TREES AND CLIMATE CHANGE

A guide to the factors that influence species vulnerability and a summary of adaptation options

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Executive Summary

Climate change is widely recognised as a significant threat to biodiversity and ecosystem services. The direct and indirect effects of increased temperature, changing rainfall patterns and rising sea levels are expected to significantly increase extinction rates for a wide range of taxa, although the vulnerability of individual species will vary depending on the level of exposure to climate change, their sensitivity to that change and their ability to adapt to that change. Identifying exactly which species, or groups of species, are most vulnerable to climate change represents an important first step towards developing climate adaptation plans for biodiversity and for the people who depend upon it.

Trees represent one group of species that merit special attention for climate change adaptation planning. Already a highly threatened group (over 17,500 species are threatened with extinction[1]), trees have a series of traits that make them particularly susceptible to climate change. In addition, many tree species underpin an array of ecosystem services vital to the wider adaptive capacity of natural systems. Despite the apparent vulnerability and importance of this group, no frameworks exist to support practitioners to identify which tree species are most vulnerable to climate change.

Through support from British American Tobacco, Fauna & Flora International (FFI) worked to address the need for climate adaptation planning across a sample of its project sites, with the long-term purpose of building resilience of natural systems to climate change. This briefing was developed in order to contribute to this planning process, and as a contribution to the Global Trees Campaign (a joint initiative managed by FFI and Botanic Garden Conservation International, BGCI).[2]

Specifically, this briefing has three aims:

(1) To evaluate the factors that influence the vulnerability of tree species to climate change;
(2) To help practitioners identify which tree species are most vulnerable to climate change;
(3) To provide a basis for designing adaptation options.

Peer-reviewed literature and unpublished reports were reviewed to develop an evidence base for the responses of tree species to climate change. A recent framework developed by IUCN to compare relative vulnerability of amphibians, birds and corals to climate change[3] was adapted for use with trees. The basis for this framework is that a species is adjudged to be vulnerable to climate change if it is likely to be exposed to climate change (**Section 1**), it has traits which make it highly sensitive to that change (**Section 2**) and if it has low capacity to adapt to change (**Section 3**).

Key points for each of these factors are summarised in the below table. These considerations are not exhaustive but provide examples of the issues to consider when reviewing the vulnerability of tree species located at a given site. **Section 4** of this briefing includes a decision key to act as a tool to help practitioners undertake their own vulnerability assessments, which should ideally be complemented by information on potential local climate change scenarios and on the biology of the target tree species.

Section 5 summarises potential adaptation options for trees in response to climate change. In general, many of the adaptation options fall within conventional conservation interventions for tree species (e.g. maintaining genetic diversity, conserving the connectivity of the species' habitat, managing other stressors etc.). However, where a serious climate-based threat is identified for a given species, a number of other adaptation options should be considered including assisted migration, disease and pest management and monitoring and management of key pollinators and seed dispersers also vulnerable to climate change.

Cover Image: Trees at their current altitudinal limit on Mount Cameroon. Rising temperatures may force (or allow) some trees to migrate to higher elevations.
Above: Found in an extremely fragmented ecosystem, the Parana pine *Araucaria angustifolia* may struggle to adapt to predicted rises in temperature in southern Brazil.

Table 1: Factors to consider when assessing the vulnerability of tree species to climate change. These are grouped into:

(1) Areas of high exposure;
(2) Traits associated with sensitivity (i.e. low tolerance);
(3) Traits associated with low adaptive capacity.

Step 1: Exposure	Step 2: Traits associated with sensitivity to exposure
A) Trees will be exposed to increased temperatures throughout the world, but particularly in Northern America, Northern Eurasia, the Tibetan Plateau, Northwest Africa and Central South America.	A) Use of C_3 carbon fixation for photosynthesis increases likelihood of carbon starvation when temperatures are high.
	Dependence on temperature-based cues for seed production and germination.
	Slow flowering response time to temperature change.
B) In some temperate regions, trees will be exposed to increased risk of frost damage.	B) High sensitivity of flowering parts to spring frosts due to early or uniform flowering times.
C) Trees will be exposed to changes in the frequency and intensity of fires throughout the world, but increases are expected in Mediterranean biomes, montane grasslands and shrublands, desert and xeric shrublands, and temperate coniferous forests.	C) Where fire increases: thin protective layer of bark.
	Lack of ability to re-sprout new roots after a fire.
	Lack of ability to re-seed after a fire.
	Where fire decreases**:** Dependency on fire for germination.
D) Trees will be exposed to increased severity and duration of drought throughout the world, but particularly in Africa, southern Europe and the Middle East.	D) When droughts are severe, anisohydric species (opening their stomata during drought) suffer from hydraulic failure.
	When droughts are prolonged, isohydric species (which close their stomata during drought) suffer from carbon starvation.
	Dependence on rainfall-related cues for seed production
E) Trees will be exposed to increasing frequency and severity of emerging diseases and exotic plant predators, particularly where temperatures rise and rainfall levels change.	E) The existence of other populations already declining due to pests and disease. Climate change increases the likelihood of diseases or pests being transmitted to unaffected populations.
F) Trees will be exposed to increased rainfall in various locations, including Northern Canada, Northern Eurasia and the Tibetan Plateau.	F) Lack of adventitious roots or lack of ability to rapidly produce new roots in response to oxygen shortage in soil.
	Dependence on rainfall-related cues for seed production.
G) Trees will be exposed to rising sea-levels in low-lying coastal habitats.	G) Lack of salt tolerance.
	Lack of tolerance to inundation.
H) Trees that are exposed to any of the above consequences of climate change.	H) Small population size – sensitivity to stochastic events.
	Interacting with one or very few pollinators or seed dispersers that may also be vulnerable to climate change.

Step 3: Traits associated with low adaptive capacity to climate change

A) Low fecundity (e.g. those with irregular reproduction or those that do not reach maturity for several years.
B) Low genetic diversity.
C) Short-range seed dispersal mechanisms.
D) Occurring in highly fragmented landscapes.
E) Occurring at the limits of altitudinal space (e.g. cloud forest species).
F) Occurring at the limits of latitudinal space.

Introduction

Climate change is predicted to cause significant changes in temperature, rainfall, sea-levels, CO_2 concentrations and fire patterns to varying degrees across the world[4]. The knock-on effects of these climatic changes on biodiversity are expected to be significant[5]. Many species have already responded to a changing environment by shifting their ranges to track more favourable conditions[6,7]. For those species that are unable to track climate change, or adapt to its consequences *in situ*, population declines are highly likely and most studies now predict that various taxa will suffer from high levels of extinction[5].

Not all taxa will be affected by climate change in the same way. Certain species and taxa will be more vulnerable to its effects than others due to variation in exposure to climate change and biological differences between species[6]. Knowledge of these differences can help identify vulnerable species that are priorities for conservation action and climate adaptation planning[3].

However, to date, understanding of climate change impacts on species has mainly been derived from individual case studies and large-scale species distribution modelling, and few frameworks have been developed to aid conservation managers and decision-makers compare vulnerability across species. IUCN has developed a framework that uses biological traits, in combination with climate projections, to assess species vulnerability. This has been tested with some success for birds, corals and amphibians[3] and may eventually be used as a factor in Red Listing assessments.

No such framework or decision-support tool has been developed for trees, despite the clear threats that this group faces from climate change. Developing a means to identify trees that are vulnerable to climate change is of importance to biodiversity conservation for several reasons:

1) Trees are already a **highly threatened group of species**. Over 17,500 species are threatened with extinction[1] and the effects of climate change are likely to increase this number. Identifying traits that make particular species vulnerable will support prioritisation of conservation action for tree species.
2) Trees, as a group, exhibit a number of traits that make them **particularly susceptible to climate change**. Their typically long generation lengths, coupled with a relatively static lifestyle, renders trees less able to adapt to changing climatic conditions than more mobile, faster-breeding species[8].
3) Trees provide habitat, food or have symbiotic relationships with other species as well as ecosystem services and resources for humans[8]. Identifying which trees are vulnerable to climate change and which require conservation interventions is a key component of broader efforts to strengthen the **adaptive capacity of ecosystems**.
4) Although wider forest-carbon conservation projects supported by initiatives such as REDD may offer increased protection for many tree species from other stressors such as land-use change, individual species will still vary greatly in their vulnerability to climate change both within and outside of these areas. Certain trees will **require specific management interventions** to help them adapt to climate change.

Briefing purpose and approach

Through support from British American Tobacco, FFI worked to address the need for climate adaptation planning across a sample of its project sites, with the long-term purpose of building resilience of natural systems to climate change. This briefing was developed to contribute to this planning process, and as a contribution to the Global Trees Campaign (a joint initiative between FFI and BGCI).

Specifically, the following briefing aims to provide a framework to (1) evaluate the factors that influence the vulnerability of tree species to climate change (2) help managers and decision-makers identify tree species vulnerable to climate change and (3) provide a basis for designing adaptation options.

A literature review was conducted to develop an evidence base for observed and predicted responses of tree species to climate change. Efforts were made to review literature from a variety of sources and from as wide a geographic and taxonomic spread as possible. Despite such efforts, most data on links between climate change and trees were collected from countries with highly developed forestry sectors in the northern hemisphere and comparatively few studies were found that covered tropical areas, where many threatened trees are found. Bias in the literature reviewed is acknowledged as a barrier to having a comprehensive assessment of tree species' vulnerability, although many of the lessons learned that are presented here are relevant at a global level.

Vulnerability to climate change is difficult to measure because it is, for each species, the product of a large number of interacting climatic factors, environmental factors and biological traits. Providing a meaningful absolute assessment of vulnerability for a given species is beyond the scope of this briefing, but here we adapt the approach taken by IUCN to estimate **relative vulnerability** (i.e. whether one species is more or less likely to be vulnerable to climate change than another)[3]. The IUCN approach simplifies the large number of factors that influence vulnerability into three distinct criteria, where vulnerability is determined by a combination of:

- **Exposure:** the extent to which a species' physical environment will change due to climate change.
- **Sensitivity:** the degree to which a species is affected by, or responsive to, climate stimuli.
- **Adaptive capacity:** a species' inability to avoid the negative impacts of climate change through dispersal and/or micro-evolutionary change.

In this briefing, a species is deemed vulnerable to climate change if it **meets all three of the above mentioned criteria** (i.e. it is likely to be exposed to a change in climate **and** it is sensitive to that change **and** has a low capacity to adapt to that change).

The requirement to meet all three of these criteria is explained in **Table 2**. In essence, exposure to a climatic change (e.g. temperature increase) may be of little consequence to a species if it has biological traits that make it tolerant to such a change or that allow it to adapt very quickly. Likewise, a species that is highly sensitive to a given climatic change (e.g. it would suffer mortality during a severe drought) is not vulnerable to climate change if there is no indication that such exposure is likely to occur.

Table 2: How vulnerability is evaluated based on the links between exposure, sensitivity and adaptive capacity.

Exposed to change?	Sensitive to change?	Unable to adapt to change?	Vulnerable?
Yes, the tree is predicted to experience an increase in mean temperature.	**Yes**, the tree species suffers from increased mortality when temperatures increases.	**Yes**, the tree species is a poor disperser and is unlikely to shift range towards favourable conditions.	**Yes,** the species is exposed to a change, is sensitive to that change and is unlikely to adapt in response to the change.
No change in temperature or rainfall predicted in the species' range.	**But, yes,** the species would not reproduce if rainfall increased significantly.	**Yes,** the species has long generation lengths indicating that it will be slow to adapt to increased rainfall.	**Not yet.** Although the species has traits that suggest increased rainfall would be detrimental to its survival, we have no evidence that rainfall will increase. As climate models are uncertain, it is worth keeping an eye on this species.
Yes, rainfall increases predicted throughout the species' range.	**No**, the species can tolerate high rainfall.	**No**, the species has short generation length and it is likely that future generations will adapt to a changing environment.	**No**, although the species is exposed to increased rainfall, there is every chance that it will be able to cope with, or even thrive under, such conditions.

The caveat to this approach is that assessments are often based on imperfect information (e.g. climate models predicting changes in exposure may turn out to be erroneous or a species may be more sensitive or less able to adapt to change than first anticipated). In order to buffer against such uncertainty, it is advisable that managers are aware of, and monitor, species meeting two of the three criteria, in the event that the third criteria unexpectedly changes.

In the main section of this briefing**, Section 1** provides examples of climatic changes that might affect trees and some examples of where these changes are predicted to occur. The factors we consider here are (A) temperature increase; (B) increased frequency of frost; (C) fire incidence increase; (D) drought increase; (E) exposure to emerging diseases and pests (F) precipitation increase; and (G) sea level rise.

Section 2 provides examples of the traits that make certain tree species sensitive to each type of exposure discussed in Section 1.

Section 3 provides examples of the traits that make certain tree species have a low capacity to adapt to climate change.

Section 4 provides a decision key to help practitioners use their own data and knowledge to evaluate vulnerability for given tree species.

Section 5 discusses potential adaption options for tree species that are vulnerable to climate change.

Note: The examples provided below on climate change scenarios, sensitivity and adaptive capacity are by no means exhaustive. Climate change science deals with large levels of uncertainty and many of the biological traits related to climate change vulnerability have not been considered here. Therefore, users are encouraged to use this briefing as a guide to carry out their own assessments.

Above: Rising sea levels will expose trees found in coastal areas to increased levels of salinity and inundation.

1) Exposure to climate change

The first stage in assessing species vulnerability to climate change involves assessing whether the species found at a given location are likely to be exposed to primary and secondary consequences of climate change.

At a global level, and on a coarse scale, predicted changes in temperature and precipitation for different emission scenarios are freely available by using various tools or resources created by The Nature Conservancy[9], the United States Environmental Protection Agency[10] or the Climate Forecast Overview[11]. Climate modelling deals with a large degree of uncertainty and managers are advised to consult local climate scientists when researching and developing climate scenarios for their given area at a local level.

Here, background on different types of climate change exposure is provided with reference to the general areas where such change is expected to occur, according to current literature.

A) Temperature increase

Trees distributed in Northern America, Northern Eurasia, the Tibetan Plateau, Northwest Africa and Central South America are likely to be exposed to extreme levels of temperature increase, although moderate levels of increase are expected globally[9].
Increased temperature may directly impact threatened tree species (through mechanism explained in 2A) but may also contribute to increased outbreaks of fire (see 1C), combine with reduced precipitation to increase frequency and intensity of droughts (see 1D) or combine with increased precipitation to facilitate transmission of emerging diseases (see 1E).

B) Increased frequency of frost

Trees distributed in temperate areas will experience variation in the frequency of frost events and these will limit tree growth and reproduction[12].
Although most trees are able to survive severe frost, the most sensitive parts of trees including flower buds, ovaries, and leaves are often severely damaged[13]. Warmer winters (see 1A) are also likely to bring forward the growing and flowering season of many trees, increasing the likelihood of reproductive organs being subsequently exposed to spring frosts[12].

C) Changing frequency and intensity of fire regimes

Climate change is expected to lead to a major re-distribution of global fire regimes. Expected fire increases in many areas will impact fire-sensitive trees, although many areas will also be subject to a decrease in fire level – potentially impacting trees dependent on fire for reproduction[14].
Maps predicting global areas of fire increase and decrease can be viewed on-line in an open-access article by Krawchuk et al. 2009. Detailed evidence of recent fire increases have been documented in Mediterranean biomes, montane grasslands and shrublands, desert and xeric shrublands, and temperate coniferous forests[15,16]. Areas undergoing high levels of deforestation, including tropical dry forests[17], are also likely to be exposed to increasing incidences of forest fires.

D) Increased frequency, duration and intensity of drought

Trees distributed in Africa, southern Europe and the Middle East as well as parts of the Americas, Australia, and Southeast Asia are likely to be exposed to high levels of drought[18]. Increased aridity has already caused an increase in the cases of drought-related tree mortality in all of the world's continents (except Antarctica)[19]. In Panama, large periods of drought led to significant changes in forest composition, with drought tolerant species superseding moisture loving species[20]. Increased drought may also exacerbate the impacts of plant predators on trees (see 1E).

E) Increased exposure to emerging diseases and invasive species

Increases in temperature alongside changes in precipitation levels is likely to expose a number of trees to emerging diseases and novel plant predators.
Increased rainfall (see 1F) alongside increased temperature (see 1A) will expose tree species to increased incidences of pathogens (e.g. large increases of needle-blight in *Pinus contorta* in Canada were associated with large increases in summer rainfall)[21]. The effects of drought (see 1D) on tree species can both amplify or be amplified by outbreaks of pest insect species (e.g. outbreaks of insect

species are commonly associated with warm dry periods and the impacts of increased herbivory on tree species already physiologically stressed by drought may lead to high levels of mortality)[22].

F) Precipitation increases

Trees distributed in Northern Canada, Northern Eurasia and the Tibetan Plateau are likely to be exposed to high increases in rainfall[9].
Increased rainfall may result in mortality of certain tree species through increased exposure to flooding and waterlogging of the soil. Increased rainfall may also facilitate emergence of new diseases (see 1E).

G) Rising sea levels

Trees distributed in low-lying coastal habitats are likely to be exposed to rising sea levels. These species will be exposed to increased levels of salinity as well as prolonged inundation.

2) Sensitivity to climate change

After developing climate scenarios for the project sites, the next step is to consider which traits exhibited by a tree species make them sensitive to (i.e. unable to tolerate *in-situ*) a given form of exposure. These traits are described below in relation to the forms of exposure detailed in Section 1, together with examples of where climate-linked changes have been observed to date, according to the literature reviewed for this briefing.

(A) Traits that make species sensitive to exposure to temperature increases

(i) Certain trees thrive under temperature increases, yet others undergo carbon starvation and hydraulic failure, which may then lead to direct mortality.
For example, high increases in temperature in North America had little effect on populations of *Juniperus monosperma* but led to carbon starvation and mass mortality of *Pinus edulis*[23]. Direct mortality of trees due to temperature increase is most pronounced when temperature rise is combined with reduced precipitation; the traits that make species sensitive to both of these factors are discussed in section 1D.

***(ii) Certain trees depend on temperature related cues to trigger seed production and germination*.**
Increased spring temperature, observed in northern USA, suppressed seed production triggers in species from certain genera (including Magnolia, Ulmus, Pinus and Fagus), which all as a result produced far fewer seeds than in cooler springs[24]. In Karoo national park, South Africa, trees that depend on cooling periods to initiate seed germination are also negatively affected by spring warming[25] and this could also be the case for a number of species that require freezing or low temperatures to kick-start germination.

(iii) Certain trees are less able to adjust their flowering time in response to temperature change.
Species with slow flowering response times are less able to track climate change than their competitors and may thus fail to flower in synchrony with pollinators, negatively affecting their ability to reproduce[26].

(B) Traits that make species sensitive to changes in frost frequency

Certain trees have flowering parts that are more sensitive to spring frosts than others[27].
Certain traits may lead to low tolerance of flowers to spring frosts. These include being pre-disposed to bloom in early spring or to develop all buds at the same time of year (rather than staggering bud development)[27].

(C) Traits that make species sensitive to changes in fire regime

Certain trees are less able to tolerate fire than others due to variations in bark thickness and post-fire response strategies.
Tree species with thin layers of protective bark are more likely to suffer than those with thicker 'insulating' layers[28]. Other species, such as 're-sprouters' (trees which store extra energy in their roots to aid recovery and re-growth post-fire), may tolerate increased fire and others, such as 're-seeders' (trees which only produce seed after fires) may actually benefit from increased fire. This was shown in Montana, USA, where greater incidence of fire led to increases in abundance of a resprouter (*Populus tremuloides*) and a re-seeder (*Pinus contorta*) at the expense of all other tree species in the forest[29].

(D) Traits that make species sensitive to increased frequency and severity of drought

Trees have two different strategies for tolerating drought: one group is in general more sensitive to prolonged drought periods whereas the other is more sensitive to extreme drought conditions.

Plants exhibit one of two distinct responses to drought conditions[30]. During periods of drought, isohydric species close their stomata to avoid water loss and desiccation. This is effective under extreme droughts, but under **prolonged dry periods**, the long-term impacts of reduced carbon intake (due to closing of stomata) leads to carbon starvation and mortality of isohydric species[31].

Anisohydric species, in contrast, are more likely to keep stomatal pores open, allowing continued water flow and carbon intake under moderately dry conditions. Yet keeping stomatal pores open endangers anisohydric species to severe water loss and eventual hydraulic failure **during extreme drought**[31].

Another trait related to drought tolerance relates to the mechanism trees use for photosynthesis. Trees which use C_3 carbon fixation (including conifers and the majority of flowering plants) are in general less tolerant to drought than species using the more advanced C_4 carbon fixation system. C_4 carbon fixation species are able to open stomatal pores and absorb $C0_2$ at night and thus lose less water during times of stress[32]. Differentiating which trees use C_3 and which use C_4 pathways can be done by investigating leaf anatomy (C_4 plants have two different cell types dedicated for photosynthesis: bundle sheath cells and mesophyll cells). C_4 pathways are adopted by fewer plant species, mainly found in the tropics.

(E) Traits that make species sensitive to increased precipitation

(i) Certain trees are more sensitive to waterlogged soils than others.

Waterlogging reduces the availability of oxygen in the soil. Some trees may tolerate these conditions, if they have adventitious roots or are capable of rapid root production, although the majority of trees lack these traits and are therefore highly intolerant to waterlogging[33, 34].

***(ii) Certain trees depend on rainfall-related cues to trigger seed production and germination*.**

For example, species from the Dipterocarpaceae family of Southeast Asia only flower en masse after long periods of wet weather are followed by drought. Changes in the level of rainfall may lead to decreases in seed production and thus the reproductive capacity of certain species[35]**.**

(F) Traits that make species sensitive to emerging diseases

Certain trees may be more susceptible to emerging diseases than others.

No clear evidence was found on specific traits that determine tolerance of trees to emerging diseases, although it is likely that species found in small populations, in single species stands or those with low genetic variation (see section 3B) would be sensitive to emerging diseases[36].

(G) Traits that make species sensitive to rising sea levels

Rising sea levels may cause direct mortality of tree species and gradual replacement of sensitive species with salt-tolerant species.

This was observed in Florida, where salt-tolerant cabbage palms have increased in response to rising sea levels[37]. Even among salt-tolerant species, such as many mangrove species, long and frequent periods of inundation causes reduced health and area of mangrove, as has recently been observed in American Samoa[38]. In Guangxi, China, species were found to vary in their ability to tolerate inundation, although it was unclear which key traits determined these different responses[39].

(H) Traits that make species sensitive to any type of climatic change

(i) Trees with small populations, or that have very limited distributions, are more likely to lose a significant proportion of the total population to one-off catastrophes.

Climate change is expected to increase the frequency and intensity of extreme weather events with potential to wipe out large numbers of trees in one event.

(ii) Species dependent on one or a few species for pollination / dispersal will have lower capacity to adapt than generalist species, if they lose key ecological relationships.

The Joshua tree (*Yucca brevifola*) is unable to disperse its seeds over large distances, and therefore track climate change, as its main historic seed disperser - the Shasta ground sloth – has been extinct for many years[40].

3) Adaptive capacity

After considering whether a tree species will be exposed to, and sensitive to, a given change in climate, consider whether the species may have the capacity to adapt to this change. Adaptive capacity relates to the capacity of a species to evolve adaptive traits to new environmental conditions within its current location; or may also relate to the species' capacity to track favourable conditions.

A) Species with low capacity to reproduce

Trees with low fecundity may be slower to respond to and track climate change than their competitors.

Trees with low and irregular reproduction (e.g. many conifer and dipterocarp species) or species that do not reach maturity for several years are less likely to (i) adapt to unfavourable conditions (because lower reproduction offers fewer opportunities for genetic change) and (ii) successfully shift their distributions in response to climate change (because lower reproduction reduces frequency of dispersal events[8]).

B) Species with low genetic diversity

Populations of trees with low genetic diversity will have lower evolutionary potential to respond to climate change.

The rate of future climate change is predicted to exceed the potential of many species to migrate and track the climate to which they are adapted. Therefore the pressure upon species to adapt to new conditions within their current range will be intense[41]. Species with low levels of genetic diversity are less likely to cope with extreme levels of exposure[42] and less likely to resist disease outbreaks triggered by climate change[43].

C) Species with low capacity to disperse seeds long distances

Trees with short-range dispersal mechanisms will be less able to colonise new habitats in response to climate change than long-range dispersal species[44].

Extreme examples of short-range dispersal species include trees that use ants for seed dispersal, typically dispersing distances of 1-2m. Ant-based dispersal is prevalent across many plant groups including trees, occurring in 4% of plant species; hotspots for ant dispersal include dry areas and regions with Mediterranean climates in Australia and South Africa.

D) Species isolated in fragmented habitats

Tree species found in fragmented landscapes will be less likely to disperse to and encounter favourable habitats[45].

It is expected that climate change will exacerbate a number of pre-existing threats to species. For example, species threatened by fragmentation (e.g. where gene flow between subpopulations is extremely unlikely) will have low capacity to migrate and track climate change; this capacity may be weakened further should climate change reduce the area of habitable space available[46].

E) Species restricted to altitudinal limits

Trees located at the limits of available altitudinal space will be unable to track favourable climate, and may be outcompeted as novel species arrive from lower altitudes.

Rising temperatures are predicted to force (or allow) some trees to migrate to higher elevations. For example, entire forest biomes have been observed to shift uphill in Vermont, USA, in response to climate change, which also increased canopy mortality and accelerated colonisation of species from lower altitudes[47]. Similar changes in species composition have been observed in Spain[48] and in *Nothofagus* forest in Australia[49]. Cloud forest trees may be especially vulnerable as they have nowhere to go; many of these species are also found in highly fragmented forests[50] (see 3D).

F) Species restricted to latitudinal limits

Trees located at the limits of available latitudinal space will be unable to track favourable climate, and may also be outcompeted as novel species arrive from other latitudes.

Rising temperatures are predicted to lead to a migration of some tree species towards the poles. Northern range shifts in response to climate change have already been documented in the USA[51] and in

China[52]. Species for which migration towards the poles is not an option due to geological barriers such as oceans or mountain ranges will be unable to do this.

4) Decision key

This decision key can be used as a thinking tool to aid evaluations of tree species' vulnerability to climate change. Information provided here on exposure and biological traits are examples and are by no means exhaustive. Furthermore, it may not be possible to answer all of the relevant steps suggested below (e.g. you may know how climate is expected to change at your site, but have very little information to hand on the biological traits of your tree species).

Therefore, the below key should not be used as a means to generate conclusive assessments of climate change vulnerability. Rather, the key should help identify important factors to be researched and monitored over time, with results feeding back into re-assessments in the future. As much as possible, users are encouraged to undertake their own research on local climate projections and on the biology of their selected species to adapt this key.

Step 1: Develop climate scenarios for your site to help identify which categories of exposure are likely to be encountered by your tree species of concern. It may help to review **Section 1** of this briefing, consult local climate experts or use web-based tools such as climate wizard to develop your climate scenario.

Based on the climate scenario for your site, **mark all of** the below forms of exposure relevant to your tree species of interest:

- Increased mean temperature — Yes? □ Look at Step 2A and 2G
- Increased frequency of spring frost — Yes? □ Look at Step 2B and 2G
- Increased fire — Yes? □ Look at Step 2Ci and 2G
- Decreased fire — Yes? □ Look at Step 2Cii and 2G
- Increased severity of droughts — Yes? □ Look at Step 2Di and 2G
- Increased duration of droughts — Yes? □ Look at Step 2Dii and 2G
- Outbreak of plant predators (possibly caused by a combination of increased temperature and reduced precipitation) — Yes? □ Look at Step 2E and 2G
- Outbreak of pathogens (possibly caused by a combination of increased temperature and increased precipitation) — Yes? □ Look at Step 2E and 2G
- Increased rainfall and therefore inundation — Yes? □ Look at Step 2Fi and 2G
- Sea-level rise and therefore salinisation — Yes? □ Look at Step 2Fii and 2G
- Other ______________________________ — Yes? □ Look at Step 2G

Step 2: Review your results from Step 1. Now go through the table in step 2 and mark the types of exposure you expect at your site. For these rows, move right along the table to identify whether the tree species you are interested in has traits that will make it sensitive to that type of exposure.

Read **Section 2** of this briefing and carry out research on your species of interest to help with this assessment.

Will your species be exposed to the below change?		If so, does it have these traits related to sensitivity?		Consequence of exposure for species with trait
2A Temperature increase	□	Photosynthesises with a C_3 carbon fixation system.	□	Carbon starvation, leading to reduced growth / increased mortality.
		Responds to temperature cues for seed production or germination.	□	Reduced levels of recruitment.
		Slow flowering response time to changing temperature.	□	Reduced pollination, reproduction and recruitment.
2B Increased frequency of spring frost	□	Early or uniform bud and flower development	□	Reduced reproduction and recruitment.
2Ci Increased fire incidences	□	Thin layer of protective bark.	□	Higher mortality post-fire.
		Unable to re-sprout new roots post-fire.	□	Less able to acquire vital nutrients post-fire than competitors.
		Unable to re-seed post-fire.	□	Less able to colonise post-fire areas than competitors.
2Cii Decreased fire incidences	□	Fire-dependent for germination	□	Reduced reproduction and recruitment.
2Di Increased drought severity	□	Exhibits anisohydric behaviour (i.e. keeps stomatal pores open as a drought response).	□	Severe water loss, reduced growth, increased mortality.
2Dii Increased drought duration	□	Exhibits isohydric behaviour (i.e. closes stomatal pores as a drought response).	□	Carbon starvation over time, reduced growth, increased mortality.
		Responds to rainfall cues for seed production or germination	□	Reduced levels of recruitment.
2E Outbreaks of plant predators or pathogens	□	If populations are affected elsewhere	□	Decreased growth, low levels of recruitment (if seeds affected) and increased mortality.
		Small population size	□	
2Fi Inundation by freshwater	□	Lack adventitious roots.	□	Less likely to avoid oxygen starvation than competitors.
		Unable to rapidly produce new roots.	□	
		Responds to rainfall cues for seed production or germination.	□	Reduced levels of recruitment.
2Fii Inundation by salt water	□	Lack adventitious roots.	□	Less likely to avoid oxygen starvation than competitors.
		Unable to rapidly produce new roots.	□	
		Unable to tolerate high levels of salt.	□	Reduced growth and/or increased mortality.
2G Any of the above	□	Small population size	□	Potential to lose large proportion of population to stochastic events
		Dependence on one or very few species for pollination or dispersal	□	Reduced ability to reproduce

Step 2 summary: If you answered yes to any of cells provided in the above table, it is likely that the tree species at question will be exposed to and sensitive to climate change. Go to Step 3 to evaluate whether your tree species is likely to be able to adapt to this change.

Step 3: If the species you are evaluating is/are likely to be both exposed and sensitive to a climatic change, it is also important to consider whether the tree(s) will be able to adapt to this change, either by tracking its preferred climate, or by evolving adaptive traits inside its current range. Go through the traits below to evaluate whether any of these are relevant to your tree species.

Does your species have any of these traits related to low adaptive capacity?		**Consequence of this trait (if species is also exposed and sensitive to a change in climate)**
3A: Low fecundity or reaches maturity over long time-period	□	Lower evolutionary potential to evolve adaptive traits to climate change than competitors
3B: Low genetic diversity	□	Lower evolutionary potential to evolve adaptive traits to climate change than competitors
3C: Uses short-range dispersal mechanisms	□	Less able to track climate change than competitors
3D: Distributed in fragmented habitat	□	Unlikely to be able to track favourable climate
3E: Distributed at the limits of altitudinal space (including coastal species unable to move inland)	□	Unable to track favourable climate and susceptible to increased competition from species arriving from lower altitudes.
3F: Distributed at the limits of latitudinal space	□	Unable to track favourable climate and susceptible to increased competition from species arriving from other latitudes.

Step 4: Final Evaluation. Looking back at answers to Steps 1, 2 and 3 is the tree species:

i) Likely to be exposed to climate change?
ii) Sensitive to the specific changes it is predicted to be exposed to?
iii) Unlikely to be able to adapt to climate change?

If you answered **yes to zero or one of these factors** there is insufficient evidence to suggest that the tree species will be seriously negatively affected by climate change in the near future.	Low risk 
If you answered **yes to two of these factors**, the tree is potentially vulnerable to climate change and should be closely monitored, in case unexpected exposure to climate change occurs, or current understanding of the species' biological traits changes.	Potential risk 
If you answered **yes to all three of these factors**, the tree is assessed here as vulnerable to climate change. Without specific management interventions, this tree may be liable to population decline as a result of climate change.	High Risk 

5) Climate adaptation options for tree species

Tree species that are vulnerable to climate change may require specific management interventions to enable them to survive in the wild. Below we list a number of available adaptation options for vulnerable tree species. The effectiveness of each of these options will vary depending on local conditions and the local vulnerabilities of the tree species of concern[53]. Moreover, the final selection of a given option should also be influenced by other factors including cost and wider management objectives. Therefore, next to these recommendations, supporting information is provided on the sets of circumstances under which these recommendations may be most effective.

It should be stressed that this is a relatively new area of species management and a substantial body of evidence on the effectiveness of these measures is lacking. This evidence will presumably accumulate over time, but in the meantime it is imperative to ensure that any adaptation measures are “no regrets”, i.e. they will yield benefits even in the absence of climate change.

Recommendation	Required under what circumstances
Improve the management of other stressors such as over-exploitation and habitat degradation to give vulnerable species the best possible chance of adapting to climate change.	If other threats are leading to population decline, dealing with these threats, when feasible, should be prioritised over other suggested adaptation options.
Improve fire management and avoid planting fire-prone species such as many eucalyptus and pines which are likely to exacerbate the impacts of fire on non-tolerant species[54].	(a) If fire sensitive species occur in landscapes which are becoming fire-prone. (b) If replanting species to meet other management objectives, especially in fire-prone landscapes.
Bolster existing populations of threatened trees through planting of seedlings into the wild, but ensure reforestation efforts include seedlings from a wide genetic stock, and if possible, select for adaptive traits.	If populations of threatened species are small, if seedlings can be planted out in secure habitats and if sufficient resource exist to monitor and provide after-care for planted seedlings.
Plant corridors, or stepping stones, of species to increase likelihood of cross-pollination and successful dispersal.	If populations of a vulnerable species are fragmented and have short-range dispersal mechanism.
Manage forests to ensure that a high diversity of species and age classes are present.	Important under all circumstances to improve overall resilience, particularly if replanting efforts are using one or very few species.
Support assisted colonization through replanting trees into novel habitats that climate change may make favourable in the near future.	If adaptation at the current site is unlikely, if natural potential for migration is low and if secure new sites are available for this species.
Grow seedlings in unfavourable conditions (in contrast to assisted colonization) to develop and identify climate-resilient genetic stock to be replanted in natural habitat.	When a large quantity of genetically diverse seedlings is available and where trials sites are available to breed resilience to climate change exposure.
Monitor and where necessary provide management for key pollinator and seed-dispersal species.	If the vulnerable species is dependent on one or very few species for successful reproduction.
Improve flood protection for coastal species.	If natural inland migration is not an option.
Monitor tree health in the wild, particularly in relation to novel pathogens and predators.	Important under all circumstances but particularly in areas where high increases in temperature and changes in rainfall are expected to occur.
Screen seedlings for pathogens - before planting in the wild[55].	When replanting seedlings into the wild, especially when they are sourced from other populations.

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