nature climate change

SUPPLEMENTARY INFORMATION

DOI: 10.1038/NCLIMATE3303

Forest disturbances under climate change

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The disturbance database

The amount of information available on the effects of climate change on forest disturbances varied strongly with disturbance agent and biome (Table S1). A majority of the information extracted from the literature (83.1%) pertained to temperate and boreal ecosystems (Figure S1). Fire was the disturbance agent most frequently addressed in the reviewed literature (39.4%), followed by insects (23.7%), drought (16.4%), and pathogens (13.9%). The majority of studies used empirical approaches (48.8%), with 37.8% applying simulation models, and only a relatively small portion of the available information coming from manipulative experiments (13.4%). Methodological approaches varied distinctly between disturbance agents, with findings on biotic agents more frequently derived from experiments (33.6%) than those on abiotic agents (4.2%). However, approximately half of the analyzed studies for both agent groups used empirical approaches (abiotic agents: 48.0%, biotic agents: 50.5%).

Table S1: Observations on climate - disturbance relationships derived from the literature. Shown is the number of observations synthesized from the literature, and their distribution over disturbance agent, biome, and study method.

Disturbance agent	Study method	Biome				
		Boreal	Temp-erate	Mediter-ranean	Sub-tropical	Tropical
Fire	empirical	93	120	22	5	27
	experimental	-	-	-	-	1
	simulation	144	91	41	14	23
Drought	empirical	15	104	13	-	21
	experimental	-	32	3	1	4
	simulation	5	45	4	-	2
Wind	empirical	1	8	-	1	-
	experimental	-	-	-	-	-
	simulation	16	21	4	-	1
Snow & Ice	empirical	2	13	-	-	-
	experimental	-	-	-	-	-
	simulation	7	20	-	-	-
Insects	empirical	37	97	6	4	-
	experimental	4	80	6	7	1
	simulation	10	45	-	-	-
Pathogens	empirical	5	26	3	1	1
	experimental	17	14	2	-	4
	simulation	3	5	-	4	1

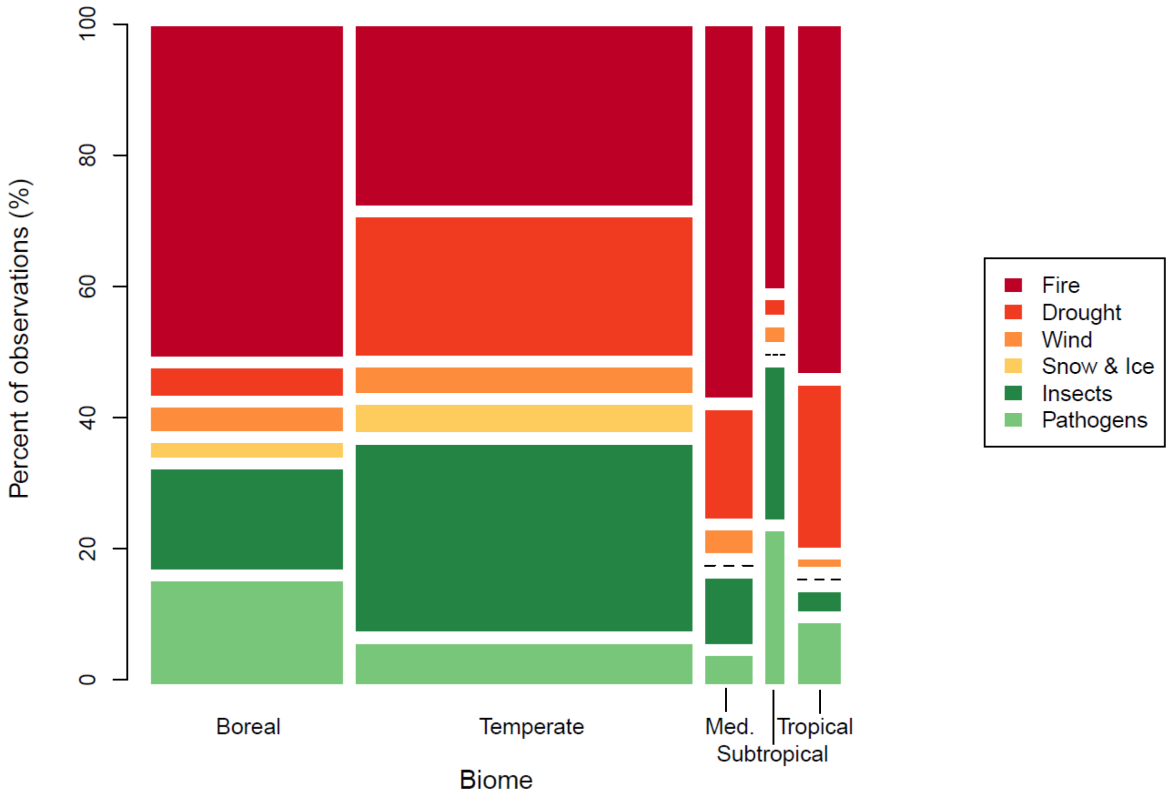

Figure S1: Distribution of observations over biomes and disturbance agents. The compartment size is proportional to the number of observations in the respective category. Med.= Mediterranean.

More than one third of the synthesized investigations on disturbance change focused on coniferous forests (39.7%), while 19.7% studied broadleaved forest types. A further 36.7% pertained to either mixed forests or included both coniferous and broadleaved forest types in their analysis (for the remaining 3.9% of the observations the forest type could not be assessed). More than 60% of all observations addressed large spatial extents, focusing on areas of $5\cdot10^9$ m² or more (i.e., regional to continental scale). However, the majority of the analyzed information was collected at a fine spatial grain, with 59.3% of the observations pertaining to the stand scale or finer grain (<$5 \cdot 10^5$ m²) (see Figure S2 for a distribution of the synthesized data over grain and extent).

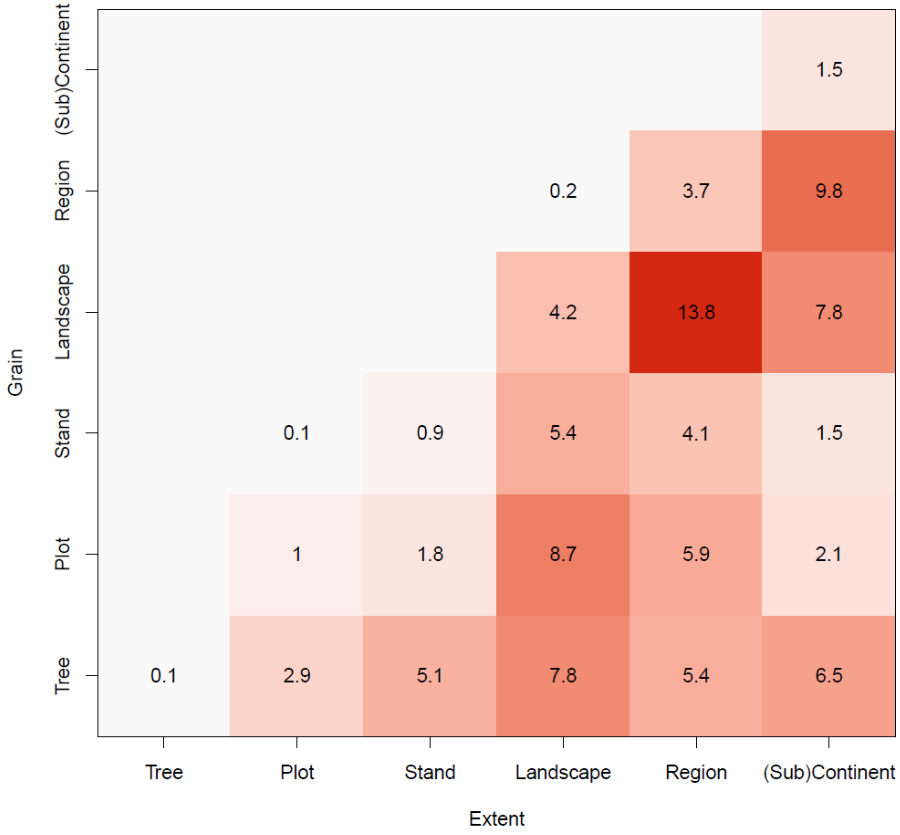

Figure S2: Observations and their respective spatial grain and extent. Grain describes the smallest unit of observation, while extent is the overall area addressed by an analysis. Values are percent of overall observations in each category. The cutoffs used in this categorization were: plot: <$5 \cdot 10^3$ m², stand: $5 \cdot 10^3$ – $5 \cdot 10^5$ m², landscape: $5 \cdot 10^5$ – $5 \cdot 10^9$ m², region: $5 \cdot 10^9$ m² – $5 \cdot 10^{11}$ m², subcontinent or continent: >$5 \cdot 10^{11}$ m².

Empirical and experimental studies were considerably finer in grain than simulation studies: While the empirical and experimental data were collected at the tree level in 33.7% and

73.0% of the cases respectively, 67.7% of simulation studies were conducted at a spatial grain of $5 \cdot 10^5$ m² or higher. Examples for the latter are, for instance, modeling studies using dynamic global vegetation models operating at large grid cells of several 100 km in size. Conversely, only 17.1% and 2.7% of empirical and experimental observations covered subcontinental or continental extents, while nearly half of the simulation approaches (44.6%) addressed disturbance changes at these extended scales. The raw data synthesized from the literature is accompanying this work as Online Supplementary Dataset.

Uncertainty assessment

In addition to indicators characterizing the synthesized literature with regard to its disturbance agent and ecological context (e.g., biome, forest type, scale of analysis), we also assessed the uncertainty associated with the information extracted from each of the reviewed studies. To consistently evaluate uncertainties we adopted an approach from the NUSAP method (Numeral Unit Spread Assessment Pedigree), which is a widely applied method to quantify uncertainty in environmental assessment [1–3]. Specifically, we utilized the approach to estimate pedigree within the NUSAP method, qualitatively scoring each observation with regard to its proxy representation and methodological rigor.

Proxy representation accounts for the fact that studies often do not directly measure the entity or phenomenon we were primarily interested in this analysis, but report some kind of proxy thereof. An example are studies reconstructing fire regimes based on charcoal records, the latter being well correlated to our variable of interest (fire activity), but not measuring the variable of interest directly. We assessed proxy representation using five categories, following the terminology and categorization developed for the NUSAP approach [1,2] (see also, http://www.nusap.net/ for examples): 4 = an exact measure of the desired quantity; 3 = good fit or measure; 2 = well correlated but not measuring the same thing; 1 =

weak correlation but commonalities in measure; 0 = not correlated and not clearly related. Almost two thirds of the observations synthesized from the literature (63.6%) were assessed to be a good or very good proxy of disturbance activity (categories 3 or 4). A distribution of observations over proxy representation categories is given in Figure S3.

The second indicator used to assess the quality of the data synthesized from the literature pertained to the methodological approach used by the underlying study. Specifically, we assessed the methodological rigor of the analysis in the context of the variety of approaches applied in the respective discipline, again following NUSAP categorization [1,2] (see also, http://www.nusap.net/ for examples). The levels of methodological rigor used in the assessment were: 4 = approved standard in well-established discipline; 3 = reliable method, common within discipline; 2 = acceptable method, but limited consensus on reliability; 1 = unproven methods, questionable reliability; 0 = purely subjective method. It has to be noted here that we did not use the main mode of investigation (i.e., whether the study used an empirical, experimental, or simulation approach) as an *a priori* evaluation criterion of scientific rigor, as we recorded study method as a separate indicator. Overall, 86.4% of the compiled observations were assessed to have high methodological rigor (categories 3 or 4). A distribution of the synthesized observations over methodological rigor categories can be found in Figure S3. Uncertainties were assessed for original research only, and review papers were omitted from the analysis. Both proxy representation and methodological rigor decreased moderately with increasing grain of the analysis (Figure S4.)

It is important to note that this uncertainty assessment does not yield an absolute measure of the quality of the reviewed work. It rather describes how relevant and reliable the information extracted from the literature is in the context of the specific research question of this study, i.e., the climate sensitivity of forest disturbance regimes. In this context the left-skewed distribution of uncertainties across our observations (Figure S3) can be explained by already omitting a large number of studies in the initial screening process for this analysis, e.g. studies for which it was already clear from the title and abstract that the reported data are only a poor proxy for changes in disturbance activity.

The approach to qualitatively assess uncertainties across published studies is inherently affected by an irreducible element of subjectivity. However, we followed a commonly applied protocol using previously developed assessment categories to achieve the largest degree of consistency possible. And while it is often debatable whether an observation falls into category 3 or 4, the approach applied here works well for identifying those observations that are poorly suited for assessing the climate sensitivity of disturbance regimes. Consequently, for all subsequent analyses we omitted all observations that were scored 0 or 1 with regard to either proxy representation or methodological rigor. An analysis of the remaining data showed that observations with only moderate proxy representation and lower methodological rigor (categories 2 and 3) did not have higher effect sizes than those that were scored highest in these two categories (Figure S5). Uncertainties in the data are thus not likely to contribute to an overestimation of the reported disturbance effect.

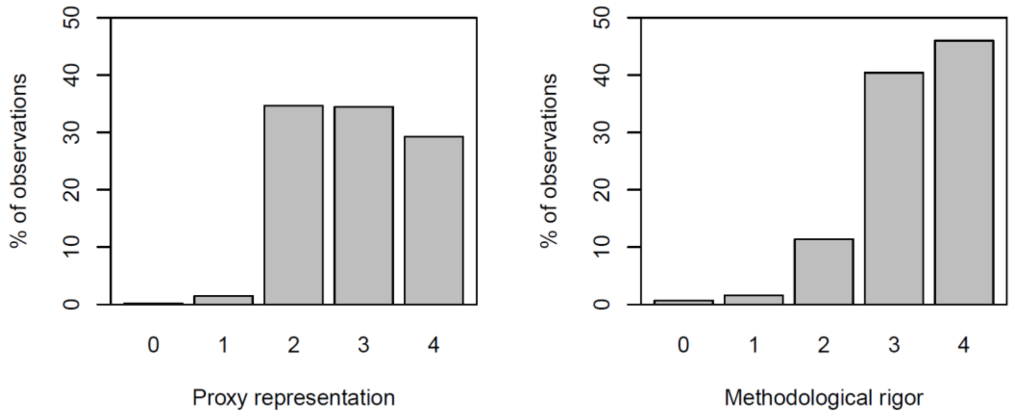

Figure S3: Assessment of uncertainties for the observations synthesized from the disturbance literature. Uncertainties are classified with regard to proxy representation (4 = an exact measure of the desired quantity; 3 = good fit or measure; 2 = well correlated but not measuring the same thing; 1 = weak correlation but commonalities in measure; 0 = not correlated and not clearly related) and methodological rigor (4 = approved standard in well-established discipline; 3 = reliable method, common within discipline; 2 = acceptable method, but limited consensus on reliability; 1 = unproven methods, questionable reliability; 0 = purely subjective method).

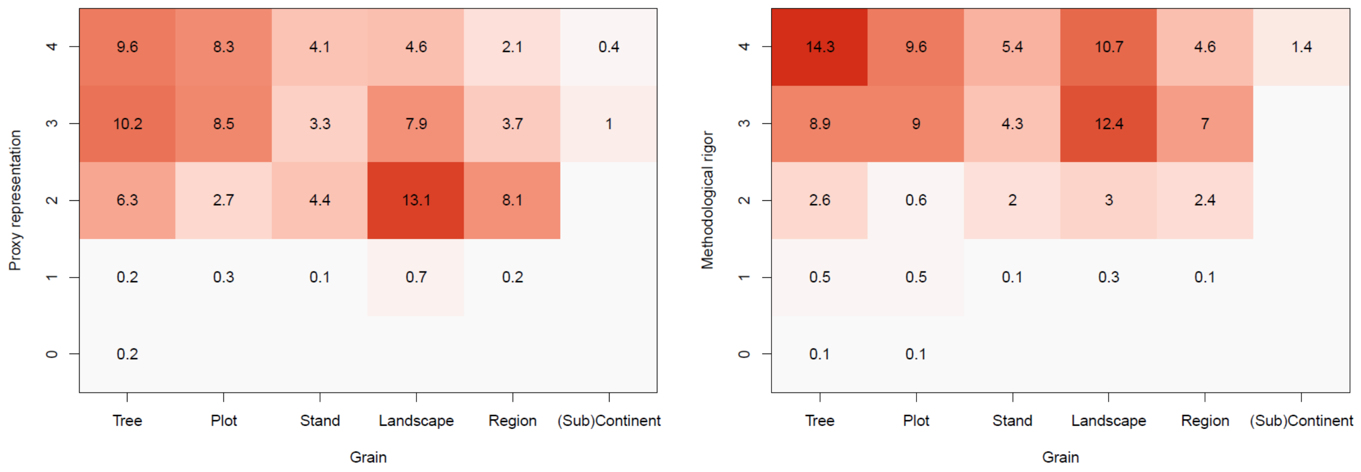

Figure S4: Distribution of uncertainties over the spatial grain of the underlying study. Uncertainties are classified with regard to proxy representation (4 = an exact measure of the desired quantity; 3 = good fit or measure; 2 = well correlated but not measuring the same thing; 1 = weak correlation but commonalities in measure; 0 = not correlated and not clearly related) and methodological rigor (4 = approved standard in well-established discipline; 3 = reliable method, common within discipline; 2 = acceptable method, but limited consensus on reliability; 1 = unproven methods, questionable reliability; 0 = purely subjective method). Categories of spatial grain were defined as: plot: <$5 \cdot 10^3$ m², stand: $5 \cdot 10^3$ – $5 \cdot 10^5$ m², landscape: $5 \cdot 10^5$ – $5 \cdot 10^9$ m², region: $5 \cdot 10^9$ m² – $5 \cdot 10^{11}$ m², subcontinent or continent: >$5 \cdot 10^{11}$ m². Values are percent of overall observations in each category.

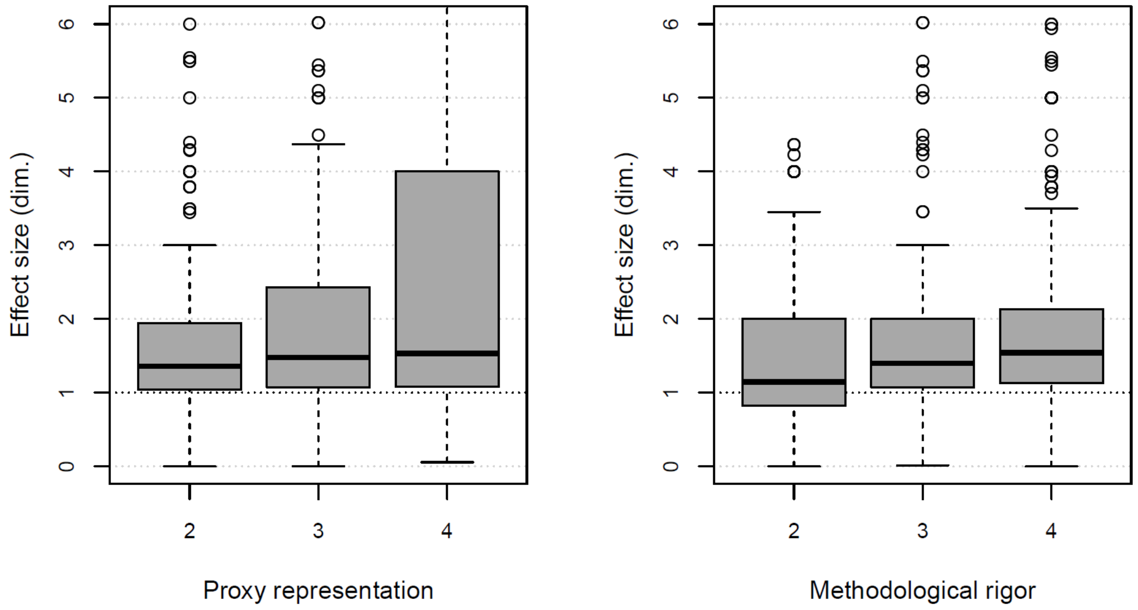

Figure S5: Variation of effect size over uncertainty categories. Effect size is calculated as disturbance under climate change divided by disturbance under baseline, and displayed by uncertainty category across all observations. Bold horizontal lines indicate the median over all studies, boxes indicate the interquartile range, and whiskers extend to the 5th and 95th percentile, respectively. An effect size >1 indicates an increasing disturbance activity under future climate change. Note that y-axes have been truncated for clarity, and that only the uncertainty categories retained for further analysis (> 1) are shown. dim.= dimensionless.

Qualitative modeling approach

Qualitative modeling is a complementary approach to quantitative modeling, trading off numerical precision for a more comprehensive consideration of the available information on a system [4]. Quantitative modeling often requires a reductionist approach to appropriately describing a process or system of interest mathematically. This, however, also means that large amounts of the available qualitative understanding remain unutilized. In contrast, qualitative modeling is able to address complex interactions [5], integrate over a wide level of varying data sources, and deal with remaining uncertainties at the system level [6]. Specifically, it has been suggested as a potent tool to assessing the climate change impact on forest ecosystems [6], and can be used to guide future quantitative model development.

Qualitative modeling frequently starts with visual conceptual models of interrelated components of the systems (cf. Fig. 1), and assigns weights and signs to the respective relationships. With the aim of being able to consistently compare across regions and agents, we here used the simplest possible qualitative model structure (Figure S6), and focused on deriving the signs of the identified effects pathways from the literature. Specifically, we distinguished between direct, indirect, and interaction effects on disturbances, and separately considered the effects of changing temperature and water availability in our qualitative analysis. We tested the null hypothesis that a changing climate will not change forest disturbances. This null hypothesis would be supported by the qualitative model if the literature indicates that there is no significant effect of changing temperature and water availability on disturbances, or if negative, dampening effects of climatic changes cancel out positive, amplifying effects. We here specifically tested this hypothesis under two different assumptions of climate change, i.e. warmer and wetter as well as warmer and drier future conditions. Warmer and wetter conditions assume an increase in both indicators of the thermal environment and water availability (e.g., warmer temperatures, higher levels of precipitation and soil moisture, or lower levels of water deficit and drought indices), while warmer and drier conditions, with an opposite direction of change for indicators of water availability under warming temperatures.

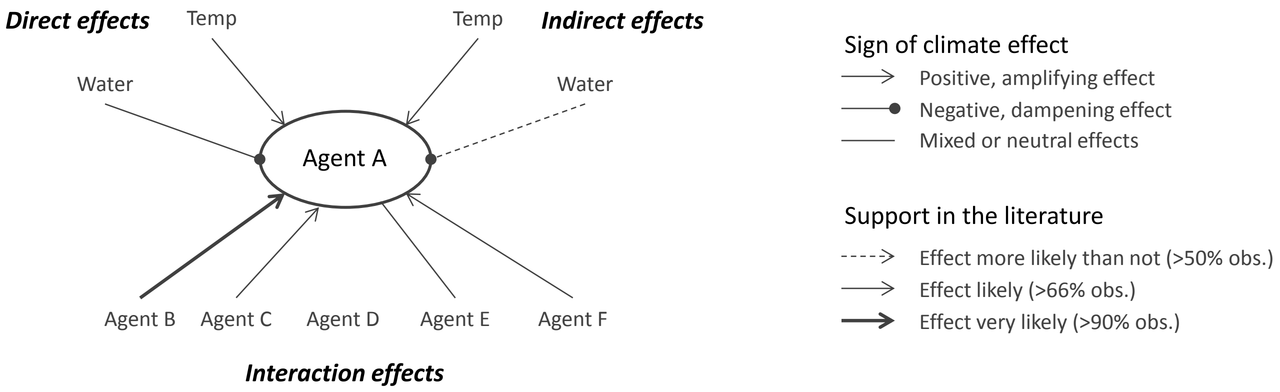

Figure S6: Qualitative model of disturbance change. Schematic depiction of the qualitative analysis of climate-related direct, indirect, and interaction effects on individual disturbance agents. Arrow types indicate the sign of the climate effect, while arrow widths indicate the support in the literature.

To set up our quantitative models of disturbance change we extracted the influence of temperature- and water-related drivers on disturbance along each pathway from the analyzed literature using ordinal response categories (+ positive, ~ neutral or mixed, - negative) (Table S2, Fig. 3). This information was subsequently aggregated using the likelihood scale employed by the IPCC [7]: If more than 50% of the evidence pointed towards an effect for a given pathway we assumed it to be more likely than not, while at >66% it was assumed likely, and at >90% very likely (Table S2).

Based on this qualitative analysis we found support for the null hypothesis of unchanged disturbance regimes under changing temperature and water regimes only for three out of the 12 climate change – disturbance agent combinations considered. Specifically, changes in disturbances from drought and snow & ice could not be substantiated from the literature under warmer and wetter conditions. Also, the alternative hypothesis of changing wind disturbances under warmer and drier conditions had to be rejected. For eight out of the 12 combinations, however, an increase in disturbances has to be expected under climate change, based on the information on direct, indirect, and interaction effects extracted from the literature. Only for disturbances from snow & ice under warmer and drier conditions did the data point towards a decreasing disturbance activity. The following paragraphs discuss the deduced effects for each agent in more detail.

Table S2: Signs and strength of evidence of direct, indirect, and interaction effects on disturbance agents. + indicates a positive, amplifying effect (i.e., an increase in the driver increases the focal agent); - indicates a negative, dampening effect (i.e., an increase in the driver decreases the focal agent); ~ indicates no or mixed effects. ++/-- indicates that a positive/ negative effect is very likely (>90% of the evidence in the literature support the effect); +/- indicates that a positive/ negative effect is likely (>66% of the evidence in the literature support the effect); (+)/(-) indicates that a positive/ negative effect is more likely than not (>50% of the evidence in the literature support the effect). Relationships with less than four observations were omitted.

Pathway of influence	Driver	Focal agent					
		Fire	Drought	Wind	Snow & Ice	Insects	Pathogens
Direct	Temperature	+	+	+	(-)	+	+
	Water	-	-	+	~	(-)	(+)
Indirect	Temperature	+	~	+	-	+	-
	Water	(-)	~	+	+	-	-
Interaction	Fire		++			(+)	
	Drought	++				+	++
	Wind	+				+	
	Snow & Ice					(+)	
	Insects	~			++		++
	Pathogens					~	

There is strong evidence that wildfire will increase in a warmer and drier world (Figure S7). All direct and indirect drivers investigated have positive, amplifying effects on fire disturbance. Neither direct nor indirect pathways had a dampening influence on fire under warmer and drier conditions. Furthermore, a strong positive interaction with drought – which is expected to increase under warmer and drier conditions (cf. Fig. 3) – is reported in the literature. Also wind and insects can be expected to interact with fire activity. These interactions will, however, have a mixed influence on fire as changes in wind disturbances remain uncertain under warmer and drier conditions (Fig. 3), and the influence of insects on fire is mixed (Tab. S2). If water availability will increase with climate warming, dampening effects are likely to offset some of the amplifying effects on fire activity. However, based on our qualitative analysis positive direct and indirect effects are still likely to exceed dampening effects, and increased water availability could introduce amplifying interactions with wind disturbances. Based on our qualitative assessment, wildfires are thus likely the increase under warmer and drier as well as warmer and wetter conditions, and the null hypothesis of no disturbance change has to be rejected.

A similar pattern of direct and indirect effects was observed for drought, with strong amplifying effects under warmer and drier conditions, and compensation from negative effects under warmer and wetter conditions (Figure S7). Interactions from other disturbance agents were not found to significantly influence the response of drought disturbance to climate change. Likewise, the response of wind disturbance to a changing climate was not significantly influenced by interaction effects from other disturbance agents. In contrast to fire and drought, wind responded more strongly positively to warmer and wetter conditions, with decreasing water availability resulting in dampening direct and indirect effects. Disturbances from snow & ice were expected to decrease distinctly under warmer and drier future conditions based on the evidence gathered from the literature. Only a positive effect of increasing insect disturbances under these conditions could amplify snow & ice disturbances.

The response was less distinct for snow & ice disturbance under warmer and wetter climate, where amplifying and dampening effects could balance each other out.

There is strong evidence that insect disturbances will increase under warmer and drier conditions. Both direct and indirect effects are strongly amplifying disturbance activity, and interactions from fire and drought are likely to further influence insect disturbances positively (Figure S8). Changes in pathogens and disturbance from snow & ice also had an influence on insect disturbances, yet their signs of influence were mixed. Wind disturbance is generally expected to further amplify insect activity (Table S2). However, changes in wind disturbances could not be substantiated for warmer and drier future conditions (Figure S7). If future conditions are characterized by increasing water availability in addition to rising temperatures, however, wind is likely to exert a positive effect on insect disturbances. And while dampening direct and indirect effects from increasing water availability are more likely than not, the overall response of insect disturbances to a warmer and wetter world is still dominated by positive, amplifying effects. Also pathogens are likely to respond positively to future climate change, regardless of whether water availability increases or decreases. Dampening influences were reported mainly via indirect effects, but overall strong positive direct and interaction effects are likely to dominate the response of pathogen disturbances to climate change.

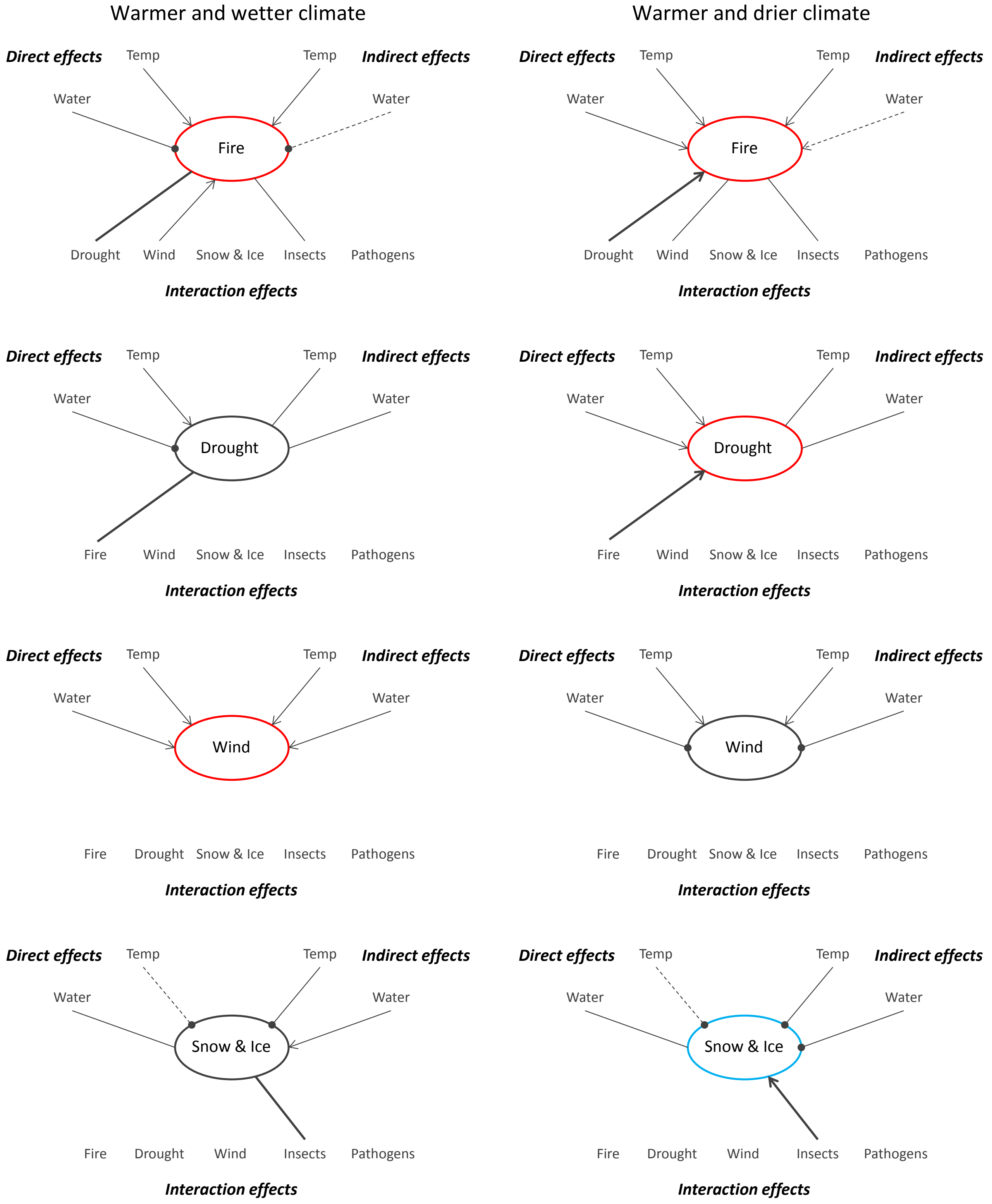

Figure S7: Effects of climate change on abiotic disturbances. Left panels show influences for warmer and wetter conditions, right panels for a warmer and drier world. Colors indicate that the null hypothesis of no disturbance change has to be rejected based on the qualitative model (red: increase, blue: decrease). For detailed legend see Figure S6.

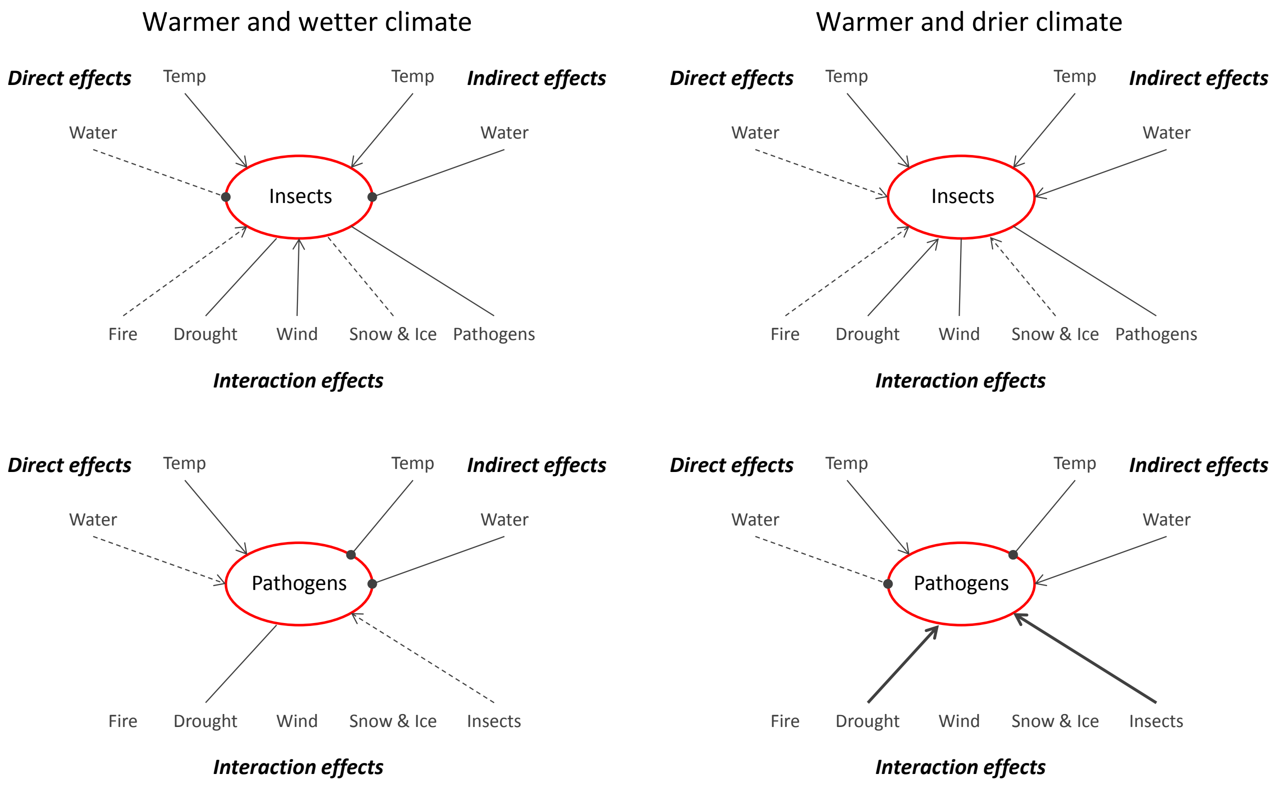

Figure S8: Effects of climate change on biotic disturbances. Left panels show influences for warmer and wetter conditions, right panels for a warmer and drier world. Colors indicate that the null hypothesis of no disturbance change has to be rejected based on the qualitative model (red: increase, blue: decrease). For detailed legend see Figure S6.

It is important to note that these qualitative results are not to be seen as a conclusive analysis of climate change effects on forest disturbances, but rather present a formalized framework for synthesizing current knowledge. As such, the influence of climate-mediated direct, indirect, and interaction effects reported here should be further tested using quantitative analyses and models. Our qualitative analysis, for instance, disregards local differences in disturbance responses to climate (cf. Figure 3) and integrates across the available information at the level of agent groups. Particularly for heterogeneous groups such as insects, local deviations from the influences synthesized here are likely [8]. The relatively high prevalence of mixed and/ or neutral effects in the data (cf. Figures S7 and S8) is an important indicator in this context, as it suggests high variability of climate effects e.g., across regions and within the broad agent categories used here. Furthermore, our simple qualitative analyses disregards differences in effect sizes and response times between influence pathways. While our data did not reveal significant differences between direct and indirect disturbance effects regarding effect size (see Figure S13 below), a systematic variation of response times between effects pathways was found (Figure S10). Consequently, dynamic quantitative models are needed to better understand spatio-temporal trajectories of disturbance change in the future.

Key climatic drivers of disturbance

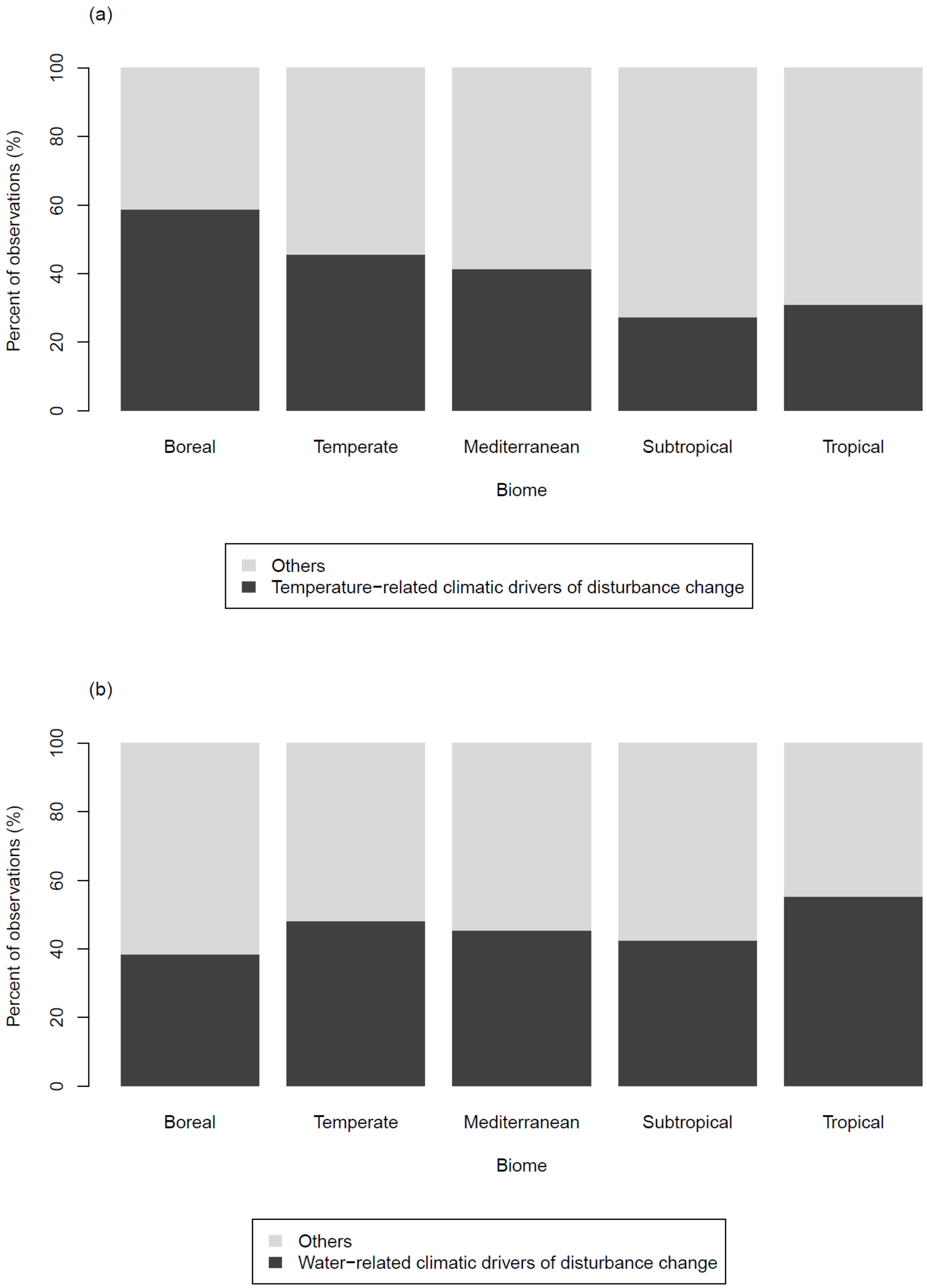

Figure S9: Key climatic drivers of forest disturbance. The importance of (a) temperature-related and (b) water-related drivers of disturbance change over biomes.

Response time and effect size of disturbance change

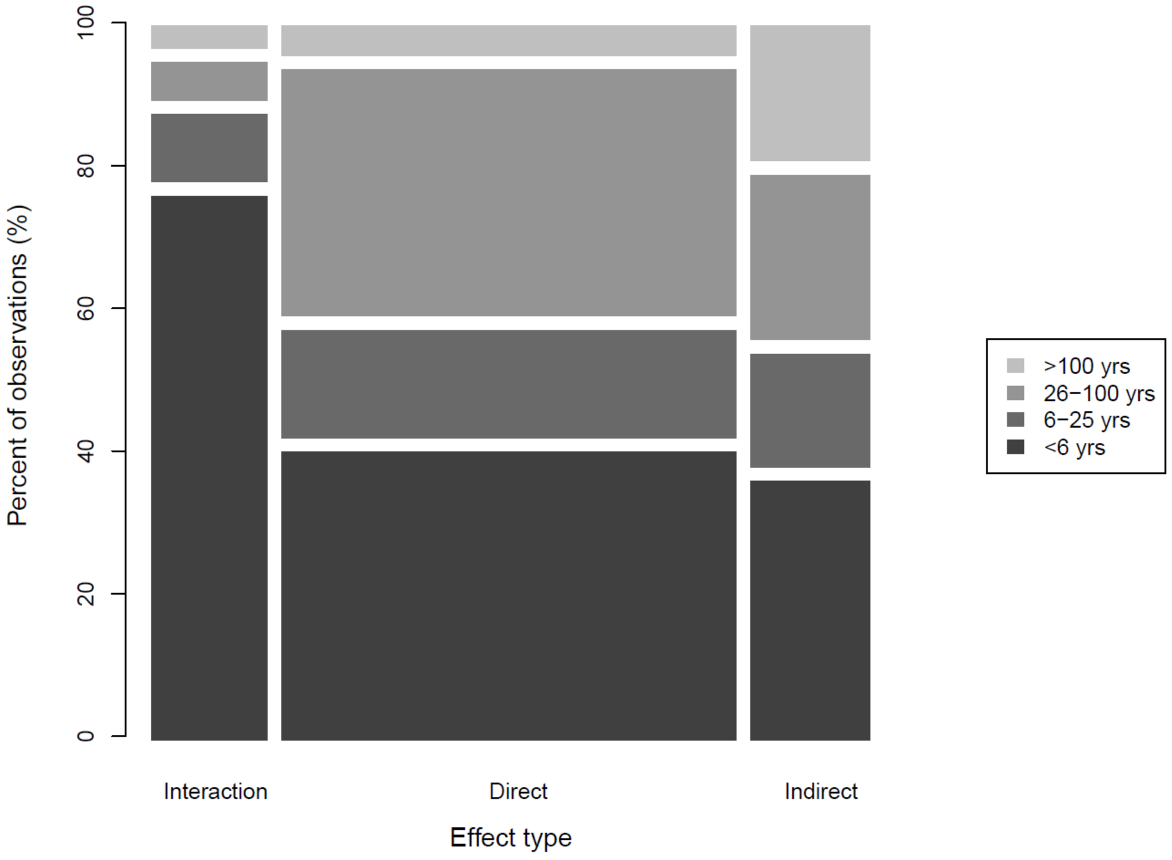

Figure S10: Response time. Distribution of observations over classes of response time and effect type. The size of every compartment is proportional to the number of observations in the respective category.

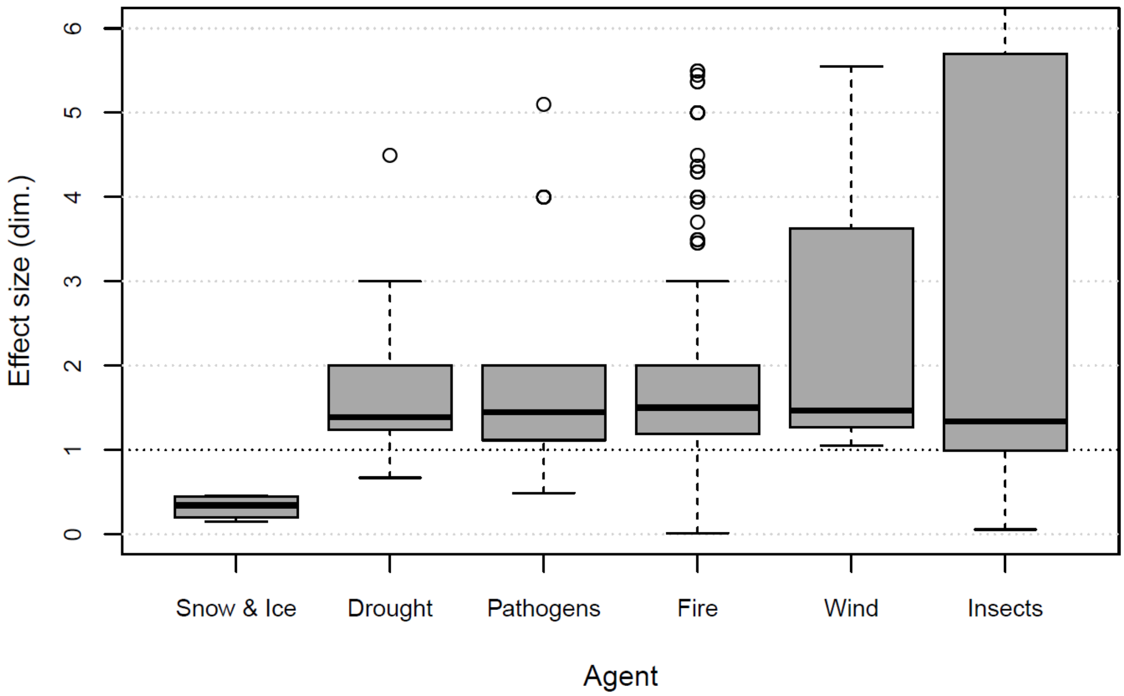

Figure S11: Size of the disturbance effect in response to future climate change by agent. Effect size is calculated as disturbance under climate change divided by disturbance under baseline, and displayed by agent over all observations and scenario conditions. Bold horizontal lines indicate the median over all studies, boxes indicate the interquartile range, and whiskers extend to the 5th and 95th percentile, respectively. An effect size >1 indicates increasing disturbance activity under future climate change. Note that y-axis has been truncated for clarity. dim.= dimensionless.

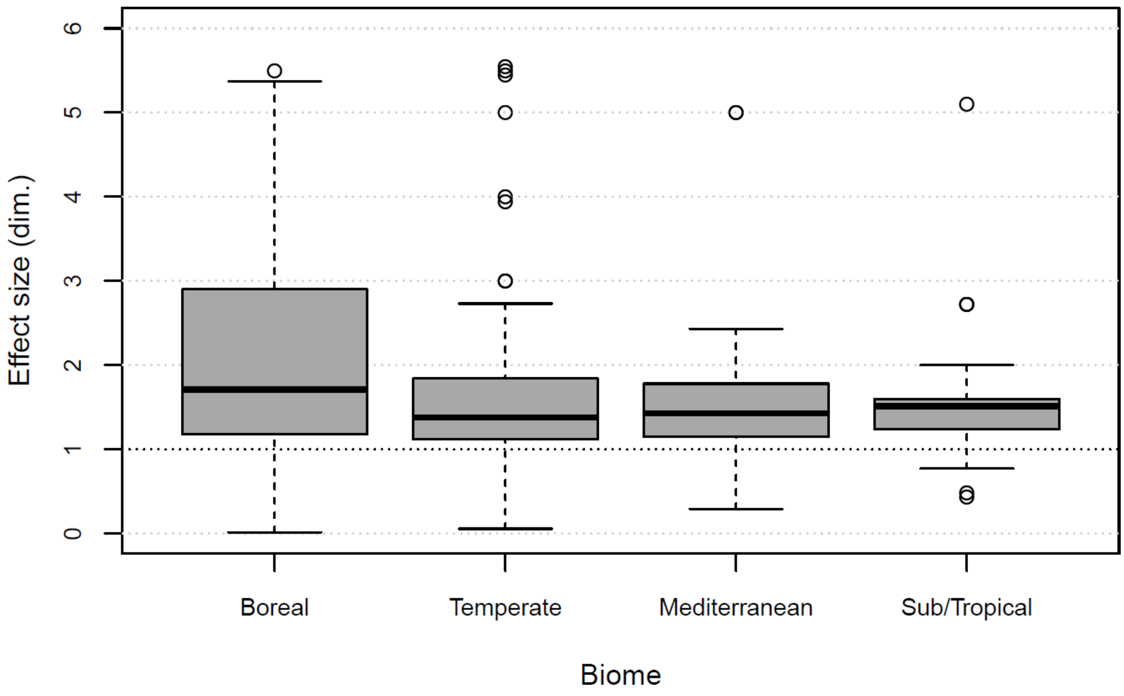

Figure S12: Size of the disturbance effect in response to future climate change by biome. Effect size is calculated as disturbance under climate change divided by disturbance under baseline, and displayed by biome over all observations and scenario conditions. Subtropical and tropical biomes were merged due to small sample sizes. Bold horizontal lines indicate the median over all studies, boxes indicate the interquartile range, and whiskers extend to the 5th and 95th percentile, respectively. An effect size >1 indicates an increasing disturbance activity under future climate change. Note that y-axis has been truncated for clarity. dim.= dimensionless.

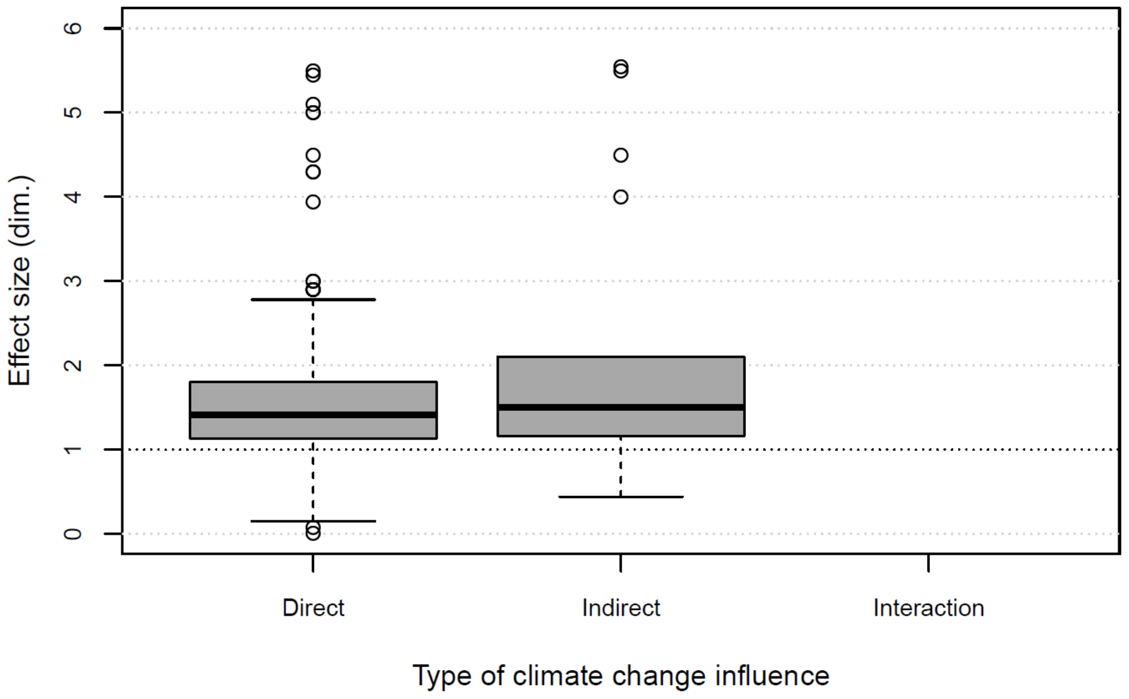

Figure S13: Size of the disturbance effect in response to future climate change by effect type. Effect size is calculated as disturbance under climate change divided by disturbance under baseline, and displayed by effect type over all observations and scenario conditions. Studies that could not be clearly attributed to a single type of climate change influence were omitted for this analysis. Please note that there was not enough information to quantitatively analyze the size of interaction effects. Bold horizontal lines indicate the median over all studies, boxes indicate the interquartile range, and whiskers extend to the 5th and 95th percentile, respectively. An effect size >1 indicates an increasing disturbance activity under future climate change. Note that y-axis has been truncated for clarity. dim.= dimensionless.

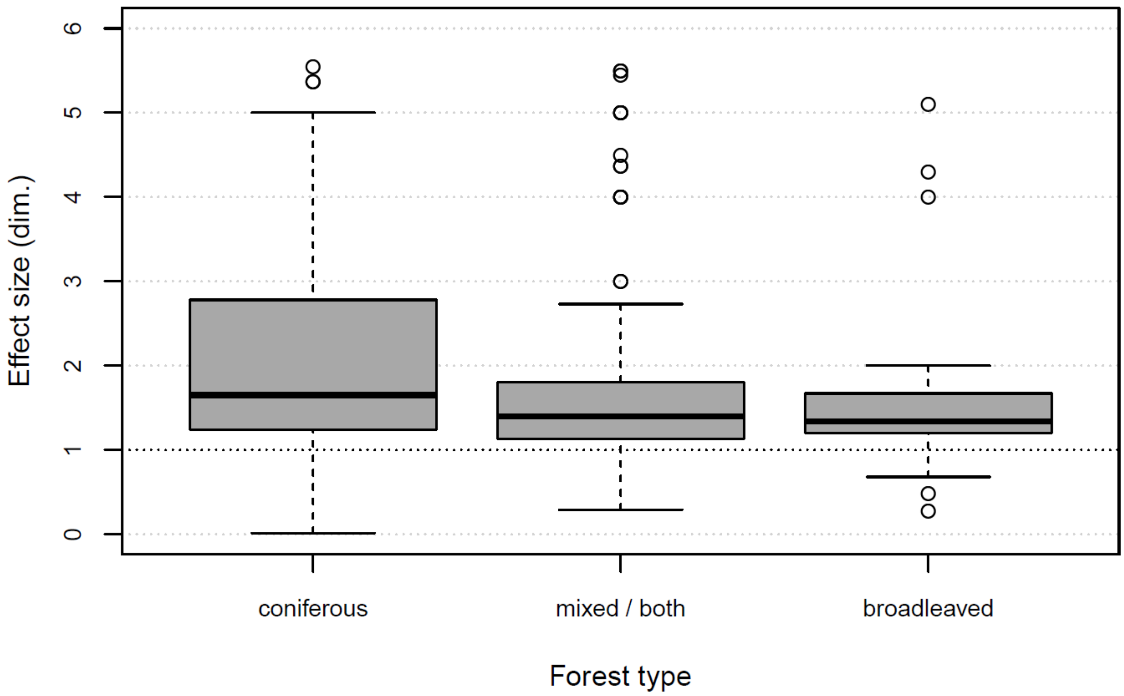

Figure S14: Size of the disturbance effect in response to future climate change by forest type. Effect size is calculated as disturbance under climate change divided by disturbance under baseline, and displayed by forest type over all observations and scenario conditions. Bold horizontal lines indicate the median over all studies, boxes indicate the interquartile range, and whiskers extend to the 5th and 95th percentile, respectively. An effect size >1 indicates an increasing disturbance activity under future climate change. Note that y-axis has been truncated for clarity. dim.= dimensionless.

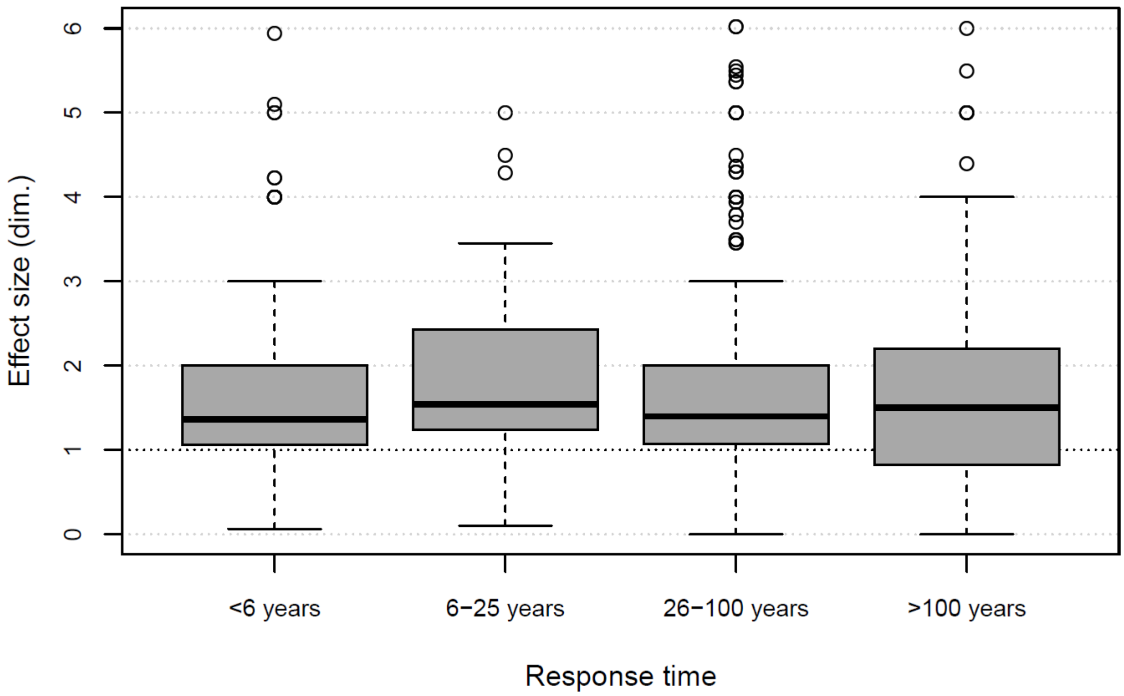

Figure S15: Size of the disturbance effect in response to climate change by response time. Effect size is calculated as disturbance under climate change divided by disturbance under baseline, and displayed by response time categories (cf. Figure S10) over all observations and scenario conditions. Bold horizontal lines indicate the median over all studies, boxes indicate the interquartile range, and whiskers extend to the 5th and 95th percentile, respectively. An effect size >1 indicates an increasing disturbance activity under future climate change. Note that y-axis has been truncated for clarity. dim.= dimensionless.

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