeted at costal heathlands that are, on average, poorly maintained and inferior to the coastal heathlands with better maintenance. As a result, the reduction in the fire risk from additional measures to clear overgrown vegetation is less significant when applied to moderately maintained heathlands than when applied to heavily overgrown coastal heathlands.

5. Reduced fire risk from increased management

To demonstrate the effectiveness of different maintenance measures in mitigating wildfire risks in grass- and shrubland areas, we have assessed the impact on fire hazard across nine distinct scenarios for increased maintenance, as outlined in Table 4. These scenarios differ in terms of both the scope of the measures, exemplified by the extent of the area under maintenance, indicated in the table header, and the specific types of measures employed, as detailed in the first column.

Table 4: Description of the different scenarios

	Percent change from current level		
	Minimum	Medium	Maximum
Types of measures	5 percent increase	20 percent increase	50 percent increase
1) Maintenance and management plans (including clearing of coastal heathlands)	Scenario 1	Scenario 4	Scenario 7
2) Maintenance and management plans and grazing animals	Scenario 2	Scenario 5	Scenario 8
3) Maintenance and management plans, grazing animals, and measures for preservation of cultural heritage and biodiversity	Scenario 3	Scenario 6	Scenario 9

We have categorised the efforts into three different levels of increase: a 5 percent increase, a 20 percent increase, and a 50 percent increase from the current level of maintenance activities. Regarding the types of measures employed, we have selected three distinct tiers. The first level only involves the implementation of maintenance and management plans for the coastal heathlands. The second level adds grazing animals to the plans. In the third and final tier, a comprehensive approach is adopted, including maintenance and management plans, the introduction of grazing animals, and a third level introducing additional measures aimed at enhancing biodiversity and preserving cultural heritage remains. This sequence leads to a gradual escalation of maintenance levels for coastal heaths, progressing from Scenario 1 to Scenario 9. In Scenario 9, nearly complete landscape restoration is achieved with a 50 percent increase in overall efforts relative to the existing maintenance level.

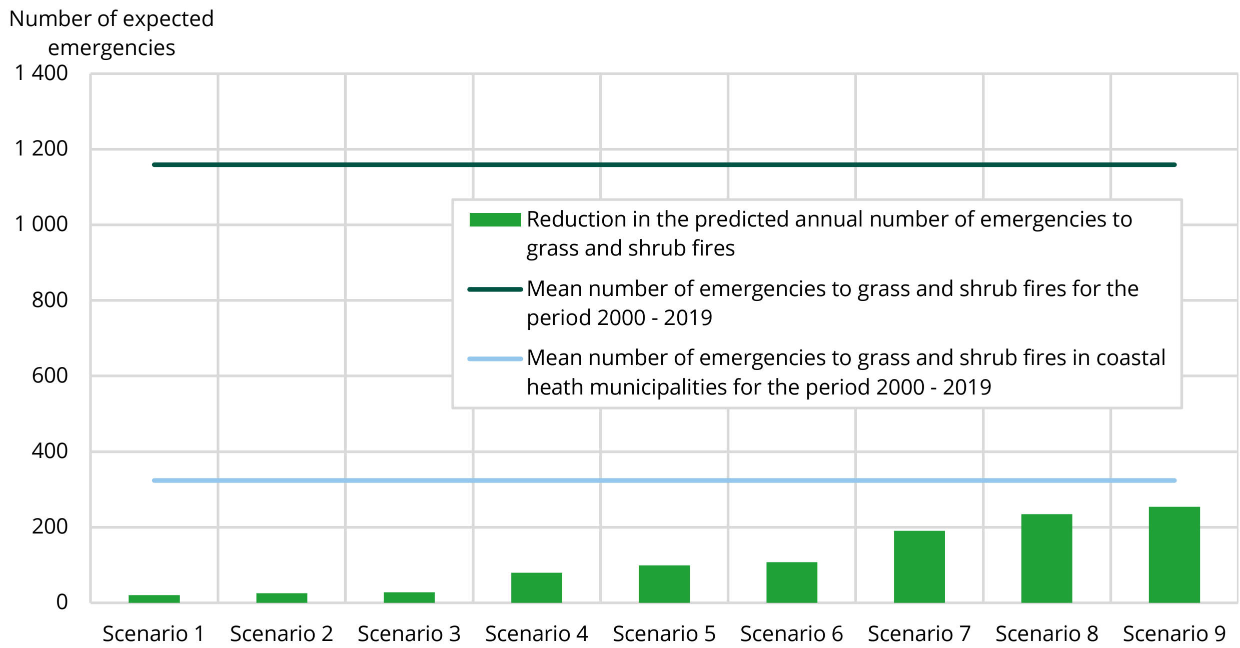
To examine how these maintenance scenarios impact the number of grass- and shrubland fires compared to the current maintenance level, we use the results described in Section 4 and scenario descriptions to calculate the expected weekly number of emergencies per municipality before and after implementing increased measures. These predictions are made for the average municipality, representing typical values for variables not influenced by the scenarios. The reduction in emergency numbers resulting from a scenario is the difference between expected emergencies in the two calculations. Since these calculations provide the expected weekly emergency count per municipality, we aggregate the predicted reductions in the expected number of emergencies to find the annually national impact of implementing such a policy.

To calculate the expected number of grass- and shrubland fire emergencies, we must be aware of how the different maintenance scenarios influence the variables in the regression model. We assume that increased maintenance primarily impacts four key variables: The average maintenance level of coastal heathlands in the municipality, the portion of coastal heathland in the municipality that is susceptible to overgrowth, the number of areas within the municipality with coastal heathlands covered by maintenance and/or management plans, and the number of coastal heathlands within the municipality with grazing animals.

In our calculations, we assume that the various scenarios influence the relevant variables differently, depending on the specific maintenance measures implemented. For example, in scenarios where the maintenance level is intended to increase by 20 percent (scenarios 4, 5, and 6), this translates to a 20 percent increase in the number of coastal heathland areas covered by plans within an average coastal heathland municipality. We also assume that this corresponds to a 20 percent reduction in the portion of coastal heathlands at risk of overgrowth across all scenarios. In scenarios 5 and 6, we further assume a 20 percent increase in the number of coastal heathlands within the municipality with grazing animals. Additionally, in scenario 6, which encompasses measures for biodiversity, cultural heritage, and so on, we make assumptions about how these diverse measures impact the average maintenance status of coastal heathlands in the municipality. We assume that the effect on the average maintenance status increases by one third for each level of measures added (as described in the first column of Table 4). That is, a 20 percent increase in maintenance, as seen in scenario 4 (involving maintenance and management plans exclusively), results in a 6.6 percent increase in the average maintenance status of heathlands within the municipality (0.2 * 0.33 = 0.066). When grazing animals are introduced alongside the plans, as in scenario 5, the average maintenance status of coastal heathlands in the municipality is expected to increase by 13.2 percent (0.2 * 0.66 = 0.132). Finally, we assume that implementing all types of measures would enhance the average maintenance status of coastal heathlands in the municipality by 20 percent.

These assumptions are used to calculate the expected change in the weekly occurrences of grass and shrub fire emergencies per municipality under the various maintenance scenarios, and then aggregated to determine the expected reduction in emergencies per year for the entire country. The results of these calculations are presented in Figure 17.

Figure 17. Reduction in the expected annual number of emergencies to grass- and shrubland fires for the entire country in the different maintenance scenarios



From Figure 17 we see that the estimated reduction in the expected number of emergency calls for grass- and shrubland fires increases across the various scenarios, ranging from 20 to 254 emergencies. Although these numbers may initially appear substantial, when we compare them to the average number of emergency calls for grass and shrub fires during the period from 2000 to 2019 (indicated by the black line in Figure 17), we find that they represent only a portion of the total annual incidents of this wildfire type in the entire country. More specifically, they account for 2 to 22 percent of the total annual emergencies nationwide (as shown by the black line) and range from 6.3 to 78.5 percent of such incidents in coastal heath municipalities (illustrated by the blue line). It is important to note that the change in the expected number of emergencies predicted here also includes fire emergencies in other grass- and shrubland terrains than coastal heathlands and in all municipalities, not only within coastal heath municipalities. Consequently, the reductions are substantial but remain within a reasonable range relative to the amount of fire emergencies overall and considering the estimated effects of maintenance measures on the fire hazard.

6. Conclusions

Unmaintained and overgrown coastal heathlands represent a significant fire risk. This risk arises from a combination of factors, including the presence of aged, dry heather, as well as the growth of highly flammable spruce and juniper. Improved management of coastal heathlands effectively lessens this fire risk, ultimately leading to a decrease in the overall costs borne by society due to wildfires. These expenses include firefighting costs, property and production losses, as well as a reduction in biodiversity.

This paper examines the fire hazard in Norwegian coastal heathlands in response to weather conditions, management strategies, and land utilization. This analysis combines data related to vegetation types, overgrowth levels, maintenance and management approaches in coastal heathlands, alongside information regarding the fire services' response to emergencies in grass- and shrublands, and forests, as well as weather data. Using panel data regression for municipalities, this study examines the fluctuations in wildfire risk, measured by the number of wildfire emergencies, in response to varying weather conditions, coastal heathland usage, and management practices.

Our results indicate that weather conditions play a pivotal role in driving these fires. More specifically, an extended period without precipitation, combined with high temperatures and strong winds, emerges as the primary contributor to the fire risk. Coastal heathlands, in particular, are prone to a higher incidence of fires, and the frequency of fire emergencies increases with reduced management and resulting overgrowth. Furthermore, the recreational use of coastal heathlands is linked to a heightened occurrence of fire emergencies. Additionally, the estimation results underscore that the probability of forest fire is significantly higher in municipalities with coastal heathlands compared to other municipalities.

A key finding is that increased management of coastal heathlands significantly lowers the risk of fires, especially during dry, hot, and windy periods. This is because well-maintained coastal heathlands have less dry vegetation that can catch fire, making them less flammable when fire risk is high. However, it is important to note that from our analysis, we cannot determine whether it is financially beneficial for society to subsidize this type of maintenance to reduce fire incidents. This decision depends on factors such as the number of preventable fires and the associated cost reductions. These cost reductions include firefighting expenses, as well as potential gains in agricultural productivity, biodiversity, and recreational value. Moreover, assessing the costs and benefits involves multiple stakeholders, including farmers/landowners, the general public, municipalities, and various central government agencies, all of whom are affected by these measures. Consequently, to determine the optimal management of coastal heathlands for the greater good of society, a comprehensive evaluation of the costs and benefits for all involved parts is necessary. It also requires an examination of the incentive structure for each party. Although such an analysis extends beyond the scope of this paper, the analysis presented in the current paper lays the foundation for future research in this area.

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