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The projected 21st century forest-fire risk in Finland under different greenhouse gas scenarios

Ilari Lehtonen, Kimmo Ruosteenoja, Ari Venäläinen and Hilppa Gregow

Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki, Finland

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We evaluated forest fire potential at four locations in Finland in the current climate and in projected future climates under the B1, A1B and A2 greenhouse-gas (GHG) emission scenarios. In evaluating the forest fire danger potential, the Canadian fire weather index (FWI) system was used. Using the results of the earlier experimental ignition studies, we further estimated the number of fire danger days in different forest stands typical to the northern boreal zone. By the end of the current century, the annual median number of days with elevated forest fire risk is projected to increase by 10%–40%, depending on the GHG scenario. In different forest stands, approximately 5–10 additional fire risk days were found annually based on the A1B and A2 scenarios. Substantially smaller changes are projected under the low-emission B1 scenario. However, there is great inter-annual variability in the forest fire potential which, in the nearest future, largely overwhelms the projected change.

Introduction

Along with wind storms, forest fires are one of the largest natural hazards that boreal forests have to cope with. On the other hand, fire is a natural phenomenon and an important factor in the process of natural forest regeneration maintaining forest biodiversity (e.g. Esseen *et al*. 1997). Nowadays in Finland, although on average almost 1000 forest fires occur annually, the area thus burnt is relatively small because of active fire suppression (Tanskanen and Venäläinen 2008). In addition, as compared with many other areas in the boreal zone, the geographical heterogeneity of Fennoscandia, with its numerous lakes and swamps, creates more natural obstacles for fires. In contrast, large wildfires are common along the southern edge of the boreal forests in Russia (Vivchar 2011), and smoke plumes originating from large fires there can affect the air quality and visibility in regions hundreds of kilometres away from the actual location of the fires (Mei *et al*. 2011, Mielonen *et al*. 2012).

Human influence on forest fires has existed for several centuries. During previous centuries, fire was intentionally used to clear forest for pasture and cultivation. Accordingly, the number of forest fires evidently increased in Finland in the late 17th century when more people moved into wilderness areas (Wallenius *et al*. 2004). Even nowadays, almost 90% of forest fires in Finland are human-caused, resulting mostly from careless handling of fire (Larjavaara *et al*. 2005). Thus, seasonal fire activity peaks in the open season for elk hunting and also when berry and mushroom pickers light campfires in forests (Tanskanen and Venäläinen 2008). The

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only natural source of ignition in boreal forests is lightning, but this causes less than 15% of all forest fires in Finland (Larjavaara *et al*. 2005).

The risk of fire is in large part determined by the moisture content of the fuel in the forests, and is thus reliant on climatic factors. In predicting a forest fire risk, various weather-based indices are used. In boreal conditions, one of the most widely used is the so-called Canadian fire weather index (FWI) system (Van Wagner 1987). This index is determined by temperature, relative humidity, wind speed and precipitation. In Finland, forest fire warnings are issued based on the Finnish forest fire risk index model (Venäläinen and Heikinheimo 2003). The highest forest fire potential in Finland occurs in the coastal areas and in the south, where the criteria for a forest fire warning are fulfilled on ~60–100 days annually (Kilpeläinen *et al*. 2010). The fire potential decreases inland and towards the north being less than 20 days per year at its lowest level in eastern and northern Lapland. Moreover, as most forest fires are of anthropogenic origin, the small population density in the north further diminishes the actual number of forest fires. Also the density of lightning-ignited forest fires is over ten times higher in southern than in northern Finland (Larjavaara *et al*. 2005), whereupon the natural fire-free intervals in Finland are notably shorter in the south than in the north.

In addition to geographical variations, the ignition probability and the evolution of a fire vary substantially among different forest stand types (e.g. Tanskanen *et al*. 2007). In Finland, the most common tree species are Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). In general, Scots-pine-dominated forests have a much higher ignition potential as compared with forests dominated by Norway spruce (Tanskanen *et al*. 2005). The main explanation for this is the humid microclimate created by the dense canopy of Norway spruce (Tanskanen *et al*. 2006) and the poorly flammable undergrowth, since the habitats occupied by Norway spruce are typically rather moist. Accordingly, fires seldom occur in Norway-spruce-dominated forests, implying that for these forests fire is not an equally important natural disturbance and forest-renewing factor as it is for pine forests (Wallenius 2002, Pitkänen *et al*. 2003).

During the forthcoming decades, anthropogenic climate change may affect boreal forests in many ways. Forest growth may increase, although in southern Finland growing conditions for Norway spruce may become sub-optimal, leading to major changes in tree species composition (Kellomäki *et al*. 2008). In addition, it is evident that climate change will have a direct impact on the forest fire risk. Climate models unanimously project higher temperatures for the future (IPCC 2007), which change favours increasing evaporation and further enhances forest fire potential. On the other hand, in northern Europe precipitation is simulated to somewhat increase even in summer, albeit the greatest increase is projected for winter (Jylhä *et al*. 2009). These two key forcing factors have opposite effects, and consequently estimation of the impact of climate change on forest fire danger is not a straightforward issue. The magnitude of the climate change is also uncertain and dependent on the amount of greenhouse-gas (GHG) emissions. There are also remarkable differences among the projections given by different climate models. However, several studies have indicated that the fire risk in northern high-latitude forests will in general increase during future decades, although some spatial variation in the change will occur (e.g. Stocks *et al*. 1998, Flannigan *et al*. 1998, 2000, 2005a, 2005b, 2009, Kilpeläinen *et al*. 2010, Wotton *et al*. 2010). Nevertheless, for the present, no significant change in the fire proneness of Finnish forests has been found, even though a statistically significant increase in the mean temperature of the forest fire season has been found (Mäkelä *et al*. 2012).

In this study, the forest fire risk will be evaluated for four locations in Finland in the current climate and in the projected future climate. Our main goal is to explore the sensitivity of the future forest fire danger to GHG emissions. A plausible hypothesis is that larger emissions will also result in a larger change in fire danger, but earlier this issue has not been studied quantitatively. To test this hypothesis, we first evaluate the forest fire potential for the recent past climate, applying daily observational weather data at four locations. The weather data are then modified, in accordance with climate model projections, to produce artificial data for three future periods, in each period also considering three alternative GHG scenarios. In addition, we present tentative estimates for the fire risk in certain coniferous forest stands common in the European boreal zone, and discuss the potential importance of changes in tree species proportions and forest management for the future forest fire risk.

Data and methods

For the baseline period 1980–2009, the forest fire risk was derived from weather observations. Next, these observational data sets were converted to represent future climate, and the resulting artificial data were used to calculate the forest fire risk for the scenario periods. The conversion of the weather data is based on model-simulated changes in the relevant weather parameters.

Observational weather data

Temperature, precipitation, relative humidity and wind speed observations carried out at four stations across Finland (Fig. 1) in the years 1980–2009 were extracted from the database of the Finnish Meteorological Institute. These observational time series were interpolated to an hourly interval. In calculating the forest fire risk, we then employed the interpolated daily values of temperature, wind speed and relative humidity at 10:00 UTC, i.e., noon local time. Similarly, for precipitation the interpolated 24-hour accumulation at 10:00 UTC was utilized.

Climate model simulations

Climate projections were produced separately for three forcing scenarios examined in the Special Report on Emission Scenarios (Nakićenović *et al*. 2000), i.e., B1 representing low, A1B medium and A2 high GHG emissions. Global climate model (GCM) simulations corresponding to these three forcing scenarios were downloaded from the Coupled Model Intercomparison Project phase 3 data archive (Meehl *et al*. 2007).

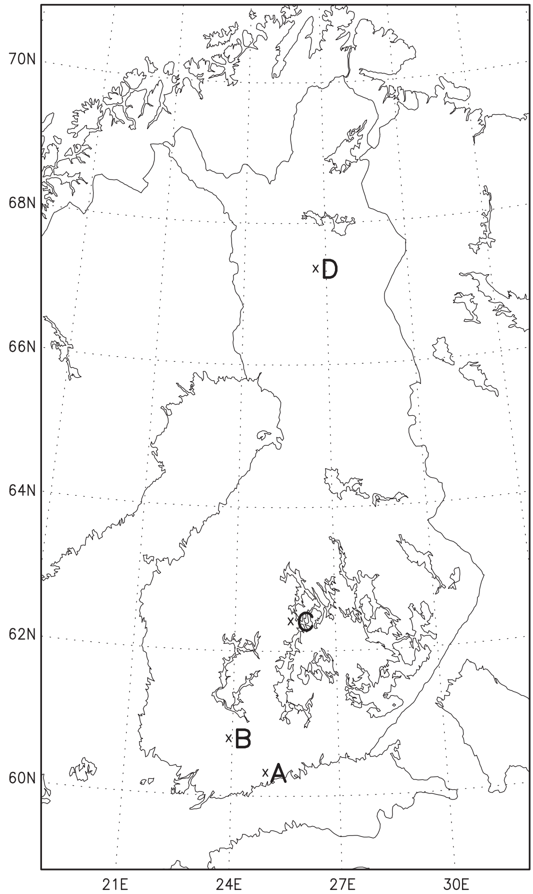

Fig. 1. Locations of the stations involved in this study. A: Vantaa, B: Jokioinen, C: Jyväskylä and D: Sodankylä.

This data archive, originally created for the production of the climate change projections presented in the Fourth Assessment Report of IPCC (2007), includes a wide set of climate model simulation outputs for various meteorological variables.

In transforming the observational weather time series into the future, we applied model-projected changes in monthly mean temperature, relative humidity, wind velocity and precipitation. In addition, model-based information is needed of the changes in the standard deviation of temperature variations in time and two precipitation indices: the number of days with precipitation > 1 mm and a simple daily precipitation intensity index, i.e., mean precipitation on days when the daily precipitation surpasses this threshold.

For monthly mean temperature and precipitation, we used the mean of the changes simulated by all the 19 GCMs (Table 1). Usable relative humidity data, by contrast, were only available from seven GCMs. Wind speeds and indices related to the temporal variations of temperature and precipitation were inferred from the GCM output represented at the daily level. For these quantities, 9–10 GCMs with relative good resolution, all of them originating from different institutes, were used. Changes in all the weather variables are expressed relative to the mean for the baseline period 1980–2009.

Artificial weather data for future climate

For the future scenarios of the forest fire risk, 30-year artificial weather data sets describing climate conditions estimated to prevail around the years 2030, 2050 and 2100 were constructed by modifying the observational time series of the weather parameters in accordance with the above-mentioned climate model projections. This is termed a delta-change method. In this transformation, the daily variations and inter-variable relationships of the observational data are retained in a qualitative sense, while the differences in the long-term climatological means between the observational and artificial future data correspond to the modelled response: a mean of 7 to 19 models, depending on the variable.

Table 1. GCMs used to calculate responses for each climate variable (*T* is temperature, RH is relative humidity, WS is wind speed, PR is precipitation). The projected changes in mean temperature and precipitation are calculated on the basis of all the 19 models, but only the ten models denoted by an asterisk are included when considering changes in the temporal variability of temperature and the intensity and number of rainy days. Further information about the models is presented in IPCC (2007: table 8.1).

Model	*T*	RH	WS	PR
BCCR-BCM2.0	X*	X	X	X*
CGCM3.1(T47)	X	X		X
CGCM3.1(T63)	X*	X	X	X*
CNRM-CM3	X*	X	X	X*
CSIRO-MK3.0	X*		X	X*
ECHAM5/MPI-OM	X*	X	X	X*
ECHO-G	X			X
GFDL-CM2.0	X			X
GFDL-CM2.1	X*		X	X*
GISS-ER	X			X
INM-CM3.0	X	X		X
IPSL-CM4	X*		X	X*
MIROC3.2(HIRES)	X*		X	X*
MIROC3.2(MEDRES)	X			X
MRI-CGCM2.3.2	X*		X	X*
NCAR-CCSM3	X*			X*
NCAR-PCM	X			X
UKMO-HadCM3	X	X		X
UKMO-HadGEM1	X			X
Total	19(10)	7	9	19(10)

In transforming temperature data into the future, both the modelled increases in monthly means and changes in the standard deviation of temporal variability were taken into account. The instantaneous temperatures for the scenario periods, T_{sce}, were calculated as follows:

$$T_{sce}(t) = T_{obs}(t) + \Delta\bar{T} + \left(\frac{\sigma_{sce}}{\sigma_{bas}} - 1\right)\left[T_{obs}(t) - \bar{T}_{obs}\right], \quad (1)$$

where T_{obs} is the temperature measured at the time t and $\bar{T}_{obs}$ is the monthly mean temperature for the period 1980–2009, $\Delta\bar{T}$ stands for the model-projected monthly mean temperature response, and σ_{bas} and σ_{sce} are the standard deviations of temperature fluctuations simulated for the baseline and scenario periods, respectively.

For relative humidity, we first determined the monthly mean saturation deficit for the baseline and future periods from the model output. To obtain a projection for relative humidity change, the observation-based 30-year mean saturation deficits for each month were multiplied by the ratio of the simulated deficit in the future period to that in the baseline period. This method was applied to reduce the influence of biases in model-simulated relative humidity. The time series of relative humidity were then transformed into the future using an iterative algorithm. At every iteration step, a small increment (or a reduction, if the models projected a decrease in humidity) was applied to the instantaneous humidity values, the increment being largest at 50% and zero for humidities of 0% and 100% (to avoid supersaturation or negative relative humidities). The procedure was repeated until the difference in the 30-year monthly-mean humidity between the datasets describing future and recent past climate deviated by less than 0.0001% from the model-based response. Furthermore, when $T < 0$ °C, the modelled relative humidity is expressed relative to ice, while in the observational and artificial weather data it is given relative to supercooled water. This requires a further correction at sub-zero temperatures, but this modification is of little relevance during the forest fire season.

For wind velocity, we first calculated a preliminary approximation by adding the projected change in the monthly mean wind vector to the observed instantaneous wind vectors. The final data for the future climate were constructed by calibrating the instantaneous wind speeds so that the difference in the long-term monthly mean scalar wind speed between the future and recent past weather data sets was exactly equal to the corresponding model-based projection.

The transformation of precipitation data was performed in four stages. In the first step, the number of precipitation days was increased or decreased according to the model-based projection. Secondly, to make the response of the simple daily precipitation intensity index consistent with the modelled estimate, daily precipitation totals were increased proportionally to the square of the amount of the observation-based precipitation exceeding 1 mm. Thirdly, an analogous procedure was repeated for hourly precipitation values, but this step does not affect the present results, as daily precipitation totals alone are used in calculating the fire risk. Finally, all hourly precipitation sums were calibrated as follows:

$$P_{\mathrm{sce}}(t) = \frac{\left(1 + \frac{\Delta\bar{P}}{100}\right)\bar{P}_{\mathrm{obs}}}{\bar{P}^*} P^*(t), \qquad (2)$$

where P_{sce} is the "final" estimate for hourly precipitation in the future, $\Delta\bar{P}$ stands for the response of climatological monthly-mean precipitation in the models (in percent), and P_{obs} and P^* are the hourly precipitation in the observational dataset and that produced by the third conversion step, respectively. A bar over a symbol indicates a tridecadal monthly mean. After the final step, the ratio of the climatological monthly-mean precipitation in the artificial weather data set to that in its observational counterpart is identical to the corresponding model-based ratio. As a result, the model-simulated changes in the two other precipitation indices are only reproduced approximately. For more details on the transformation procedures, *see* Ruosteenoja *et al.* (2013). Artificial tridecadal time series were produced separately for all three forcing scenarios (A1B, A2 and B1).

The observation-based time series of the weather variables, along with the artificial data for the future, are shown in Fig. 2. For clarity, only one warm-season period (out of 30) for the most extreme climate change scenario, i.e., A2 for the year 2100, is displayed. For all variables, the course of the temporal variations is qualitatively very similar in both the observations and the time series representing the future. According to the model simulations, from May to July the temporal variability of temperature does not change markedly, i.e., $\sigma_{\mathrm{sce}} \approx \sigma_{\mathrm{bas}}$, and therefore the difference between the measured and artificial future temperatures is nearly constant within each month. In the other seasons, however, $\sigma_{\mathrm{sce}} < \sigma_{\mathrm{bas}}$ and, according to Eq. 1, lower temperatures are raised more than higher ones. In the scenario displayed in Fig. 2, the mean temperatures increase by 3–4 °C from June to August and by 4–5 °C in April–May and September–October (Ruosteenoja *et al.* 2013). Changes in the other weather variables are fairly modest. Relative humidity will decrease by ~1% in summer and increase slightly in spring and autumn, although these findings, based on only seven GCMs, are not very robust (Ruosteenoja and Räisänen 2013). Wind speeds will increase in southern Finland in autumn by 2%–4% (Gregow *et al.* 2012). Monthly mean precipitation will increase from June to September by ~10% and in April–May and October by nearly 20%. Moreover, the precipitation climate tends to become more extreme in the future, leading to a substantial increase in the most intense precipitation events (Orlowsky and Seneviratne 2012, Lehtonen *et al.* 2014).

As compared with the above-exemplified case, the changes calculated for the other scenarios and less distant future periods are of the same sign but smaller in magnitude.

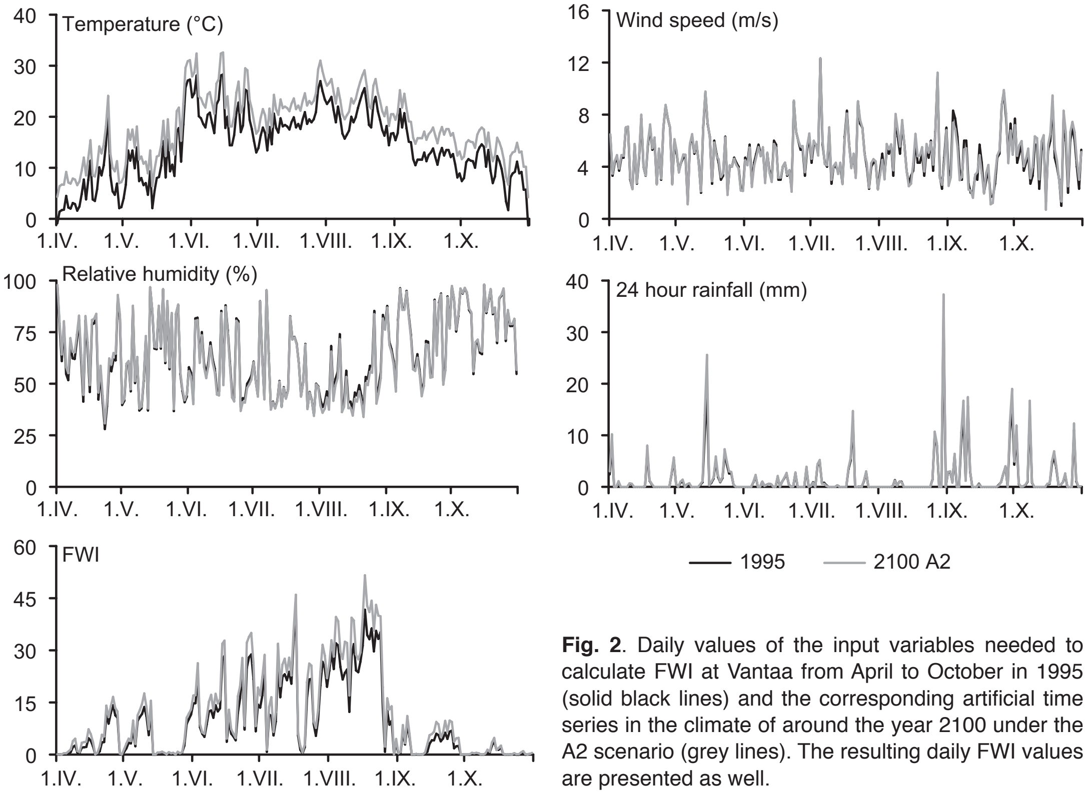

Fig. 2. Daily values of the input variables needed to calculate FWI at Vantaa from April to October in 1995 (solid black lines) and the corresponding artificial time series in the climate of around the year 2100 under the A2 scenario (grey lines). The resulting daily FWI values are presented as well.

Estimation of fire danger

The forest fire risk is assessed using the FWI system. The FWI has six components that describe the moisture content of organic layers at different depths and predict the rate of fire spread and the frontal fire intensity. These indices are computed on a daily basis using the air temperature, relative humidity and wind speed observations at local noon and the total precipitation sum of the preceding 24 hours (Fig. 3). FWI is a dimensionless quantity indicating the likely intensity of a fire; the value of the index determines four fire danger classes: low, medium, high and extreme (Table 2). In this study, days falling into the two highest danger classes are regarded as days with an elevated general fire risk. The FWI system was originally developed empirically for Canadian boreal conditions, the typical situation being a mature red pine (*Pinus resinosa*) stand. However, the FWI indices have proved to be realistically linked to the moisture content of different forest fuels in many kinds of environments (Viegas *et al*. 2001). Because of its relative simplicity and robustness in a variety of environments, the FWI system has become widely implemented around the world (Taylor and Alexander 2006). The FWI rating has been found to be most sensitive to wind speed, secondly to relative humidity and thirdly to temperature (Dowdy *et al*. 2010). The temporal evolution of FWI in one example year is shown in the bottom panel of Fig. 2, separately for the observed and projected future climate.

We estimated the number of potential fire days for different forest-stand types on the basis of the experimental ignition studies of Tanskanen *et al*. (2005). In that study, ignition tests were carried out in Norway spruce and Scots pine stands of different ages from June to August during one summer at a test site located in southern Finland. A total of 24 experimental plots were established, Scots pine stands representing typically xeric or sub-xeric and Norway spruce stands mesic or herb-rich heaths. Tanskanen *et al*. (2005) found that among the output codes

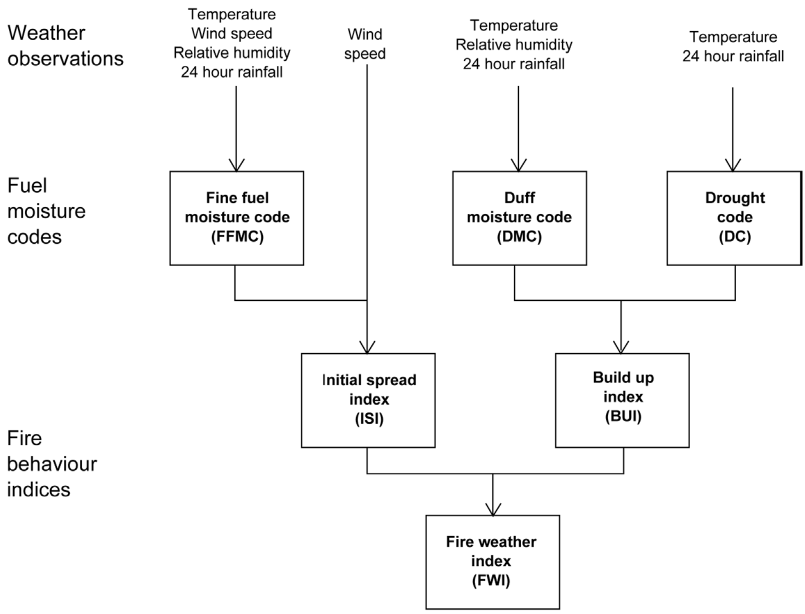

Fig. 3. Fire-weather-index calculation scheme.

of the FWI system, the fine fuel moisture code (FFMC) and the initial spread index (ISI), as well as the FWI rating itself (Fig. 3) had the best correlations with successful ignitions. For these three codes and for the different stands, they determined threshold values for which 90% of ignitions had been successful. Finally, an average of the estimates of all three indices was used to give the predicted number of potential fire days in a certain stand. An exception to this was the Norway spruce clear-cut stand in which successful ignitions occurred rather randomly. Hence, the number of potential fire days for that particular stand was estimated by proportioning the mean ignition frequency of the Norway spruce clear-cut stand to the mean ignition frequency of the 30–45-year-old Scots pine stand in which the ignition frequency most closely corresponded to that of the Norway spruce clear-cut stand. The threshold values were determined separately for the early (June–July) and late (August) seasons because the ignition success at comparable index levels was in general substantially lower in the late than in the early season. This was evidently due to the shorter day lengths and an increased occurrence of dew and fog in the late season; the influence of dew formation on fine fuels has typically been ignored in models that estimate fuel moisture.

In this study, we employed the threshold values of FWI, FFMC and ISI defined by Tanskanen *et al*. (2005) for our four locations to estimate the number of annual potential fire days in Scots pine and Norway spruce clear-cut stands, in 30–45-year-old Scots pine stands and in 40–60-year-old Norway spruce stands. These stands occur commonly in managed forests in Finland. We used the early season threshold values from the beginning of the fire season until the end of July, and the late season values from the beginning of August until the end of the fire season.

Results

General fire risk level

In the baseline period 1980–2009, the total annual number of days with an elevated forest

Table 2. Fire danger classification in the FWI system.

FWI value	Fire danger class
> 32	Extreme
17–32	High
8–16	Medium
< 8	Low

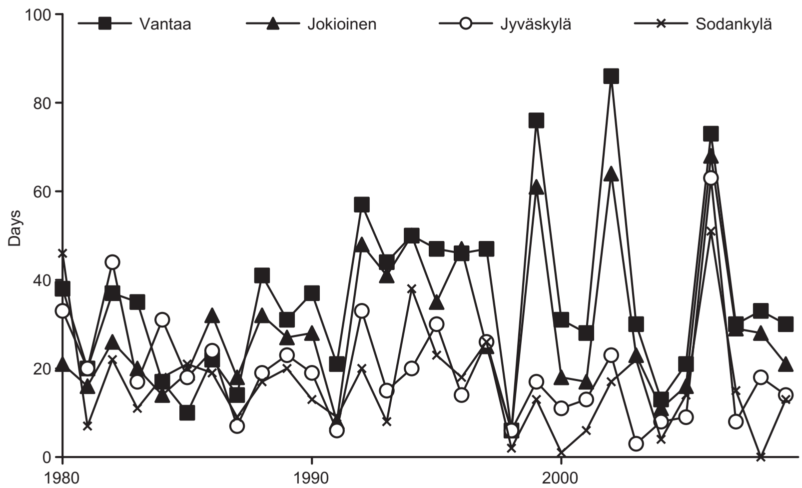

Fig. 4. Annual number of days with a high or extreme forest fire index value during the years 1980–2009 at Vantaa, Jokioinen, Jyväskylä and Sodankylä.

fire risk in Finland had a great year-to-year variation (Fig. 4). On average, the southernmost location, Vantaa, showed the largest while the northernmost location, Sodankylä, had the smallest number of potential forest-fire days. The annual median number of days with a forest fire risk being high or greater, as evaluated on the basis of daily FWI values, varied from 16 at Sodankylä to 32 at Vantaa, and for the extreme forest fire risk from 0 to 3, respectively. However, at all four stations there was at least one year with more than 50 days with elevated an forest fire risk. These years were typically characterized by long dry and relatively warm periods at some time between May and September. Conversely, in the wettest summers, there were less than ten days with a high forest fire risk, even in southern Finland. In considering the days with extreme fire danger, the inter-annual variability is even more pronounced, as not even at a single station did such days occur in every year.

In the forthcoming decades, the annual number of days with an elevated forest fire risk is projected to increase to some extent (Fig. 5a). In the climate prevailing around the years 2030 and 2050, the increase in the median is approximately 10%–25%, depending on the location and the scenario. As compared with the inter-annual variability, the change is nevertheless rather small, and thus will probably be difficult to detect in observations. For the climate of the year 2100, the increase in the median value is about 40% under scenarios A1B and A2, while a smaller change of only about 10% is projected under low-emission B1 forcing. For the upper extreme values of the distribution, the increase is in relative terms generally slightly smaller than for the median. Notwithstanding, these changes are quite considerable, as at both Vantaa and Jokioinen the median value of the baseline period is, under scenarios A1B and A2, exceeded in more than three years out of four.

The projected changes in the annual number of days falling into the class of extreme fire danger are qualitatively similar to those for days with less intense forest fire danger (Fig. 5b). Again, all scenarios show an increase in the number of fire danger days, but in the next few decades the interannual variability largely overwhelms the change. Under A1B and A2 forcing, the annual median value is projected to more than double by the end of the 21st century, even though the absolute number of days in this class still remains relatively small. However, for instance at Vantaa, while the maximum annual number of days with an extreme forest fire risk is 24 in the baseline period, this number is expected to be over 40 in a year with analogous weather conditions in the climate prevailing around the year 2100.

Fire risk level in different forest types

The annual number of potential fire days was estimated in Scots pine and Norway spruce stands with a closed canopy and in clear-cuts.

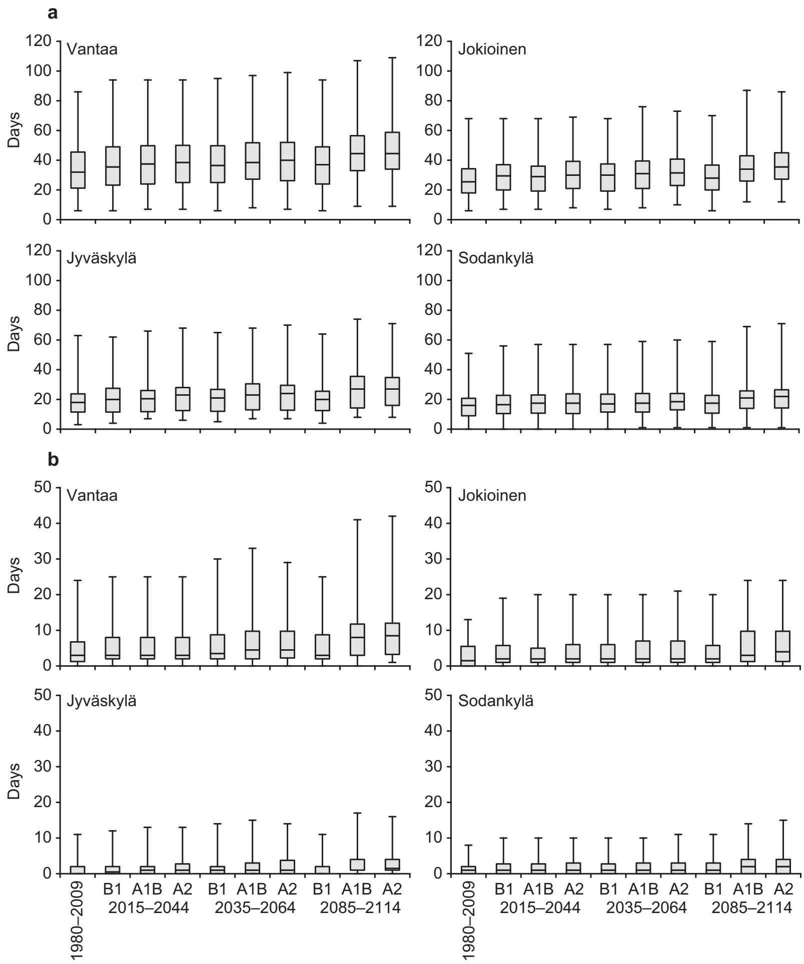

Fig. 5. Annual number of days with (**a**) a high or extreme, and (**b**) an extreme forest fire index value in the baseline period 1980–2009 and in the scenario periods as a response to the various GHG scenarios. The boxes indicate the central 50% range and the median of the distribution. The whiskers extend to the minimum and maximum values.

In general, as compared with Norway spruce stands, Scots pine stands in southern locations exhibited a three- to fourfold, and in the north a four- to fivefold fire potential (Fig. 6). Moreover, at clear-cut sites the number of potential fire days was two to three times greater than in stands with a closed canopy. The inter-annual variability in the number of fire danger days in specified forest types was basically slightly smaller than in the general fire danger (Fig. 5). For example, in the most flammable case, a Scots pine clear-cut stand, there were more than 30 potential fire days every year, even in the north (Fig. 6a).

Future projections show a slight increase in the number of annual fire danger days in the different forest stands, commensurate with the projections for the general fire risk level. However, depending on the stand type, even for the furthermost period around the year 2100 under high-emission A2 forcing, only 5–10 additional fire danger days are projected in the south. In central and northern Finland this increase is even smaller, albeit comparable in relative terms. Likewise, the projections based on low-emission B1 scenario show only a minor increase in the fire danger days. Assuming A2 scenario to be realized, it can be stated that current forest fire risk levels at Vantaa, Jokioinen and Jyväskylä would be transposed during the next 100 years to Jokioinen, Jyväskylä and Sodankylä, respectively.

Discussion

The projected increase in forest fire risk is in accord with the conclusion of Kilpeläinen *et al.*

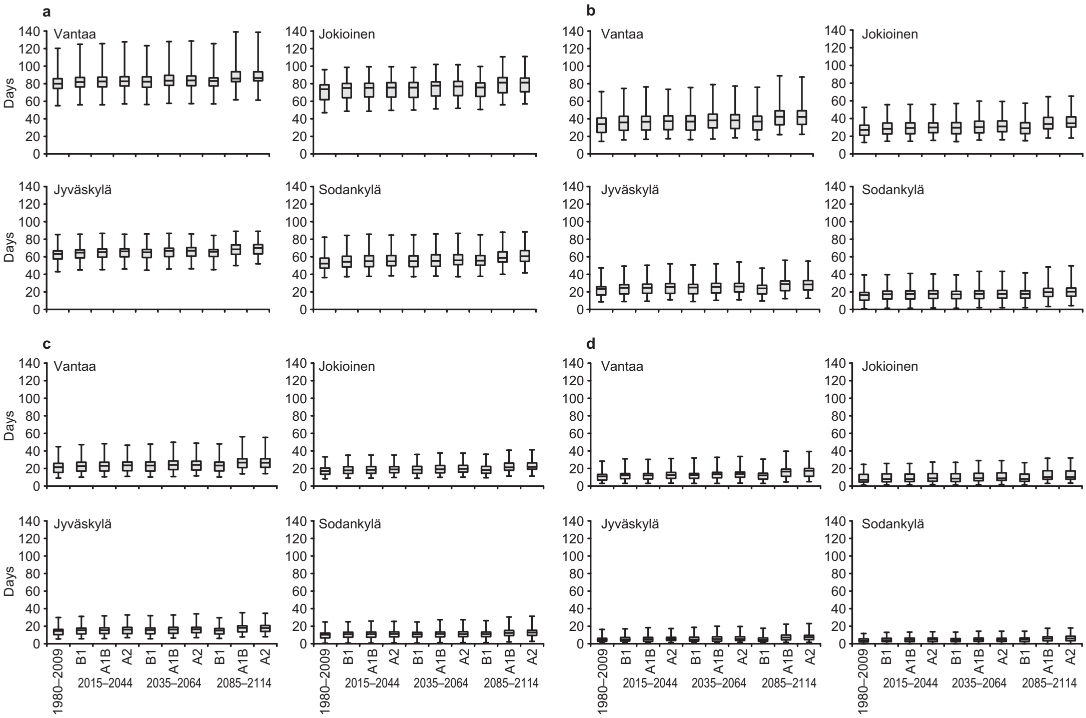

Fig. 6. As in Fig. 5, but for annual number of potential fire days in (**a**) Scots pine clear-cut stands, (**b**) 30–45-year-old Scots pine stands, (**c**) Norway spruce clear-cut stands, and (**d**) 40–60-year-old Norway spruce stands.

(2010) that, under A2 forcing until the end of the present century, the number of forest fires in southern Finland would increase by 20% and the number of forest fire alarm days by over 30%. Also in other parts of the boreal zone, the forest fire risk is projected to generally increase in response to climate change, as summarized by Flannigan *et al*. (2005a). A more recent study by Wotton *et al*. (2010) suggests that in Canada fire occurrence might even increase by 140% by the end of this century. The area burned in Canada is concurrently projected to double (Flannigan *et al*. 2005b). Nevertheless, previous studies have suggested that there is a notable spatial variation in the response, and that in parts of Finland the forest fire risk could even decrease (Flannigan *et al*. 1998). However, the findings of Flannigan *et al*. (1998) were based on a single GCM with two nine years simulations, and accordingly this conclusion is not very robust.

As expected, we found the projected increase in the fire risk to be smaller when using the scenarios with lower GHG emissions. This is particularly prominent in the case of low-emission B1 scenario, whereas the results for A1B and A2 scenarios were more similar. This is not surprising either, especially concerning the near-future scenarios, because GHG concentrations in these two latter scenarios evolve rather similarly until the 2060s.

Presumably the projected increase in the number of fire risk days is mainly due to the enhanced evaporation in a warmer climate leading to a reduced soil moisture content. In addition, an earlier snow melt in the future (Räisänen 2008, Räisänen and Eklund 2012) might cause the fire season to start earlier in spring. In contrast to temperature, no very prominent change is projected for precipitation, relative humidity or wind speed (Fig. 2). While the mean precipitation in Finland is projected to increase considerably in winter, only a modest increase of about 10% is expected for summer by the end of the current century (Jylhä *et al*. 2009). Furthermore, the number of rainy days is assumed to remain approximately unchanged in summer, and hence the increase in total precipitation is due to an intensification of individual rainfall events. When considering a forest fire risk, possible changes in the duration of individual dry spells between rainfall events would be noteworthy. In our approach of modifying the weather observations to respond to the anticipated climate change, this kind of change could not be taken into account properly. However, climate change scenarios indicate that interannual variability of precipitation is likely to increase (Räisänen 2002, Giorgi and Bi 2005, Giorgi and Coppola 2009). Moreover, Zolina *et al*. (2013) found that the changing number of wet and dry days cannot explain the observed long-term variability in the duration of wet and dry periods. Hence, we conclude that a regrouping of wet and dry days might be an important additional factor increasing the forest fire potential and its interannual variability in the future.

In addition to the direct influence discussed above, climate change may affect the fire risk through, for instance, changes in tree species composition and fuel loads. Fuel loads in forests depend on the history of forest management, the volume of timber and needles, the prior occurrence of fires and land-use changes (e.g. Robertson and Ostertag 2003). In Finland, forest management includes, for instance, the tending of seedling stands, thinning, harvesting and final cutting. Dry branches are recommended to be removed by pruning. Besides improving the tree wood quality, this action decreases the fuel load in the forest.

Ecosystem model simulations indicate that the growth of broadleaved trees and Scots pine will increase as the climate becomes warmer, whereas in southern Finland the growing conditions for Norway spruce may become suboptimal (Kellomäki *et al*. 2008). Hence, the proportion of birch (*Betula* spp.) and Scots pine may increase, especially at less fertile sites with a relatively low water-retention capacity (Kellomäki *et al*. 2008, Peltola *et al*. 2010). Concurrently, the total growing stock is projected to increase, which may increase the fuel loads (the volume of timber and the needles) in forests, especially in pine-dominated stands. It can be further hypothesized that the projected changes in tree species composition could lead to an increase in the number of forest fires, as the ignition probability in Scots pine forests is on average more than threefold that in Norway spruce forests. However, actual changes in fuel loads and tree species composition depend not only on climatic factors but also on forest management. In fact in recent years, a preference for Norway spruce in forest regeneration has increased significantly, mainly because of the large damage caused by elks to sapling stands of Scots pine (and birch), but also due to the prevailing good timber prices for Norway spruce. Accordingly, the above-cited climate-change-induced projections for tree species composition are not necessarily plausible. Moreover, despite the low flammability of spruce stands, Norway spruce is actually the most susceptible tree species in Finland to burn explosively (Lindberg *et al*. 2011). Accordingly, Norway-spruce-dominated forests, though resistant to ignition, are more susceptible to high-intensity crown-fires compared to Scots pine stands.

To conclude, possible changes in the fuel loads in forests, in the tree species composition and in other aspects that are sensitive to forest management may change the general characteristics of forest fires in Finland. Finally, it should be recalled that, as the large majority of all forest fires in Finland is human-induced, possible changes in human behaviour may substantially affect the average annual number of forest fires actually ignited.

Conclusions

The forest fire potential at four locations in Finland was explored using the FWI system. The frequency distribution of the index was derived from observational time series of temperature, relative humidity, wind speed and precipitation. To assess the risk in the future, time series of these variables were transformed to represent future climatic conditions by applying climate model simulations.

In response to the anthropogenic climate change, the forest fire potential is projected to increase. However, in the near future the projected change in the fire danger is not very prominent compared to its large interannual variability. By the end of the current century, the median annual number of days with elevated forest fire risk is projected to increase by about 10%–40%, depending on the emission scenario selected. In studying the fire risk in different forest stands, in the last scenario period no more than 5–10 additional potential fire days were found as compared with the baseline period, depending on the stand and the location. The increase in fire danger was smallest under low-emission B1 scenario, in which the increase in temperature is modest as compared to the scenarios with higher GHG emissions. The projected increase in the forest fire risk in Finland accords with the idea that the fire danger in the boreal zone will generally increase due to climate change.

Any possible qualitative changes in precipitation climate, e.g., regrouping of rainy days or changes in interannual variability, may contribute to the forest fire risk more than could be judged based on this study. Because of these factors, as well as possible changes in tree species composition, for instance, the actual increase of forest fire potential may be underestimated in the present projections. It would therefore be worthwhile to study the response of forest fire potential to climate change with some alternative methods. These could include utilizing the climate model results directly by applying some bias correction methods (e.g. Räisänen and Räty 2013).

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