Food and Agriculture
Organization of the
United Nations

A review of existing approaches and methods to assess climate change vulnerability of forests and forest-dependent people

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A review of existing approaches and methods to assess climate change vulnerability of forests and forest-dependent people

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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Summary

Until recently, considerably more attention was paid to using forests to mitigate climate change, through the absorption of carbon dioxide (CO_2) from the atmosphere, than there was on considering the need to adapt forests to avoid the worst effects that climate change could have on them. The switch from a mitigation-heavy approach to one that considers adaptation in a more balanced manner underscores the need to have approaches to assess the vulnerability of forests to climate change.

One reason for this more balanced focus may be due to the realization by the broader public, governmental organizations and the forest science community that the climate change that has already occurred is permanent in human terms, because it takes centuries for much of the CO_2 emitted from fossil fuel sources to be removed from the atmosphere. There are already substantial impacts that are being seen in the world's forests. These impacts are certain to continue increasing until CO_2 emissions drop to lower levels. For that reason, adaptation of the world's forests requires attention.

The approaches to assessing vulnerability can be categorized according to the focus they each provide. Contextual vulnerability addresses current issues of climate and is usually evaluated using participatory techniques with people who live in, or work with, forests. Outcome vulnerability looks at the biophysical vulnerability of forests; it is often used to assess the cause-and-effect of climate change on a biological system. Vulnerability assessments can be highly technical and quantitative, using advanced computer programs and geographic information systems, or they can be based on social science approaches to obtaining qualitative information from people.

Deserted land in Yemen

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1 Introduction

Forests around the world are at risk due to the effects of climate change. Trees, in particular, are vulnerable because they are long-lived and migrate slowly, so that they will be increasingly maladapted as climate change progresses (Lindner *et al.*, 2010). As forests respond sensitively to climate change, so do the people, communities and socio-economic activities that depend on them (Bernier and Schoene, 2009). Some of the most severe impacts of forest maladaptation to climate will be felt by people who depend on affected forests for subsistence food, shelter and economic opportunities, because they lack the resources to absorb the shocks from climate change (Devisscher *et al.*, 2013; Tiani *et al.*, 2015). Millions of forest-based communities depend directly on forests and their products and forests provide diverse ecosystem services which contribute to human well-being indirectly (Bernier and Schoene, 2009). Hence, adaptation of forests to climate change is significant for people on Earth. For that reason, taking steps to avoid harmful impacts is important, and to do that requires identifying which forests, and which value they provide, will be at risk. Identification of sources of vulnerability of forest and forest-dependent people to climate change is an important first step. The process of identifying such risks is commonly carried out using a vulnerability assessment.

There has been considerable use of vulnerability assessments to evaluate potential responses to climate change. Vulnerability assessments have been carried out to understand responses by natural ecosystems (Ellison, 2015, Sharma *et al.*, 2015) and agricultural systems (Olesen *et al.*, 2011), and for human infrastructure (van Vliet *et al.*, 2012), health (Haines *et al.*, 2006) and social systems (Hahn *et al.*, 2009). The scale of vulnerability assessments have ranged from continental (Lindner *et al.*, 2010, Schröter *et al.*, 2005) to local (Shrestha *et al.*, 2012) and have been used to evaluate risks caused by present-day conditions (Allen *et al.*, 2010) and those that may arise for climate conditions decades into the future (Lindner *et al.*, 2010).

The variety of uses for vulnerability assessments has helped to create a diversity of approaches for carrying them out. This document provides an overview of vulnerability assessment methods and considers how they can be adapted to evaluate the vulnerability of forests and forest-dependent communities to climate and climate change. In particular, the approaches that are described here are relevant to assessing the biological vulnerability of forests, as well as the vulnerability of forest-dependent communities. Moreover, this review is intended to provide the basis for developing a generic methodology for assessing forest and forest-dependent community vulnerability to climate change that can be used to address a range of circumstances.

Ideally, an approach to forest vulnerability assessment will be highly flexible: able to be used with a range of forest types (e.g. tropical, temperate, boreal); to assess present risks caused by climate and extreme weather and future risks under a range of potential climate change scenarios; and usable at multiple scales, from small, local forests of a few hundred hectares to regional forests covering hundreds to thousands of square kilometres. In addition to the above objectives, a methodology for assessing vulnerability should lead naturally to the articulation of adaptations to reduce the risks of damage from climate change. One way to accomplish this objective is to use a methodology that provides mechanisms for engaging with people who have a stake in reducing vulnerability. Such engagement is dependent on the twin steps of education and involvement – education about climate change and the threats that are posed by it, and involvement that comes about by participating in a vulnerability assessment. Motivated by engagement in the assessment process and provided with information generated by a vulnerability assessment, the intent is to create conditions suitable for crafting measures for adaptation to avoid the most harmful impacts of climate change.

FAO is currently developing a Framework Methodology for Climate Change Vulnerability Assessments of Forests and Forest-dependent People. This document was written to facilitate the preparation of the framework methodology. It provides background information on climate change and the impact of climate change on forests. Using the definition of the Intergovernmental Panel on Climate Change (IPCC), this document describes the concepts underlying vulnerability and provides examples of approaches that have been used to assess forest and forest-dependent community vulnerability.

Signs of landslides, soil erosion and flooding of the roads near Sandhikharka, Nepal

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2 Climate change and forests

Climate change is a worldwide phenomenon with diverse impacts. Changes in climate have considerably impacted natural and human ecosystems across the globe (IPCC, 2014). Seasonal activities, migration patterns, abundances and interactions of many terrestrial, freshwater and marine species have shifted in response to ongoing climate change (IPCC, 2014a). IPCC (2007) forecasted an increase in extinction risk of global flora and fauna species led by the global average temperature increase of 1.5–2.5°C, which implies climate change poses considerable threats to ecosystems and their biota (Lamsal *et al.*, 2017).

Forest ecosystems, especially, play an important role in the global biogeochemical cycle and exert significant influence on the earth's climate. The close link between climate and forests makes severe change in one area influence the other (FAO, 2012). Forests influence climate change, both as sources of greenhouse gases and as sinks for carbon and they are also influenced by climate change in growth, productivity, and distribution (Bernier and Schoene, 2009).

Over millions of years, forests have adapted continuously to climate change through modification in phenology, species diversity, species composition, and growth patterns (Davis *et al.*, 2005; Carcaillet *et al.*, 2010; Corlett and LaFrankie, 1998; Xu *et al.*, 2009; Gauthier *et al.*, 2014). Climate change and increased species invasion drives degradation of ecosystems and loss of biodiversity (Burgiel and Muir, 2010).

Climate change has already altered many forest ecosystems worldwide and increases risks of forests and indigenous forest dwellers depending directly on forests (Bernier and Schoene, 2009). However, climate change is expected to be greater in rate and magnitude than what has occurred thus far (IPCC, 2001, 2007; Gauthier *et al.*, 2014). Additionally, the effects of increases in temperature will be diverse depending on geographical location.

For boreal and temperate forest regions, temperature increases alone would have a positive effect, however, interaction with other climatic and regional factors can lead to various responses (Lindner *et al.*, 2010). With the uncertainty of future climate change and the vulnerability of forests, it is essential to understand how forests are impacted by climate change and how they adapt. Based on this, proper forest management practices can be implemented and adaptation strategies can be developed. Better management of forests will help both with adaptation as well as mitigation to climate change (Bernier and Schoene, 2009).

2.1 ANTHROPOGENIC CLIMATE CHANGE

Humans have been adding large amounts of carbon dioxide (CO_2) to the atmosphere for approximately 200 years, mainly by burning fossil fuels but also by converting forests, which store large amounts of carbon, to non-forested land that stores much less. These types of CO_2 emissions to the atmosphere are problematic because CO_2, and certain other gases that are emitted by human actions, are like a blanket surrounding the Earth, preventing heat from escaping back into space. The added heat warms the atmosphere, which in turn changes the climate. The pace of climate change has already been too rapid to allow many natural and human systems[1] to adapt, with harmful consequences globally.

Compounding the problem, CO_2 stays in the atmosphere for long periods, accumulating and causing progressively warmer temperatures. Therefore, for every litre of gasoline that is combusted or every hectare of land that is permanently deforested, the CO_2 emitted as a result of those actions is added to the atmosphere where much of it stays for centuries. As a result, levels of CO_2 in the atmosphere have risen from 280 parts per million in pre-industrial times to 400 parts per million now, increasing global mean temperature by 0.85°C since 1888 (Field *et al.*, 2014). Another 0.7°C of warming is considered likely to occur by 2035, based on probable greenhouse gas emissions (IPCC, 2013).

As noted earlier, warming of the atmosphere by the addition of greenhouse gases alters the Earth's climate. Climate is defined by the IPCC (2014) as "the average weather", described statistically as the mean and statistical variability of "relevant" quantities, such as temperature, precipitation and wind. Climate is usually described as a 30-year average. Climate change, therefore, is understood to be the change in the mean and/or the variability of the relevant quantities over time.

Apart from some of the common ways to express climate change, such as mean average annual temperature, average seasonal temperatures, and total annual or total seasonal precipitation, climate change can be expressed in ways that are designed to meet the goals of the topic of interest. For example, farmers may be interested in expressions of climate that are related to crop growth, such as the length of the frost-free season, the accumulation of a certain number of heat units, or the length of time between significant rainfalls. Expressions of climate, therefore, can be aligned with the needs of particular groups of people.

In addition to climate change being expressed as mean values of relevant quantities and their statistical variability, climate change can also be expressed in terms of the occurrence and/or severity of extreme weather events. Examples of extreme weather are heavy precipitation events and extreme daily maximum temperatures. Expressing climate change in terms of extremes rather than averages can be very meaningful for natural systems and for human wellbeing, since changes in the occurrence or intensity of extreme conditions can be more impactful than changes in mean values.

According to the IPCC (2014), "an extreme weather event is an event that is rare at a particular place and time of year". A rare event normally refers to one that has less than a one in ten chance likelihood of occurring, based on historical observations and

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[1] A system refers to what is that is being assessed. It can be an ecological system, like a forest, an economic system, like a forestry industry, or a social system, like a community or an organization. Often, a system bridges more than one of these elements. For example, it could be a socio-economic system, which includes both a community and an industry, or a socio-ecological system, involving, for example, both a community and forests.

extreme weather that goes on for a season or longer is called an extreme climate event (IPCC, 2014). For example, a prolonged period of heavy rainfalls can produce an extreme climate event, if over the course of a season the total precipitation exceeds the 90th percentile for total rainfall, compared to weather records (IPCC, 2014).

This document is concerned with current climate, extreme weather and extreme climate events, and how climate and extremes may change in coming decades, especially over the next 30 years. For the sake of brevity, throughout the remainder of this document, climate and climate change will refer to the average or the change in the average of relevant climate qualities, as well as the intensity and frequency of extreme weather and extreme climate events, unless otherwise stated.

2.2 CLIMATE CHANGE IMPACT ON FORESTS AND FOREST-DEPENDENT PEOPLE

Understanding which forest regions may suffer impacts because of climate change is vital because of the global importance of these ecosystems. According to the FAO Global Forest Resources Assessment 2015 (Keenan *et al.*, 2015), forests covered about 31% of land area, or 3.99 billion hectares, 44% of which is tropical, 31% boreal, 17% temperate and 8% sub-tropical. It is believed that forests managed according to the principles of sustainable forest management are in a better position to reduce their vulnerability and increase their resilience to climate change (Bernier and Schoene, 2009). However, the practice of sustainable forest management is hindered in much of the world's forests, since only 37% of the forest area in low income countries is covered by forest inventories and only 6% of forests in tropical regions have management practices that are certified as sustainable (MacDicken *et al.*, 2015). Implementing sustainable forest management is crucial to the millions of people relying on forests for their livelihoods and for whom forests are crucial for their subsistence. It is a universal practice for adapting forests to climate change that will be increasingly important as climate change has increasingly adverse effects on forests in coming decades.

Climate change that has already occurred has had some negative effects on some forests. This includes: increases in severe outbreaks of forest fires and damaging insects; the altered timing of key biological events, such as flowering and the timing of growth resumption and cessation; and increased incidence of widespread tree dieback and mortality (e.g. Medlyn *et al.*, 2011, Parmesan, 2006). Species in tropical countries are likely to be most affected by warmer temperatures because they are already near their thermal tolerance (HLPE, 2017). These effects already threaten the wellbeing of some communities that depend on forests. Those at risk include the 10 million people for whom forests provide direct employment and the 410 million who are highly dependent on forests for subsistence access to food and fuel. Economically, climate change creates risk for the wood and manufactured forest products industries, which add more than $450 billion to the world economy annually (Köhl *et al.*, 2015).

Climate change is also putting the ecological benefits that forests provide at risk. Those ecological benefits can be even more important than the economic value of goods and services that are derived from forests (Costanza *et al.*, 2014). For example, forests provide habitat and food for many animals and plant species and as climate change alters the types of tree and plant species in forests, there will also be changes in the fauna that live in forests. Forests also store water and intercept rainfall to allow it to slowly infiltrate into soils, reducing flooding and erosion. Some of the water stored by forests is transpired and evaporated back into the atmosphere, where it is cycled back into clouds and falls again as rain, helping to moderate local and regional climates. If climate change reduces the area and age of forests, there will be increased risks of flooding and erosion, and altered local and regional climates.

Forests are also important because they are carbon sinks, helping to mitigate climate change by removing large amounts of CO_2 from the atmosphere by photosynthesis and storing the carbon in trees, soil and dead organic matter (Le Quéré *et al.*, 2015). If climate change reduces the strength of forest carbon sinks, there is a risk that this could create a positive feedback loop, whereby less carbon is removed from the atmosphere by forests causes more warming, which in turn further reduce carbon absorption by forests.

Additionally, one important climate change impact on people and communities who live both near and far from forests is the impact on the sustainable supply of ecosystem services. Change in ecosystem services can measure increase or decrease of human well-being under the influence of global climate change threats (Metzger, Leemans and Schröter, 2005). For people who manage forests or who live in forest dependent communities, understanding what aspects of forests and which ecological processes are at risk because of climate change can allow adaptive measures to be identified that reduce negative impacts. This is increasingly being done by conducting vulnerability assessments.

In Nicaragua, project beneficiaries build a small dam out of stones which will slow the flow of water down the mountainside during rains thereby helping to guard against soil erosion. FAO Project UTF/Nic/028/Nic

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3 Principles for assessing vulnerability

Vulnerability is a word that is familiar to most people and is commonly used to refer to something that is at risk of being harmed. Many specific technical definitions of vulnerability have been developed to meet the needs of different social and ecological fields of investigation. This document uses the technical definition of vulnerability given by the Intergovernmental Panel on Climate Change (the IPCC), where vulnerability is described as:

> *…the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.* (IPCC, 2014)

Resilience, a concept related to vulnerability, is also considered when projecting how systems may respond to climate change. The IPCC (2014) defines resilience as:

> *"…the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation."*

Vulnerability and resilience are, therefore, related aspects of how systems are affected by climate change – vulnerability reflects the harm that may be caused to a system by climate change, while resilience reflects the ability of a system to "carry on" despite being exposed to climate change (Brugère and De Young, 2015). Although they are closely linked concepts, vulnerability and resilience are not opposing concepts, since a system can be both vulnerable to climate change and resilient, if it has the capacity to recover from and adapt to damage caused by climate change (Buckle *et al.*, 2001, Gallopin, 2006).

Vulnerability and resilience can be analysed by considering the impacts on a system caused by climate or extreme weather. Impacts are often characterized using three factors: the exposure to potentially damaging climate or weather; the sensitivity of the system to that exposure, and the ability of the system to adapt once the exposure has happened. These three factors, exposure, sensitivity and adaptive capacity, are core elements of many approaches to assessing the vulnerability and resilience of systems to climate change (Fritzsche *et al.*, 2014).

The IPCC (2014) defines exposure, sensitivity, impacts and adaptive capacity as follows:

- Exposure is the presence of people, ecosystems, infrastructure, or a species, in an area expected to be exposed to changes in climate or to extreme weather, either under present conditions or in future.

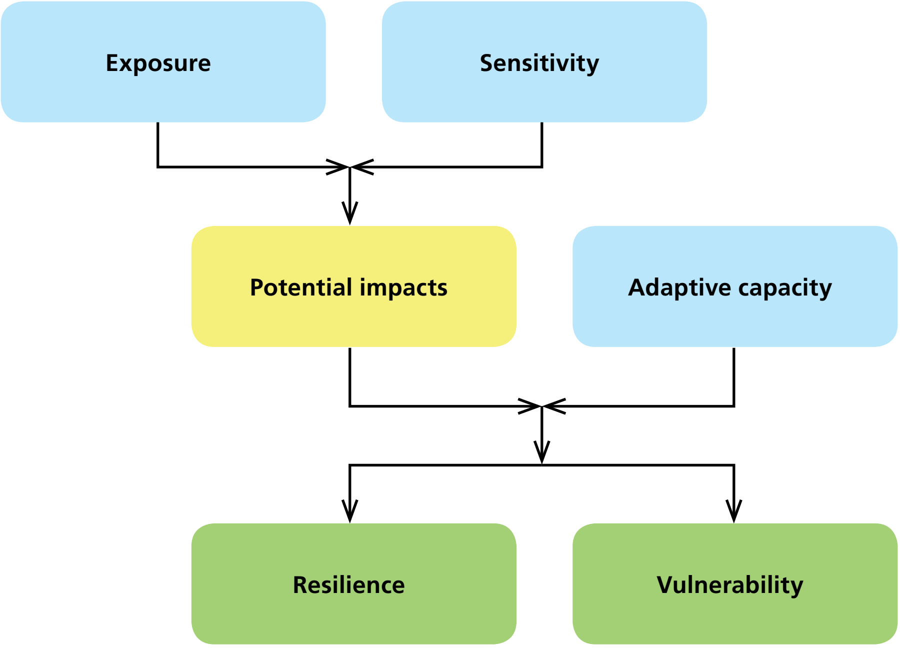
- Sensitivity is the magnitude of the direct or indirect effects of climate or extreme weather, either adversely or beneficially, relative to the climatic event.
- Impacts are the observed effects of climate and extreme weather.
- Adaptive capacity is the ability of a system or a species to respond to climate change or a climatic event in a way that reduces harmful impacts.

The relationships of vulnerability and resilience to exposure, sensitivity and adaptive capacity are shown diagrammatically in Figure 1. The damage caused to the system – which reflects the system's vulnerability – is the outcome of the exposure, sensitivity and adaptive capacity. The ability of the system to retain its function – the system's resilience – reflects how well the system can recover from the exposure to climate change. Among the components, exposure and sensitivity is determined by the intrinsic attributes of the system. Exposure and sensitivity can increase or decrease according to the perturbation of external environments. Adaptive capacity of a system concludes how much a system is vulnerable or resilient to the perturbation.

In the simplest terms, a vulnerability assessment evaluates what is at risk from climate change. The objective of obtaining this information can vary and can be used for educational purposes, so that people and organizations are informed about current

FIGURE 1

A model of factors that can be used to assess the vulnerability and resilience of systems



Source: Based on Füssel and Klein, 2006, and Gauthier *et al.*, 2014 risks from climate and extreme weather and about the potential for future changes in climate to affect communities and local ecosystems (Fritzsche *et al.*, 2014; Brugère and De Young, 2015). Vulnerability assessments can also be used to identify which locations and activities are more at risk of being harmed, and whether climate change may provide benefits and create new opportunities that can be exploited (O'Brien *et al.*, 2004). Vulnerability assessments can also be used to implement adaptive measures proactively, which is preferable to responding to damage after it has occurred (Williams *et al.*, 2008). This is especially important in cases where a vulnerability assessment could have improved or saved lives, by identifying the risks of extreme outcomes.

In providing a systematic approach to evaluating what is at risk from climate change, a vulnerability assessment should answer the question *"what (or who) is vulnerable to what"* (Gitz and Meybeck, 2012). The first "what" to be identified describes the system that is to be evaluated and what aspects of that system may be at risk. Describing *"what is vulnerable"* can be done by answering the following general questions (Brugère and De Young, 2015):

- Which people/species/activities are vulnerable?
- Where are vulnerable people and systems located?
- Who will experience the greatest consequences (economic or social) because of their vulnerability?
- Where and for whom might climate change result in opportunities and benefits?

The second *"what"* in *"what is vulnerable to what,"* is a description of the aspects of climate that create risk (Gitz and Meybeck, 2012). As previously noted, climate is a broad term that will need to be defined more specifically before carrying out the vulnerability assessment. For example, temperature can be expressed as an annual mean value, a mean for the growing season, the likelihood of a temperature being above seasonal norms, a threshold value that marks the start and end of the growing season, and more. A large number of expressions are also used to express precipitation, often related to the risk of either extremely heavy precipitation events or drought. The expressions of climate that are used in a vulnerability assessment need to be relevant to what is being assessed.

The clarification of both parts of *"what is vulnerable to what"* sets the scope for the vulnerability assessment. Within that scope, the vulnerability assessment will evaluate the system's identified potential exposure to the climatic risk, the sensitivity of the system to that climatic risk, and the system's capacity to adapt to the climate risk (Füssell and Klein, 2006). As shown in Figure 1, the interactions among exposure, sensitivity and adaptive capacity produce impacts on a system. A system that is more negatively impacted is more vulnerable and less resilient. Most vulnerability assessments use some combination of the indicators in Figure 1 – exposure to a potentially damaging climatic factor, sensitivity of the system to that climatic factor, project the possible consequences (impacts) that may result from the exposure and consider how the adaptive capacity of the system could reduce those impacts, by modifying exposure or sensitivity (e.g. Hammill *et al.*, 2013, Kok *et al.*, 2016).

Farming soil in several areas near Monywa, Myanmar has dried up after flooding and devastation caused by Cyclone Komen in July-August of 2015

©FAO/HKUN LAT

4 Major approaches to understanding vulnerability: contextual versus outcome assessments

Extensive literature has been published on vulnerability and how to assess it (for instance, see Adger, 2006; Brugère and De Young, 2015, Fritzsche *et al.*, 2014; O'Brien *et al.*, 2007). Many of the studies on vulnerability can be categorized either as contextual approaches (also referred to as bottom-up or starting point vulnerability), or as outcome approaches (also known as top-down and end-point vulnerability) (see Figure 2 and Table 1).

The contextual approach has usually been applied to assess vulnerability of people or human systems to current climate extremes, by considering the contextual factors that affect it. However, the approach can also be applied to ecosystems, such as forests. In comparison, the outcome-vulnerability approach starts with a scenario of future climate change and asks: "How will a system respond if the climate changes in this way?" (Hammill *et al.*, 2013, UNFCCC, 2011). While contextual and outcome and vulnerability assessments may differ in additional ways (some of which are described in Table 1), the timeframe and the subject of the impacts are the main distinguishing features of these approaches.

Specifically, current impacts are considered in contextual approaches and future impacts are considered in outcome approaches; and impacts on multiple social and ecological factors are considered in contextual approaches and in outcome approaches the biophysical climatic impacts on the selected system are accounted for (biophysical impacts are those affecting physical and biological attributes).

Contextual assessments often use what are termed "participatory" approaches to evaluating vulnerability (Fritzsche *et al.*, 2014). Participatory approaches provide qualitative information obtained from people about their own perceptions of vulnerability, or the vulnerability of aspects of their local community or nearby ecosystems. In comparison, outcome vulnerability assessments usually employ modelling approaches that require software and advanced technological knowledge of computers and modelling (Fritzche *et al.*, 2014). Outcome assessments are usually carried out to evaluate the vulnerability of infrastructure, agricultural systems or natural ecological features (GIZ, 2013). Outcome vulnerability assessments may also facilitate comparisons between assessments done at different times and different locations, since the inputs and outputs are less subject to bias and interpretation than contextual approaches that rely on information provided by people on their own unique circumstances (Fritzsche *et al.*, 2014).

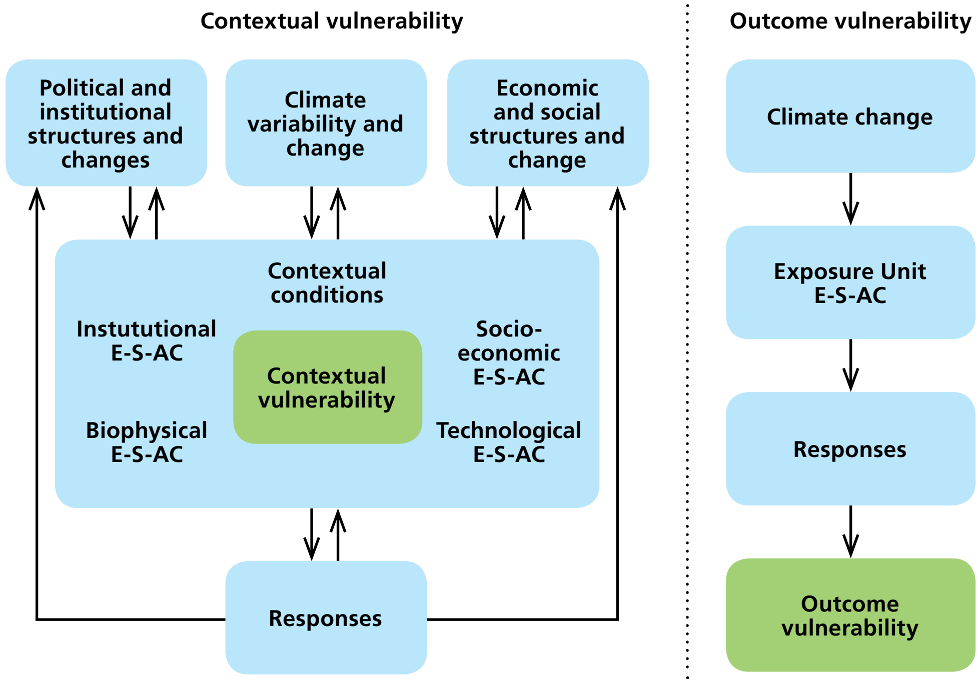
4.1 CONTEXTUAL VULNERABILITY

Contextual vulnerability focuses on vulnerabilities that presently exist (O'Brien *et al.*, 2004, Brugère and De Young, 2015), and address the ability of human and ecological systems to cope with current extreme weather and climate (IPCC, 2014). By focusing on the near term, contextual vulnerability assessments will provide adaptations to reduce current risks.

A contextual approach accounts for the contributions of multiple contextual conditions to vulnerability of a system (Figure 2, Table 1). Contextual conditions can be institutional, socio-economic, biophysical and technological (Figure 2). Climate not only can alter the contextual conditions, but the contextual conditions can also influence exposure to climate change (O'Brien *et al.*, 2007). In practice, a contextual vulnerability assessment does not follow a straightforward one-to-one causation structure. Instead, contextual assessments aim to consider many of the "moving pieces" that can be at play when systems are affected by climate. Brugère and De Young (2015) describe the contextual approach as being iterative, since each contextual condition is, in turn, evaluated, to reach a composite evaluation of vulnerability.

FIGURE 2

Conceptual models of contextual vulnerability assessment (left) and outcome vulnerability assessment (right) to climate change



Source: O'Brien *et al.*, 2007, and Brugère and De Young, 2015

TABLE 1

Contrasting features of contextual and outcome vulnerability assessments

Perspectives	Contextual or bottom-up vulnerability	Outcome or top-down vulnerability
Root problem to be addressed	Climate change impacts on people	Adapting to climate change; human impacts on climate
Objectives of the assessment	Adaptation of people/communities or ecosystems to changing climate	Adaptation of "things" – technical adaptation; climate change mitigation
Relationship between vulnerability and adaptive capacity	Determining vulnerability indicates adaptive capacity	Determining adaptive capacity indicates vulnerability
Dominant focus	Reactive to current vulnerability to climate extremes; short-term (0–30 years); may also be long-term	Predictive of future long-term climate hazards (scenarios), e.g. doubled CO_2 or 30–100 years in future
Usual scale conducted?	Usually local, sometimes regional, national or global scale	Global, sometimes regional, or local scale if using downscaled climate information
How issues are framed	Multidimensional human security problems that consider food security, economic security, social and cultural wellbeing etc. Considered qualitatively using a social science perspective	Natural science approaches that express exposure quantitatively and where resulting consequences are quantifiable for selected ecosystems, people, infrastructure, etc.
Meaning of vulnerability	Susceptibility to damage by climate extremes (sometimes climate change) as determined by prevailing socio-economic factors	Expected net damage for a given level of climate change (net refers to consequences remaining after adaptation has taken place)

Source: Modified from Brugère and De Young, 2015, with additions from Pielke *et al.*, 2013

A linkage between the model of vulnerability shown in Figure 1, and the models of contextual and outcome vulnerability shown in Figure 2, is demonstrated by the letters E-S-AC in Figure 2. These letters refer to exposure, sensitivity and adaptive capacity from Figure 1. In contextual vulnerability, E-S-AC may be evaluated for each of the contextual conditions in Figure 2, where they regulate the type and magnitude of the responses to climate change. In outcome vulnerability, they are embodied within what is called the exposure unit.

Contextual vulnerability assessment approaches may be preferred for several reasons:

- Some communities, species or ecosystems may already be in a condition so precarious that concern about future outcomes may be moot. By focusing on current vulnerability, people's conditions could be improved and threatened species or ecosystems that are at risk of being lost might be protected.
- Focusing on current vulnerability will put resources towards adaptations that address issues of relatively higher certainty, as the vulnerability assessments are based on historical impacts of climate and weather extremes. This avoids the greater uncertainty that arises when deciding on adaptation priorities based on vulnerability assessments that cover a large range of possible future climates (Dessai and Hulme, 2004).
- A contextual study can be carried out without climate projections if it focuses only on current vulnerabilities (Kwadijk *et al.*, 2010).

- Vulnerability assessments done using a contextual approach can be used to empower communities, harnessing their knowledge of local conditions and threats to address risks, and can similarly be used to engage key decision makers in communities, governments and non-governmental organizations, whose participation can facilitate implementing adaptation measures.

However, contextual assessments can also have drawbacks such as:

- The approach often relies to a large extent on expert judgement and produces qualitative results that can be more difficult to decide among multiple options for adaptation.
- By not considering future impacts in a vulnerability assessment, adaptations to future conditions that require long lead-in times may be missed (McGranahan *et al.*, 2007).
- The chance of finding adaptations that can reduce both current and future vulnerability may be lost if both current and future impacts are not evaluated (Ford *et al.*, 2008).
- In the worst-case scenario, actions that reduce current vulnerability might unwittingly increase future vulnerability.
- In complex systems, the length of time to conduct a contextual study can be prohibitively long (Kwadijk *et al.*, 2010).
- Contextual assessments that restrict their focus to current vulnerabilities may lead to investments in adaptation of lost causes, by not identifying socio-economic systems, communities, species or ecosystems that have a limited chance to thrive with future changes in climate. For example, a contextual assessment that failed to account for future environmental changes could result in resources being directed towards conserving a species that has limited chances of avoiding extirpation in the long term.
- Some systems may be too complex to account for all important contextual conditions (Kwadijk *et al.*, 2010), and this complexity can make it difficult to form simple conclusions about the causes and implications of impacts (Jones and Preston, 2011).

By supporting adaptations to current climate challenges, a contextual vulnerability assessment can provide information that improves present-day outcomes for people and the things people currently value. In the case of marginalized communities, a contextual vulnerability assessment could lead to adaptations that markedly reduce threats faced by people in those communities. Addressing the present- day adaptation needs of people in developing countries, identified using a contextual vulnerability assessment, would be of greater present value than addressing most, if not all, of the adaptation needs identified from an outcome vulnerability assessment focused on risks that may, with less certainty, appear further in the future (Dupuis and Biesbroek, 2013).

4.2 OUTCOME VULNERABILITY

A typical outcome vulnerability assessment asks the question: “What happens to a system if a particular climate change scenario comes about?” (IPCC, 2014, Kwadijk, 2010). Put another way, an outcome vulnerability assessment evaluates the cause-and-effect of climate change on a system, as represented in Figure 2 (right) (Brugère and De Young, 2015). O'Brien *et al.* (2007) provide a more technical description of outcome vulnerability, describing it as "a linear result of the projected impacts of climate change on a particular exposure unit (which can be either biophysical or social), offset by adaptation measures".

The term "outcome" applied to this type of vulnerability assessment is used because the approach usually reflects a cause-and-effect relationship between a system and climate. This type of approach is also called a top-down assessment, because it often uses climate projections from general circulation models (GCMs) that have been downscaled from global to local scales (Jones and Preston, 2011).

The results from outcome vulnerability assessments can be used to reduce harmful impacts, by reducing exposure or by implementing adaptations that reduce sensitivity or increase adaptive capacity (O'Brien *et al.*, 2007). Outcome vulnerability assessments are less focused on explaining why differences exist among systems (e.g. why one forest area would be more or less sensitive than another), because the information collected for the assessment is mainly concerned with determining the impact of climate, rather than exploring the reasons underlying the sensitivity of a system (Brugère and De Young, 2015). The results of outcome assessments can often be expressed quantitatively (see Janowiak *et al.*, 2014), which can facilitate making comparisons among different assessments (Jones and Preston, 2011).

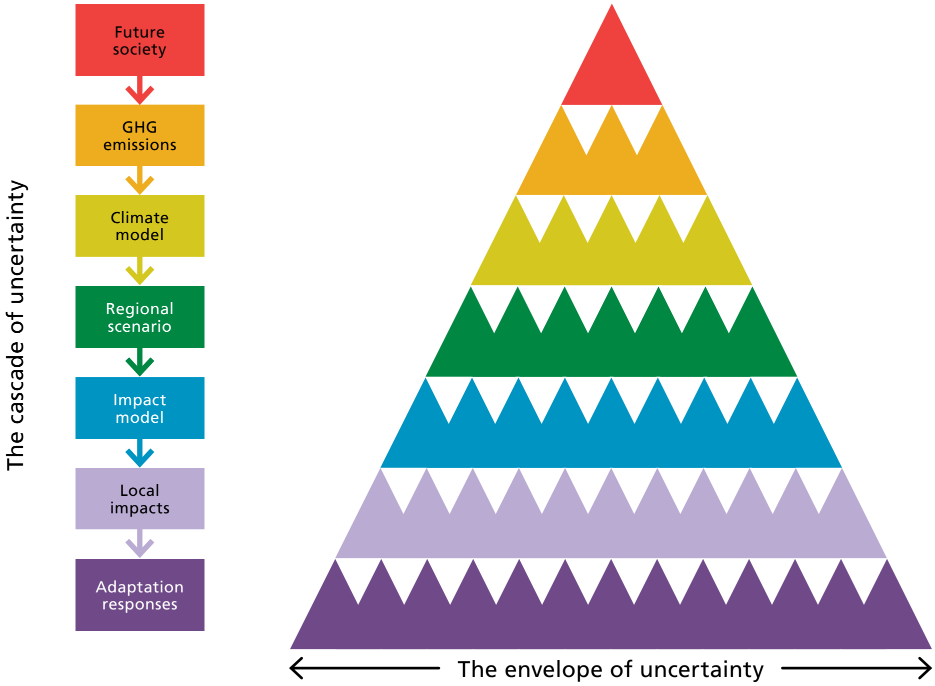
Because outcome vulnerability assessments rely on projections of climate and extreme weather, they should take into account uncertainty about what the climate will be in the future (Wilby and Dessai, 2010). The same steps to evaluate uncertainty should be applied to variability of extremes in the current climate.

Uncertainty occurs at each step in a vulnerability assessment (Figure 3). Some sources of uncertainty occurring at the macro-scale are due to social factors (e.g. what path of development will societies take in future, which will determine greenhouse gas emissions?). Some are due to modelling i.e. different climate models produce different outcomes and different climate downscaling techniques can carry their own uncertainty). Some sources of uncertainty are environmental i.e. how do different ecological systems respond to climate? Finally, at local scales, some uncertainties have social dimensions i.e. how do people respond to local climate? (Dessai and Hulme, 2004, Wilby and Dessai, 2010, van Vuuren *et al.*, 2011).

Some of these sources of uncertainty can be addressed. For example, the IPCC considers the use of an ensemble of GCMs to be best practice (Flato *et al.*, 2013), since they provide estimates of mean changes in climate variables. However, as Wilby and Dessai (2010) explain and Figure 3 demonstrates, "the range (or envelope) of uncertainty expands at each step of the process to the extent that potential impacts and their implied adaptation responses span such a wide range as to be practically unhelpful." Stated more pessimistically, the range of possible outcomes can be so large that planning adaptation actions from outcome vulnerability assessments presents the potential risk that they may have no benefit, or worse, may lead to more damage than if no action were taken (Barnett and O'Neill, 2010). Wilby and Dessai (2010) suggest that the answer to uncertainty is

FIGURE 3

Representation of the expanding uncertainty that occurs when moving from one step to the next in an outcome vulnerability assessment. The more triangles at each level down the pyramid indicate increasing permutations and resulting increased uncertainty



Source: Wilby and Dessai, 2010

to implement adaptations that are "low regret", which may provide positive outcomes regardless of future climate.

In comparison to a contextual approach, an outcome vulnerability assessment can facilitate adaptations that require longer lead-in times, such as altering forest tree species composition or shifting populations geographically to places they are climatically better adapted.

4.3 APPROACHES THAT COMBINE CONTEXTUAL AND OUTCOME VULNERABILITY

Vulnerability assessments that combine aspects of both contextual and outcome methodologies address some of the shortcomings in either approach. One way of combining contextual and outcome vulnerability can be to present downscaled projections of future climate to those people who understand local contextual issues (Jones and Preston, 2011). In this way, projections of future climate could be used as an additional factor in a contextual assessment that would contribute to projecting how climate change could modify the possible changes in a system, in concert with other factors (Jones and Preston, 2011).

One example of a combined contextual-outcome vulnerability approach was provided by O'Brien *et al.* (2004). For the outcome component of their analysis, they evaluated the vulnerability to future climate change of agriculture in sub-regions across India using expert-based evaluations of factors related to adaptive capacity, sensitivity and exposure. Downscaled climate information was used to produce a climate exposure index based on one GCM and a doubled-CO_2 greenhouse gas scenario. Vulnerability was a quantity calculated from indices of climate sensitivity under the climate change scenario summed with an index of adaptive capacity that they had also quantified. The resulting outcome vulnerability map for sub-regions in India was subsequently meshed with contextual information, obtained through local village case studies conducted using participatory techniques, to evaluate whether the case studies agreed with the macro-scale results from the outcome assessment. The value provided by the contextual case studies was to reveal the effects of institutional barriers and support systems have on local-level vulnerability, which would have been masked with only an outcome vulnerability assessment.

Girard *et al.* (2015) provide another example of a combined contextual-outcome vulnerability assessment, in their case for evaluating river water flow in a largely urban–agricultural river basin. The outcome component of the study used future climate projections downscaled from nine GCMs, all using the same single greenhouse gas emissions scenario (a scenario considered average among future possible emissions pathways). The downscaled climate information from the nine GCMs was subsequently used in a rainfall–runoff model for the study area to project future monthly flow rates in the year 2030. Contextual vulnerability was evaluated using a participatory process of interviews and workshops with a stakeholder advisory group to develop scenarios for future agricultural and urban growth and to identify adaptive measures that might be undertaken. The contextual forecast of agricultural growth was used with a crop water-demand model to simulate the effects of climate change on irrigation demand for the nine GCM climate projections. An econometric model was applied to the urban growth forecast to project future urban water demand. Next, adaptive capacity was evaluated based on literature reviews, expert opinion and stakeholder consultation workshops. The contextual and outcome approaches were integrated in a river basin management optimization model that considers cost of adaptations while meeting basin water flow requirements. The approach provides a measure of vulnerability through ranking of the proposed adaptations according to how well they allow the projected demand requirements to be met.

Both of the case studies of combined contextual-outcome vulnerability assessment described above rely on computer modelling to obtain downscaled climate results, and to interpret those climate parameters in terms that are relevant to the biophysical features of concern (in these cases, agriculture and basin water flow). In the instance of O'Brien *et al.* (2004), the contextual information was used to identify institutional issues impeding (or aiding) adaptation, while Girard *et al.* (2015) used contextual information to help parameterize models. In both cases, the contextual vulnerability component of the assessment used participatory approaches to elicit feedback on one or more aspects of exposure, sensitivity or adaptive capacity.

Additional case studies combining contextual and outcome vulnerability assessment are being produced that blend social and biophysical elements into a single assessment (Bhave *et al.*, 2014). However, the integration of outcome/quantitative approaches with contextual/qualitative approaches has also been done using two technically complex modelling approaches: vulnerability mapping and agent-based modelling.

Vulnerability mapping is a GIS-based approach that integrates socio-economic and biophysical data, including data on climate, climate change and extreme weather. The information is combined into an index that spatially represents a multidimensional portrayal of vulnerability (de Sherbinin *et al.*, 2015). Mapping identifies vulnerability "hotspots" that can facilitate decision-making about where to place adaptation efforts (CIESIN, 2015).

The United Nations Environment Programme (UNEP) Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA) Research Priorities on Vulnerability, Impacts and Adaptation (Hinkel *et al.*, 2013) considers the use of mapping as a tool to integrate information on the vulnerability of people and ecosystems to be a high priority. O'Brien *et al.* (2004) provide an early example of vulnerability mapping that demonstrates its potential great value. However, applications of vulnerability mapping today require advanced technical skills in GIS and data handling (see CIESIN, 2015) that can preclude the approach of those vulnerability assessment projects that do not have high levels of financial and/or personnel support.

Agent-based modelling can be applied to understand the interactions that occur among "agents" (people, communities, organizations, plant species, insect behaviour, etc.) in socio-ecological systems. The model may be coupled with a GIS-based system to capture the spatial heterogeneity existing within complex systems (Filatova *et al.*, 2013). An agent-based model is set up with a series of rules by which the agents in the model behave (Grimm *et al.*, 2006). The model is run at the micro- (agent) scale with a number of agents following the model rules that cause the agents to act in their own interest; the model uses this to produce a macro-level outcome (Macal and North, 2006). An agent-based model of a complex socio-ecological system can be used to evaluate how climate change may affect complex ecological systems and the responses of people and communities (Grimm *et al.*, 2006). Although agent-based modelling is an attractive way to integrate biological and social aspects of climate change vulnerability, the technical complexity of the approach means that organizations considering using this methodology will require high levels of expertise, experience and time to carry out the assessment.

Fishing boats in southern Bangladesh, an area hit hard by Cyclone Sidr.

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5 Assessing forest vulnerability to climate change

A climate change vulnerability assessment for forests evaluates the biophysical effects of climate on forest structure and/or forest function. A biophysical effect is a biological response to the physical environment, which in the case of forests primarily concerns the effects on tree species and other types of plants of temperature, water (as precipitation or moisture availability in soil) or atmospheric CO_2 concentration.

Forest structure and the effects of climate on structure can be expressed in a number of ways – it can refer to the species of trees and other plants that are present, which

TABLE 2

Examples of information that can be used for evaluating exposure, sensitivity, impacts and adaptive capacity in a biophysical vulnerability assessment. Broad scale information concerns more general features that are more often used at larger levels of organization (e.g. regions, landscapes or watersheds) and narrow scale information concerns more specific features at smaller levels of organization (e.g. groups of or individual forest stands or species within them)

Indicator	Broad scale information	Narrow scale information
Exposure	Historical average annual and seasonal temperature and precipitation. Likelihood of temperature and precipitation being outside of a defined range based on current climate and future climate scenarios. Temperature and precipitation expressed together to reflect soil moisture in a species' or ecosystem's climatic niche.	The likelihood that temperature or precipitation will be outside of a known threshold for selected forest elements (a species, a process, etc.) based on current climate and future climate scenarios.
Sensitivity	Trends in a species' range, growth, regeneration, or other expressions of behaviour that are correlated with historical climate. Modelled alteration of future species composition where climate drives change.	Historical examples, expert opinion, or traditional knowledge of thresholds of a climatic factor (e.g. temperature, precipitation) that causes harmful effects. Modelled effects of climatic factors on specific ecological processes.
Impacts	Changes in species health or forest composition following a climatic event. Changes in the occurrence of stand replacing disturbances (e.g. fire), damaging insects and disease.	Responses of specific ecological processes or ecosystem structure to climatic events.
Adaptive capacity	Presence of attributes that mitigate harmful effects of climatic events to a forest (e.g. greater species functional diversity increases the likelihood that some species will be adapted to climate conditions).	Species life traits that reflect tolerance to the effects of climatic events (e.g. a species is less vulnerable if it is able to photosynthesize over a wider range of environmental conditions).

can be expressed in terms of the diversity of species and functional types (e.g. shade-tolerant, drought-hardy, etc.). The frequency of tree ages and sizes, the area affected by disturbance and how long ago that disturbance happened can also be affected by climate change. Structure can also refer to the spatial arrangement of stands with different characteristics within a forest landscape. In comparison, forest function refers to the ecological processes occurring in forests. There are numerous ways to consider forest function, including but not limited to the growth of trees, their carbon sequestration, the processes involved in forest regeneration, and the actions of insects and diseases. Structure and function of forests can also extend to species that reside in or use forests for food or shelter, and on other ecological functions related to forests, such as the retention and flow of water through forests and into streams and rivers.

Deciding which aspects of structure or function will be evaluated is therefore a key defining step in scoping a forest vulnerability assessment – is it a species, an ecological process, or a forest area, etc. An assessment may evaluate the risks that climate change would alter an ecosystem that has unique ecological or social significance. It could focus on the vulnerability of processes that are important for economic reasons, such as tree growth rates and the regeneration of commercially important trees or non-timber forest products. An ecological process, such as carbon sequestration in a REDD+ forest area, might also be of interest in a vulnerability assessment, because of its importance in climate change mitigation. For any aspect being evaluated, a biophysical vulnerability assessment should provide information on some or all of the projected impacts of climate change, exposure to climate, sensitivity to climatic factors, and the capacity for adaptation to climate change. Examples of each type of information are given in Table 2.

There are a number of approaches to assessing the vulnerability of forests to climate change. They can be grouped into the following categories based on the types of information that is used or generated in the assessment:

- Expert opinion
- Retrospective analysis
- Forest condition and life traits
- Climatic niche models
- Physiological models

5.1 EXPERT OPINION

Perspectives on forest vulnerability assessment can be obtained from expert opinion and local knowledge. In some cases, the information can be obtained from published literature or through participatory approaches.

Traditional indigenous knowledge can provide information on ecological responses to climate and weather (Mazzocchi, 2006). Such information is a cultural heritage that is passed down across generations to explain the relationships of people with other beings and the natural environment (Berkes *et al.*, 2000). Indigenous knowledge can address aspects of biodiversity, ecological processes, sustainable resource use and climate change (Alexander *et al.*, 2011, Berkes *et al.*, 2000). Traditional knowledge tends to be local and multidimensional, expressing a holistic viewpoint rooted in stewardship of the land (Alexander *et al.*, 2011). Contributions of traditional indigenous knowledge to a biophysical vulnerability assessment are most likely to occur through a participatory process (see Section 6.2).

Input from experts in fields of knowledge related to forests can be obtained individually, in group sessions, or through questionnaires to address either current climate conditions or to obtain expert opinion on responses to future climates (e.g. Daust *et al.*, undated[2]). For example, in the case of Massachusetts, (United States of America), an expert panel of ecologists and wildlife biologists was assembled to answer a series of questions designed to address vulnerability of wildlife species to climate change (Manomet, 2010). The assessment considered twenty habitat types that were rated according to vulnerability to climate change using a numerical rating system for selected habitat characteristics. Within habitats that were rated as vulnerable to climate change, animal species were subsequently similarly rated for vulnerability by the expert panel. The result was a comprehensive assessment based on expert opinion of the habitats and species that are most vulnerable to climate change (Manomet, 2010).

Forest managers are an expert group, surveyed in group sessions, to examine vulnerability of forests and forest management to climate change. In a national survey, Johnston *et al.* (2010) conducted meetings with forest management professionals to invite their observations of climate change impacts, current adaptive actions and their adaptive capacity and barriers to adaptation. They conducted meetings with different groups, spanning First Nations, government, forest industry and ecologically focused non-governmental organizations, to evaluate whether differences in perspectives existed. A similar approach was employed by Sonwa *et al.* (2012) in Cameroon. Their expert consultation involved science-policy workshops with non-governmental organizations, government departments, research institutions, universities, and others, to identify regional concerns related to climate change. Also, Sharma *et al.* (2015) used forest domain knowledge and working experience in forestry to assess the inherent vulnerability of the forest in South India. Expert judgement was employed to identify and select vulnerability indicators which constitute a vulnerability index and used to develop weightings for indicators (Sharma *et al.*, 2015).

Furthermore, knowledge and ideas of stakeholder groups can be involved in assessment throughout planning and implementation stages for scoping and knowledge-sharing. Contributions of stakeholders can be achieved by communication through consultation, emails, meetings to share reports and results (Ellison, 2015).

In another approach to obtain expert viewpoints, Klenk and Hickey (2011) used a form of survey called a "Delphi process" to elicit views of forest sector experts, and de Franca Doria (2009) used the process to define the meaning of successful climate change adaptation. The aim of a Delphi process is to obtain expert consensus on a complex problem (Donohoe *et al.*, 2012). The approach gathers input from a group of experts in a field of interest where different views and opinions may exist. First, a questionnaire

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[2] https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nrs-climate-change/applied-science/3a_va_case_studyaug30final-dd.pdf

is distributed that defines a problem to be addressed and asks participants to provide ideas, solutions, and approaches. The results of the first questionnaire are compiled and redistributed to participants in a second questionnaire. Participants again comment on each idea, providing additional ideas, clarifications and thoughts on feasibility. Once again, the responses are compiled and shared with participants. This time the participants rank the ideas in order of importance and feasibility. This third set of responses is compiled and used to place ideas in order of priority established by the participants (University of Illinois, undated[3]).

According to Hinkel *et al.* (2013), expert opinion can provide a rapid assessment of the risks posed by climate change. However, expert opinion is not devoid of biases that may occur depending on which experts take part and their academic backgrounds (Hinkel *et al.*, (2013). Obtaining expert opinion from a diversity of experts across a number of fields of study will reduce the risk of bias affecting overall results in a vulnerability assessment.

5.2 RETROSPECTIVE ANALYSIS

Another approach related to expert opinion is the use of published retrospective analyses to reveal historical climate-species relationships. These reports can be used to assess current sensitivity in a contextual vulnerability assessment, and in some cases can be used in outcome vulnerability assessment for projected future climate conditions. Studies of forest impacts that are attributable to climate and extreme weather were often carried out because the effects were severe and attracted attention. For example, Man *et al.* (2009) examined a case of severe freezing damage in a widespread area of the boreal forest that had experienced an unusual mid-winter thaw. Hanna and Kulakowski (2012) attributed widespread mortality of aspen across western North America to changing climate conditions that increased drought.

There is a large amount of published information describing changes caused by recent climate change that has occurred in ecological systems around the world (Parmesan and Yohe, 2003). Biophysical vulnerability assessments are often done by reviewing this literature to compile information on how species or ecosystems respond to climatic events or to changes projected for future climate.

The experimental and observed studies provide useful sources of long-term data reflecting climate change such as a physiological change, a phenological change, distribution and composition of species, species interactions, structure and dynamics of ecosystems, and consequences of these changes (Walther *et al.*, 2002). For example, Medlyn *et al.* (2011) reviewed diverse primary and grey literature discussing overall impact of climate change on vegetation and the ecosystem services of Australian forests. They used existing evidence of direct stresses such as CO_2 concentration, temperature, precipitation, and indirect stresses such as forest fire, pests and weeds and plant processes in the literature to assess current and future vulnerability (Medlyn *et al.*, 2011). In addition, Boisvenue and Running (2006) presented climate impacts on forest production,

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[3] http://www.communitydevelopment.uiuc.edu/sp/Step6/Delphi%20Technique.pdf

and trends in net primary production (NPP) by reviewing papers since the 1950s. They acquired diverse data on carbon sequestration, global radiation trends as well as on forest types, forest management planning and activities from the literature, based on which, generally positive climate change impact on forest productivity on less water-limited sites since 1950s is estimated (Boisvenue and Running, 2006). Similarly, Gauthier *et al.* (2014) analysed climate change vulnerability and adaptation approaches of Canadian boreal forest.

A large amount of published literature is available online and can be found using search engines. For example, Google Scholar, Science.gov, the National Center for Biotechnology Information (pubmedcentral at ncbi.nlm.nih.gov) and mendeley.com provide search functions for scientific articles and provide links to where many articles can be downloaded. If articles are not freely available for download, in most cases, they can be obtained directly from the authors through email.

Meta-analysis, one kind of popular retrospective analyses, is a technique to combine data and information from a number of studies to create a single, more precise estimate of an effect (Ferrer, 1998; Hoffman, 2015). As meta-analysis applies objective statistical formulas, it becomes an alternative to subjective literature reviews (Wolf, 1986). Parmesan and Yohe (2003) used global documented literature to show that recent biological trends correspond with climate change predictions. With long-term, large-scale and multi-species data, they found evidence that climate change is already affecting ecosystems, particularly, focusing on the phenomena of range-boundary changes and plant phenology shifts (Parmesan and Yohe, 2003).

The usefulness of retrospective studies varies greatly. One of the strengths of using forest observations is that it provides results for older trees in forest ecosystems, so they reflect the complexity of forests that is not captured in other approaches. A major drawback of many observational studies, such as the examples provided by Man *et al.* (2009) and Kulakowski (2012), is that they do not provide information on so-called "dose-response" relationships between climate and an ecological response (by a tree, forest or ecological process). For this reason, many retrospective studies have limited value as they cannot be used in a predictive manner when evaluating responses to future climate. For example, a study that describes mortality after one severe drought episode is considerably less valuable than a study that reports a range of mortalities under different levels of drought. Obtaining dose-response information can be done in studies that have made observations over large geographical areas over extended time periods, to acquire information that spans a range of environmental conditions, such as in the study undertaken by Michaelian *et al.* (2011).

Retrospective studies are unable to evaluate the effects of future atmospheric CO_2 concentrations on plant development, growth and increased tolerance of soil moisture deficits. One special type of retrospective study is a provenance test. These are plantings of trees from a range of climatic origins across a species' range, planted at a range of planting sites with differing climates (e.g. Lu *et al.*, 2014). Provenance test results can be interpreted to produce response functions, which can be used to predict a tree population's sensitivity to drought and/or temperature (e.g. Montwé *et al.*, 2016, Wang *et al.*, 2006).

5.3 LIFE TRAIT EVALUATION

Vulnerability assessments of forests can also be based on the current condition of the forest and on the life traits of forest species of concern. This is usually accomplished through an exercise of obtaining expert opinion and extracting information from published literature.

Beardmore and Winder (2011) describe several vulnerability assessment methodologies that have been used for tree and plant species. These include the Forest Tree Genetic Risk Assessment System (ForGRAS) (Potter and Crane, 2010) and the NatureServe Climate Change Vulnerability Index (Young *et al.*, 2011). Both methodologies use multiple factors to assess vulnerability of plant or tree species. They express the output using a rating of relative vulnerability among species.

Potter and Crane (2010) developed ForGRAS to use "ecological and life-history traits to rank the predisposition of species to climate change and other threats, for conservation planning, for the evaluation of species' genetic resources, and for the early detection of vulnerability." Trees are rated for risk factors relating to factors that are species attributes such as population structure, fecundity and seed dispersal, external threats to genetic integrity – including climate change, insects and disease – and what they call conservation modifiers (e.g. is the species listed as being at risk and what proportion of the species' total range occurs within the region being evaluated). Each factor is given an indexed value that is weighted according to importance and then all the values are summed to give a rating of a species' regional risk.

The NatureServe Climate Change Vulnerability Index (CCVI) separates vulnerability into components: a species' exposure to climate change, its sensitivity to the change in climate, and its adaptive capacity to change (Young *et al.*, 2011). The CCVI approach, as with other life trait approaches, has to be developed specifically for the ecosystem of concern. Recently, a version has been translated into Spanish and adapted for use in the tropical Andes (mainly in Venezuela (Bolivarian Republic of)), Columbia, Ecuador, Peru, Bolivia (Plurinational State of) and northern tropical regions of Argentina and Chile (Tognelli *et al.*, 2016).

One of the challenges in applying life trait evaluations of vulnerability is that the detailed information on species may be lacking for some types of forests. More importantly, the methodologies of Potter and Crane (2010) and Tognelli *et al.* (2016), and the concept of an integrated framework for assessing species vulnerability to climate change proposed by Williams *et al.* (2008), are not readily scaled up from individual species evaluations to a forest level assessment of vulnerability. The latter deals with the challenge of trying to understand how the complex interactions among species (e.g. regeneration, competition, differential responses to climate), may sort themselves out, as species respond uniquely to changing climate.

5.4 CLIMATIC NICHE MODELLING

Niche-based models use statistical relationships between current and projected future geographic distributions and environmental attributes of species (Pereira *et al.*, 2010). In this approach, the climate in which a species or ecosystem is currently found is characterized (the species' climatic niche, also called climate envelope) and its location identified on a map (e.g. Joyce and Rehfeldt, 2013, Wang *et al.*, 2016). Niche-based models include bioclimatic envelope models or climate envelope models and species distribution models.

To predict species ranges for different climates is generally done by using current geographic distribution of a species or communities (Miles, 2004) to infer its environmental requirements such as climate, habitat, or other environmental variables (Hijmans and Graham, 2006; Janowiak *et al.*, 2014). Based on these attributes, past, current and future geographic distribution of each species can be predicted. From the compiled results of recent studies on the effect of projected climate change, a huge number of species may lose most of their range of niche (Thomas, 2004; Hijmans and Graham, 2006).

By comparing the current location of the species to the future location of the climatic niche, geographic dissimilarities between the future location of the climatic niche (due to climate change) and the current location of a species, and/or in fragmentation of a species' climatic niche (and by inference, future species distribution) are used to indicate exposure to climate change (Foden and Young, 2016).

As an example of using climate niche models for vulnerability assessment, Villers-Ruiz and Trejo-Vázquez (1997) applied the two models: Holdridge Life Zone Classification and Mexican Classification to assess the forest ecosystem vulnerability to climate change in Mexico with three climate models. They estimated how vegetation in Mexico will be changed according to the climate change scenarios.

One shortcoming of this approach is that the current climatic niche is based on current presence or absence of a species, which may have occurred for reasons other than climate (for example, interspecies competition may exclude a species, even if the climate is suitable for the species (Clark *et al.*, 2014). More crucially from the point of view of determining adaptation approaches for a species, dissimilarity between future location of the climate envelope and its current location does not indicate whether, or at what point, this climate change exposure would result in a species experiencing stress or being unable to cope with the new climate. Such information would require knowledge about a species' biology, which is not required when using a climatic niche model (Foden and Young, 2016).

As most niche-based models use a realized niche of species and not a fundamental niche, models pretend to underestimate current niche size and suitable habitat in the future (Janowiak *et al.*, 2014). Also, competition among species, disease, and predation can constrain future species distributions, which makes species distribution models overestimate the amount of future suitable habitat (Janowiak *et al.*, 2014). Furthermore, it is not clear that models successful in predicting current distributions can predict accurate distributions under different climates (Hijmans and Graham, 2006). As climate envelope models are statistical models, they do not describe the causal relation between model parameters and results thus they may not classify future environment correctly with appearance of unprecedented climate in the future (Guisan and Zimmermann, 2000; Pearson and Dawson, 2003; Kearney and Porter, 2004; Hijmans and Graham, 2006).

5.5 PHYSIOLOGICAL MODELLING

A major step up in complexity from climatic niche models occurs with physiological models that simulate how trees and forests may respond to climate change. Some of these types of models are able to simulate multiple species over decades- to centuries-long time frames. They often describe changes in growth or productivity of tree species in response to temperature and soil moisture availability.

Physiological models can simulate changes in forest growth and/or development using computer-generated responses to environment that are scaled up from finer level processes (e.g. effects of temperature on leaf photosynthesis and respiration may be applied to trees or even landscapes to estimate carbon sequestration). These forest development models typically apply climatically driven mathematical expressions of physiological or biochemical processes (for example, see Sprintsin *et al.*, 2012), one of the most common being Farquhar's biochemical model of CO_2 assimilation (Farquhar *et al.*,1980).

For example, Morin *et al.* (2008) identified 16 North American tree species range shifts using a process-based model, PHENOFIT. Process-based models simulate biological processes at daily to yearly rates, integrating transient dynamics, which can overcome the limitations of niche-based models (Morin *et al.*, 2008). Therefore, process-based models are suited to analyse the time-lag between climate change and species distribution change, to identify the locations where populations may be particularly affected by climate change, and to identify which processes are involved in the possible range shifts (Morin *et al.*, 2008).

Physiological models are also called process-based models which simulate processes such as population growth or mechanisms such as eco-physiological responses (Pereira *et al.*, 2010). Process-based models such as LANDIS-II and PnET-CN simulate community and tree species dynamics based on interactive mathematical representations of physical and biological processes (Janowiak *et al.*, 2014). Process models can simulate future change in tree species dispersal, succession, biomass, and nutrient dynamics over space and time.

Process models have several assumptions and uncertainties that should be taken into consideration when results are applied to management decisions. They rely on empirical and theoretical relationships that are specified by the modeller. Any uncertainties in these relationships can be compounded over time and space and can lead to an erroneous result (Janowiak *et al.*, 2014).

Physiological models are often based on information obtained from controlled environment experiments. It is important to recognize that the parameterizations of the physiological models contain the biases that occur in experiments designed to evaluate responses to environment. On the positive side, experimental studies can manipulate one or more aspects of the environment related to climate change, most often temperature, moisture supply and CO_2 concentration in the air (e.g. Morin *et al.*, 2010, Wu *et al.*, 2011). They are usually done in controlled or semi-controlled environments and the results can provide dose-response information and thresholds that indicate sensitivity to the environment. However, because such experiments are usually carried out in controlled environments using seedlings or young trees, the results may overestimate sensitivity compared to what occurs for older trees in natural environments, where tree size, age and ecological interactions may reduce sensitivity to the environment.

Physiological models may also be linked with landscape models to take into account landscape functions, such as stand replacing disturbance, regeneration and species migration that can affect forest structure over longer timeframes. Such linked physiological-landscape models can account for processes such as forest succession and disturbance, allowing them to project changes in species composition and forest productivity with climate change (for example see Coops *et al.*, 2010, Duveneck *et al.*, 2014 and Koca *et al.*, 2006).

Coops *et al.* (2010) used a process-based model: Physiological Principles for Predicting Growth (3-PG), to evaluate how climatic variation might alter growth of Douglas-fir. The model calculates rates of photosynthesis, leaf litterfall, and transpiration at monthly intervals, and growth allocation annually. Most importantly, it also calculates variables recorded in forestry yield tables (i.e. tree density, basal area, mean diameters, standing volume, current and mean annual increment). To estimate site index variation with the 3-PG model across the province, simulations were run with four climate scenarios (Coops *et al.*, 2010).

Physiological models are technically complicated and require significant training and expertise to parameterize the models and to use them. They are attractive because they have the ability to provide projections of future forest structure and forest function. They are most suitable for landscape-scale applications, especially if linked to large-scale disturbances. In addition, from a practical perspective, the time and expense of running these models means the return on investment is better if applied to large areas.

Dynamic global vegetation models, which play an important role in many scenarios, are complex ecosystem models integrating processes such as photosynthesis, respiration, plant competition for resources, and biogeochemical cycles (Pereira *et al.*, 2010).

Dynamic global vegetation models simulate the changes in potential distribution of vegetation and associated biogeochemical and hydrological fluxes due to climate change. Dynamic global vegetation models simulate the annual or monthly dynamics of ecosystem processes (Choi *et al.*, 2011). For example, Choi *et al.* (2011) applied a MAPSS-CENTURY (MC1) model to a forest ecosystem in Korea to assess the vulnerability under climate change with the temporal range of the past (1971–2000), near future (2021–2050), and far future (2071–2100). The MAPSS-CENTURY (MC1) model is a Dynamic global vegetation model to assess the climate change effects on ecosystem structure and function. The vulnerability of forest ecosystems in the study is composed of vulnerability of vegetation distribution and forest ecosystem function, such as Net Primary Production and Soil Carbon Storage However, using Dynamic global vegetation models revealed limitations relating to difficulty to consider the heterogeneous topography and micro-climate of Korea and the direct anthropogenic effects on forest ecosystem.

There are therefore significant gaps in this methodology. Medlyn *et al.* (2011) presented a real mismatch between predictions of vulnerability coming from bioclimatic and eco-physiological models. The result of vulnerability assessment using bioclimatic models, based on observed climatic niches, found that many Australian species have narrow ranges and concluded they are very vulnerable to climate change, while eco-physiological models, based on mechanistic understanding of climate impacts on plant processes, predicted widespread increases in forest production (Medlyn *et al.*, 2011).

5.6 OTHER METHODOLOGIES

Apart from the methodologies mentioned above, there are diverse ways to assess the vulnerability of forest to climate change. One of the popular methods used is the indicator-based vulnerability assessment.

Sharma *et al.* (2015) and (2017) conducted a current vulnerability assessment of Indian forests using indicators of exposure, sensitivity and adaptive capacity of the forests. They set the criteria for assessing the current vulnerability, identified parameters to measure criteria, and collected necessary data of each indicator through a participatory survey, literature review, and expert opinion. Through mathematical calculation, they added weightings to indicators to calculate the vulnerability index of Indian forests.

Upgupta *et al.* (2015) applied a similar approach for assessing the vulnerability of the Indian Himalayan region. They used biological richness, disturbance index, canopy cover, ground slope, and forest dependence of rural communities as indicators that determine current vulnerability of forests and added weightings to each indicator using a pair-wise comparison method.

The indicators used usually represent the ecological characteristics of a forest as well as the social and anthropogenic environment characteristics. This means that the indicator-based approach is a hybrid approach comprising both biophysical and social dimensions of vulnerability, and the gradual incorporation of resilience aspects into such methodologies (Nguyen *et al.*, 2016). Vulnerability indices can help identify and prioritise vulnerable regions, sectors or population groups, raise awareness, and can be part of a monitoring strategy.

In selecting the appropriate indices for assessing vulnerability, statistical methods, such as participatory community analysis, participatory approaches can be used. For example, Seidl, Rammer, and Lexer (2011) conducted a study to evaluate climate change vulnerability under sustainable forest management strategy for commercial forests managed by the Austrian Federal Forests. They adopted a process of consultation with internal and external stakeholders such as the strategic planning team, nature conservation specialist, field managers, and other experts to select and define a set of indicators sensitive to climate and management. Participatory approaches also provided relative weights to the vulnerability indicators by combining a ranking and scoring approach through a series of workshops with the stakeholders (Seidle, Rammer, and Lexer, 2011; Lexer and Seidl, 2009). Tran *et al.* (2002) integrated ecological indicators through a fuzzy decision analysis method, which combines a fuzzy ranking method and the analytic hierarchy process for ecological vulnerability assessment. As indicators are acquired from different ways and sources, integration and calculation is complicated.

Generally, vulnerability index development involves sequential stages including the selection of indicators, normalization of indicators to a common scale, and aggregation to a final value. First, choose proxy variables for the underlying theoretical dimensions of vulnerability comprising physical and social factors related to the components of vulnerability assessments: exposure, sensitivity, and adaptive capacity. Second, normalize data to a common (comparable) scale and subsequent summation of the normalized data is generally used. Finally, aggregate the transformed, normalized, and weighted indicators into the final index (Tate, 2013; Nguyen *et al.*, 2016).

Integrated models for assessment of the effects of climate change have been developed (Dowlatabadi and Morgan, 1993; Hulme 1994; Alcamo, 1994; Rotmans, Hulme and Downing, 1994; Kenny *et al.*, 1995). CLIMPACTS is one of a fully integrated system, linking together a range of models and analytical tools. It produces time-dependent scenarios of regional changes in climate and associated environmental effects. It is developed by linking a model for making time-dependent predictions of global-mean temperature changes from emissions of greenhouse gases with possible patterns of climate change for New Zealand, as derived from selected General Circulation Model results and the paleoclimatic record (Kenny *et al.*, 1995).


Decimated boats piled up after the 2005 tsunami that struck the south eastern coast of India.

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6 Assessing the vulnerability of forest-dependent communities to climate change

Vulnerability assessments of forest-dependent communities can be carried out by quantifying communities based on their demographics, economic and social statistics. This can be carried out using approaches such as expert opinion, retrospective analysis and community trait analysis, similar to the approaches described below. Such sources can provide information on exposure, sensitivity, impacts and adaptive capacity of forest-dependent communities.

However, to examine the relationships between people in communities and ecological systems, a vulnerability assessment can take into account the value-laden views among different groups of people that work, live in, and have different uses and attributions of value of forests. A participant-based approach to vulnerability assessment, has often been used to take the views and experiences of people directly involved with forests into account.

6.1 VULNERABILITY ASSESSMENT THROUGH PARTICIPATORY APPROACHES

Information for a vulnerability assessment can be obtained from participants in a number of ways and the selection of the approach can depend on the purpose of the assessment. If the assessment is intended to guide new policy development requiring perspectives that have broader applicability, then an approach to obtain expert opinion may be preferred. If, on the other hand, the goal of the assessment is to discern how local factors vary from one community or social group to another to affect vulnerability, or to provide information to help local people develop their own approaches to adapting to climate change, then some form of participatory action research is likely to be a more effective option.

Among the methods for obtaining participant-based information (reviewed by Rowe and Frewer, 2005), participatory action research (PAR) has been a popular approach. This approach involves the project team and local stakeholders in a shared learning process and exchange of information that is intended to benefit both parties. Examples of the use of PAR for community vulnerability assessments are abundant in published literature (for example, Ampomah and Devisscher, 2013, Bele *et al.*, 2013, Devisscher *et al.*, 2013, Obeng *et al.*, 2011, Pavageau *et al.*, 2013, Somda *et al.*, 2014 and Tiani *et al.*, 2015).

As those responsible for initiating and guiding the process, the project team needs to have knowledge of the basic tenets of PAR processes and be familiar with appropriate engagement approaches, communication methods and learning techniques (Boog, 2003). This is necessary to fulfil the key goal of the dialogue in PAR, which is to expand the understanding of the participants, giving them information that can be used to improve their own situation (Gaffney, 2008). When PAR is used in a climate vulnerability assessment, the researcher may obtain local knowledge of recollected impacts of historical climatic events that might be useful as data on exposure, sensitivity, impacts and adaptive capacity (e.g. Johnston *et al.*, 2010). When PAR is used in an outcome vulnerability assessment, changes in future climate or extreme climatic events are posed to participants, who are asked to speculate on potential impacts in what is called participatory scenario development by Hinkel *et al.* (2013).

Because each situation where PAR is conducted is unique, the project team must learn about the people that will participate in the process before the exchange of information begins. In the case of community-level research, the project team needs to learn about the community's history, its key members, local customs, laws, public policies and governing institutions. Such pre-study information could be acquired in a pilot investigation, which may also allow identification of a group termed "critical friends" that can provide guidance to and work with the researcher as the project progresses. A drawback of PAR is that it may not be possible to generalize from one group of participants to another (Dick and Swepson, 2013). Generalizability can be addressed by sampling multiple groups across a range of socio-economic conditions.

Participatory action research may be conducted in group settings, using individual interviews, or by written surveys. The researcher will be looking for commonality among key points raised during discussions and in written responses. These commonalities can be identified using an approach called thematic analysis (Braun and Clarke, 2012), which is a method of analysing qualitative data to identify patterns within responses that are relevant to the objectives of the study. In the case of a vulnerability assessment, the objective will include gaining knowledge about exposure, sensitivity, impacts and adaptive capacity to climate change. For example, Pavageau, Butterfield, and Tiani (2013) conducted a baseline assessment to analyse vulnerability of five landscapes in the Congo Basin. The analysis focused specifically on social aspects of vulnerability related to human actions and their interactions with the natural environment. Through participatory workshops involving local authorities, decision makers, and communities with different ethnic groups, local perceptions on social dynamics, ecological dynamics, and major disturbances to each group were captured (Pavageau, Butterfield, and Tiani, 2013).

6.2 RETROSPECTIVE ANALYSIS

Retrospective analysis is also used to assess the vulnerability of climate change on forest-dependent communities. Ofoegbu *et al.* (2017) provides an example of applying retrospective analysis for assessing vulnerability of forest-dependent communities in Africa.The study discussed the strong linkage between socio-economic conditions and vulnerability of forest-based rural communities and the negative effect of climate variability and change on rural people and their livelihoods based on diverse literature.

Ofeogbu *et al.* (2017) concluded that improving the socio-economic conditions of forest-based communities such as forest management, employment and healthcare service facilities might be effectively enhancing communities' livelihoods and resilience to climate change.

Damage in Jeremie, Haiti following Hurricane Matthew.

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7 Examples of vulnerability assessments relevant to forests and forest-dependent communities

In the previous discussion of contextual and outcome vulnerability assessments, the framing of the assessment approaches are done based on the underlying questions that are being asked, as indicated in Table 2. Contextual vulnerability assessments focus on adapting people and communities to climate change, often with the aim of understanding how current climate affects vulnerability, and they use social science approaches to obtain information. In contrast, outcome vulnerability assessments focus on finding adaptations to climate change, often use future climate change scenarios, and use natural science approaches.

In considering which approach is most suitable for forests and which to use for forest-dependent communities, there is a clear affinity for forests to be assessed using an outcome approach and for forest-dependent communities to be assessed using contextual vulnerability assessment. Brugère and De Young (2015) classified the approaches used in published literature that evaluated vulnerability of fisheries, aquaculture and other sectors. They observed that outcome vulnerability was invariably applied to natural systems and were assessed using quantitative methods. They also found that contextual vulnerability was invariably applied to human systems and was assessed using qualitative methods. Nevertheless, this does not exclude the possibility of obtaining information on forest vulnerability using participatory methods, nor does it rule out the possibility of employing biophysical approaches for assessing the vulnerability of forest-dependent communities.

This section examines several vulnerability assessment methodologies that can be applied to forests or forest-dependent communities. These studies were selected because they express a range of approaches: contextual or outcome, participatory or modelling, current or future and social or ecological.

The methodologies are:

1. A continental scale outcome vulnerability assessment performed using ecological models for European forests (from Lindner *et al.*, 2014) (Figure 4);
2. A method for contextual ranking of current tree species vulnerability using forest tree species inventory data, expert opinion and published literature (from Devine *et al.*, 2012) (Figure 5).
3. A participatory methodology for assessing current social vulnerability, prepared by Tiani *et al.* (2015) for the Center for International Forestry Research (Figure 6).

4. The Adaptation Toolkit, developed by Ampomah and Devisscher (2013) for the United Nations Institute for Training and Research (UNITAR) (Figure 7).

5. Assessment of vulnerability to climate change of forest-dependent communities in Cameroon (Bele *et al.*, 2013) (Figure 8).

6. Vulnerability mapping to integrate contextual and outcome vulnerability to multiple stressors, by O'Brien *et al.* (2004) (Figure 9).

The characteristics of each methodology are summarized in Table 3. Two of them were applied to forests – one using an outcome vulnerability approach (Devine *et al.*, 2012)

TABLE 3

Key features of five methodologies to vulnerability assessment applied to communities or biological systems

Authors	Approach		Methodology		Time frame		Type of data		Study objective
	Contextual[1]	Outcome[2]	Participatory	Modelling	Current	Future	Social	Ecological	
Forests									
Lindner *et al.*, 2010		X		X		X		X	Analyse and synthesize scientific knowledge as a basis for offering decision support to practitioners and decision makers in forest management
Devine *et al.*, 2012	X			X	X			X	Quantify and rank tree climate change vulnerability to identify factors contributing to species vulnerability
Communities									
Tiani *et al.*, 2015	X		X		X		X		Analyse current vulnerability of local communities to climate variability
Ampomah and Devisscher, 2013	X		X		X		X		Use a multi-stakeholder process to develop adaptation strategies based on current community capacities
Bele *et al.*, 2013	X		X		X		X	X	Focus group sessions with multiple groups in two communities to identify current vulnerability and potential adaptive actions
Combined agricultural system and communities									
O'Brien *et al.*, 2004	X	X	X	X	X	X	X	X	Assess sector vulnerability to climate in light of climatic, social, technological factors

[1] A contextual assessment evaluates the combined influence of multiple interacting factors on vulnerability, of which climate (and/or extreme weather and climate change) can be one. In other words, a contextual assessment asks, "how does a system respond to the complex of factors that define the context in which the system exists?"

[2] Outcome assessments evaluate the response of an element to exposure to a factor. In the case of exposure to extreme weather or climate change, an outcome assessment evaluates the outcome or effect of the biophysical exposure.

and one using a contextual approach (Lindner *et al.*, 2010); three were developed for vulnerability assessment of forest-dependent communities (Tiani *et al.*, 2015, Ampomah and Devisscher, 2013 and Bele *et al.*, 2013), and one used a combination of methodologies that addressed both contextual and outcome vulnerability of both forests and forest-dependent communities (O'Brien *et al.*, 2004).

The methodologies use a variety of data sources and analytical methods, ranging in technical difficulty. Some of the methodologies use a single projection of future climate (one GCM and greenhouse gas emissions scenario) and others use sophisticated modelling requiring advanced training and technical proficiency.

For each of these methodologies, a conceptual diagram was constructed to show the major steps involved and the key sources of information required. Since the methodologies were not necessarily prepared to address vulnerability of forests or forest communities, where appropriate, wording was rephrased to express steps using forest vernacular. Each major step of each methodology is presented in a separate box within the diagram. The diagrams were prepared to allow comparison of the steps among the methodologies.

7.1 FORESTS

Outcome vulnerability at a continental scale for European forests

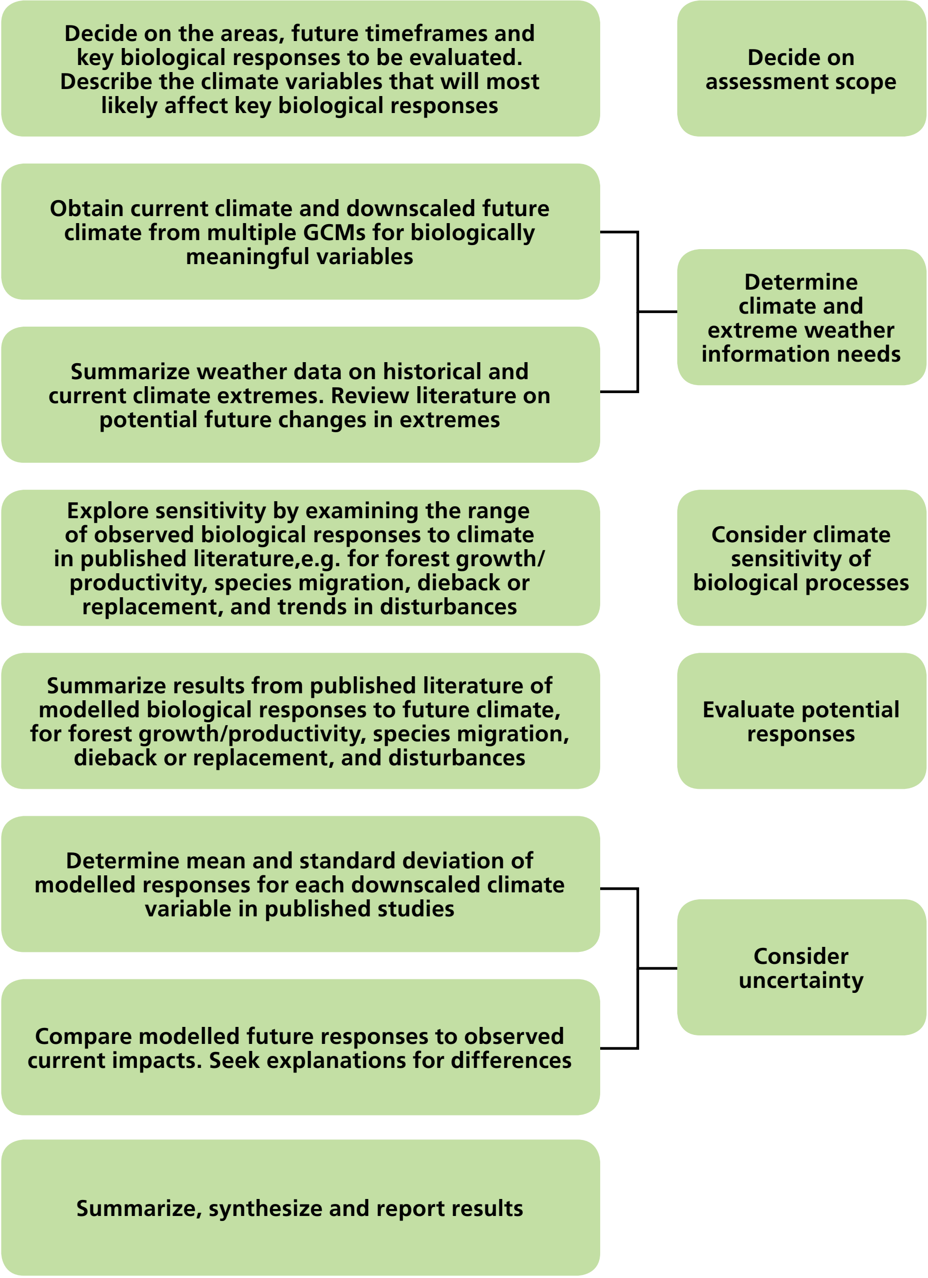
This study (Lindner *et al.*, 2014) is an example of outcome vulnerability assessment of forests conducted on a largescale. The objective of the study was to provide information on forest vulnerability to assist decision makers and practitioners in responding to current and future climate change. It does this by analysis and synthesis of scientific knowledge related to the vulnerability of European forests to climate change. It relates future climate projections and recent changes in climate and climate extremes to projected and observed impacts on European forests.

While the schematic approach shown in Figure 4 is brief, each of the steps is time consuming and technically complex, requiring "considerable expert knowledge and scientific understanding" (Lindner *et al.*, 2014). In particular, the authors indicate the importance of the manner in which climatic information is used. They state that good practice should involve the following steps:

- Identifying biologically-important processes and the climatic variables that they are sensitive to;
- Downscaling climatic data for multiple General Circulation Models;
- Projecting the biological effects for each downscaled climate scenario; and,
- Obtaining averages and standard deviations for each biological variable based on the multiple downscaled General Circulation Model projections.

The importance of using downscaled climate data from multiple General Circulation Models in this outcome study contrasts with the use of downscaled data from a single General Circulation Model by O'Brien *et al.* (2004). In practice, implementing the rigorous approach identified by Lindner *et al.* (2014) is challenging due to time constraints and knowledge limitations about the relationships between biologically important variables and specific aspects of climate.

FIGURE 4
An outcome vulnerability assessment approach using top-down modelling of forest biological responses to climate



Source: Lindner *et al.*, 2014

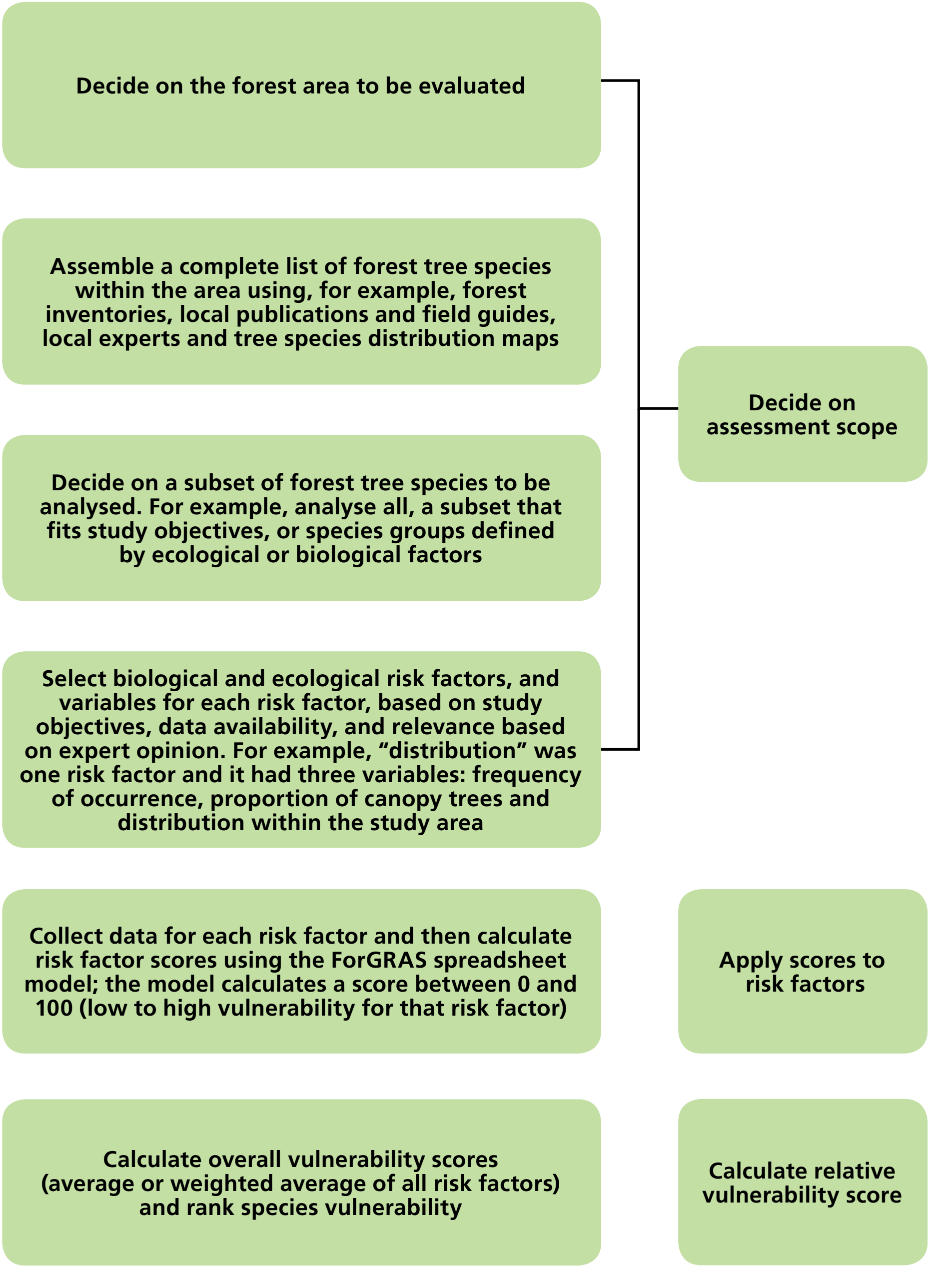
Method for contextual ranking of current tree species vulnerability

This methodology (Figure 5), is a version of the Forest Tree Genetic Risk Assessment System (ForGRAS) developed by Potter and Crane (2010). The product of the analysis is a relative ranking of tree species vulnerability to climate change. The species' scores are derived from averaging the scores given multiple biological and ecological risk factors; the risk factor rank scores are estimated based on one or more variables that are themselves given a rank score. Scoring for forest tree species was based on analysing forest inventory data, expert opinion and published literature. The authors evaluated several vulnerability assessment models and chose this approach "because it is straightforward to apply, transparent, and can be easily modified to fit specific objectives and assumptions" (Devine *et al.*, 2012). The ease of use is attributable in part to the straightforward Microsoft Excel program that is used to enter data and produce ranking in the ForGRAS model.

The approach used by Devine *et al.* (2012) does not use climate projections. Instead, it ranks the current vulnerability of species and by implication concludes that species at greater risk based on current biological and ecological risk factors will be at greater risk with climate change. The risk factors chosen for use by Devine et al. (2012) were a select subset of a larger list provided by Potter and Crane (2010); for each new forest area to which the methodology is applied, the complete list or risk factors can be revisited to determine the most appropriate ones to include.

Forest sunset ©Sílvia Margarida Oliveira Fernandes

FIGURE 5
A contextual vulnerability assessment methodology of current tree species vulnerability



Source: Devine *et al.*, 2012

7.2 FOREST-DEPENDENT COMMUNITIES

Participatory methodology for assessing current social vulnerability

The vulnerability assessment method developed for the Center for International Forestry Research (CIFOR) by Tiani *et al.* (2015) is a contextual participatory approach to evaluate current vulnerability. The approach includes a preparatory phase that emphasizes the importance of developing communications with local partners and authorities prior to meeting with local community members. The preparatory phase also includes secondary research to describe the area to be assessed (Figure 6).

The core approach of the CIFOR methodology is participatory fieldwork to elicit discussion about three components of vulnerability: exposure to climate and extremes, sensitivity of the elements being assessed, and their adaptive capacity. The focus on current vulnerability is explored by examining past trends in climate and extreme events and the strategies used in local settings to cope with them. There is no examination of future climate scenarios, although that could be incorporated in the participatory processes.

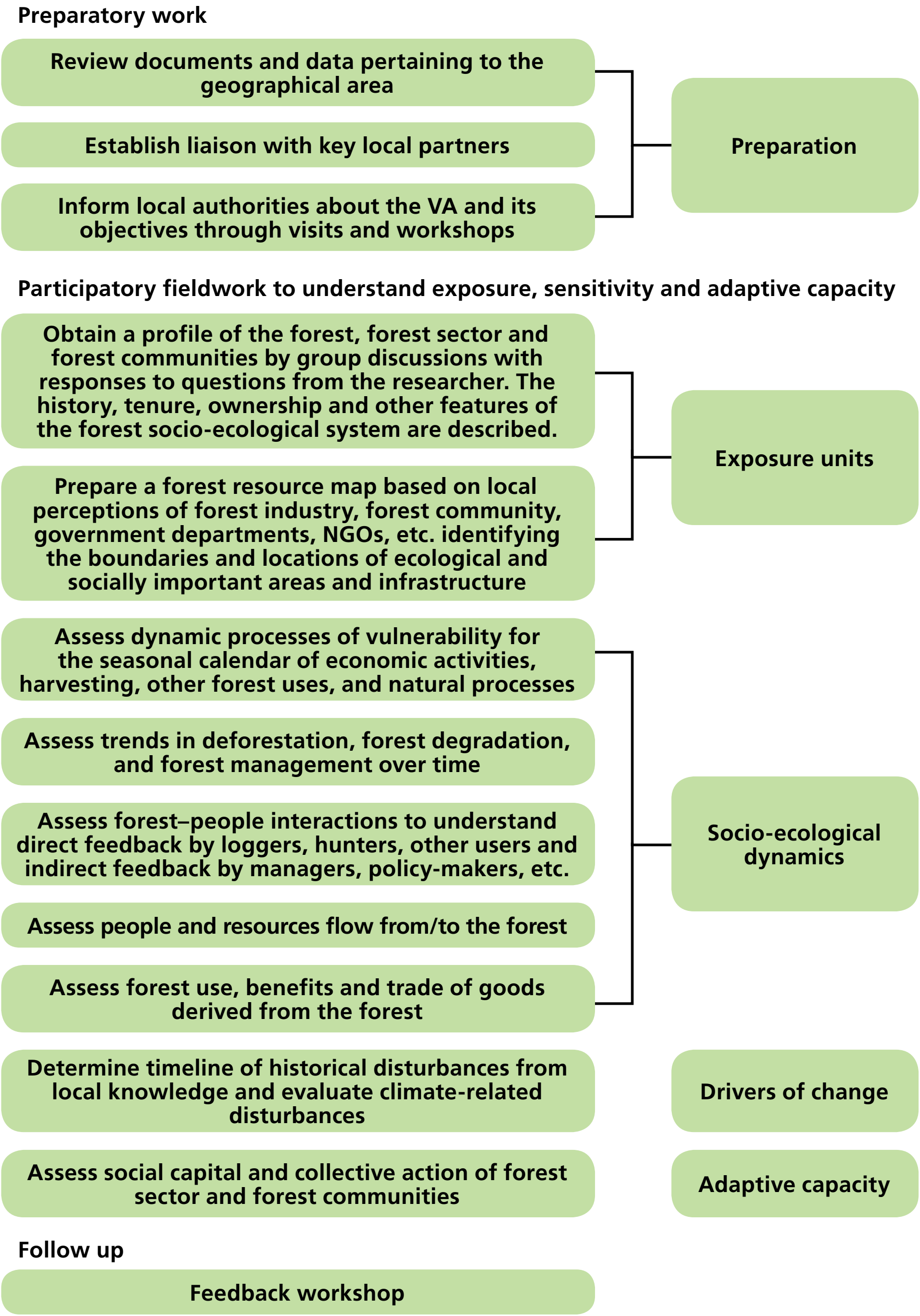
The assessment takes a human-centred approach, examining how communities use forests and how those uses have been affected by past climate and extremes. Tiani *et al.* (2015) provide examples of a number of participatory exercises that can be used in the assessment.

The methodology does not include a biophysical assessment of past climate (i.e. no historical climate data is used) and it does not use scientific sources to describe climate effects on forests. Instead it examines local perceptions of these factors. The time period covered by the assessment was at least the prior three decades.

A feedback workshop is held after the fieldwork to provide community leaders, local NGOs and key stakeholders with a summary of the results. This feedback workshop was also used to discuss possible approaches to build adaptive capacity.

My forest, my home ©Eko Bambang Subiyantoro

FIGURE 6
Major steps in the vulnerability assessment methodology presented by the Center for International Forestry Research (CIFOR)



Source: Tiani *et al.*, 2015

The adaptation toolkit

The adaptation toolkit methodology (Figure 7) was developed by the United Nations Institute for Training and Research, so that communities in developing countries could evaluate the risks that climate change brings when added to issues of lagging infrastructure, rapid urbanization and limited financial and technical capacity (Ampomah and Devisscher, 2013). As in the CIFOR methodology described previously, this is a contextual assessment approach that uses participatory approaches to obtain information about current vulnerability.

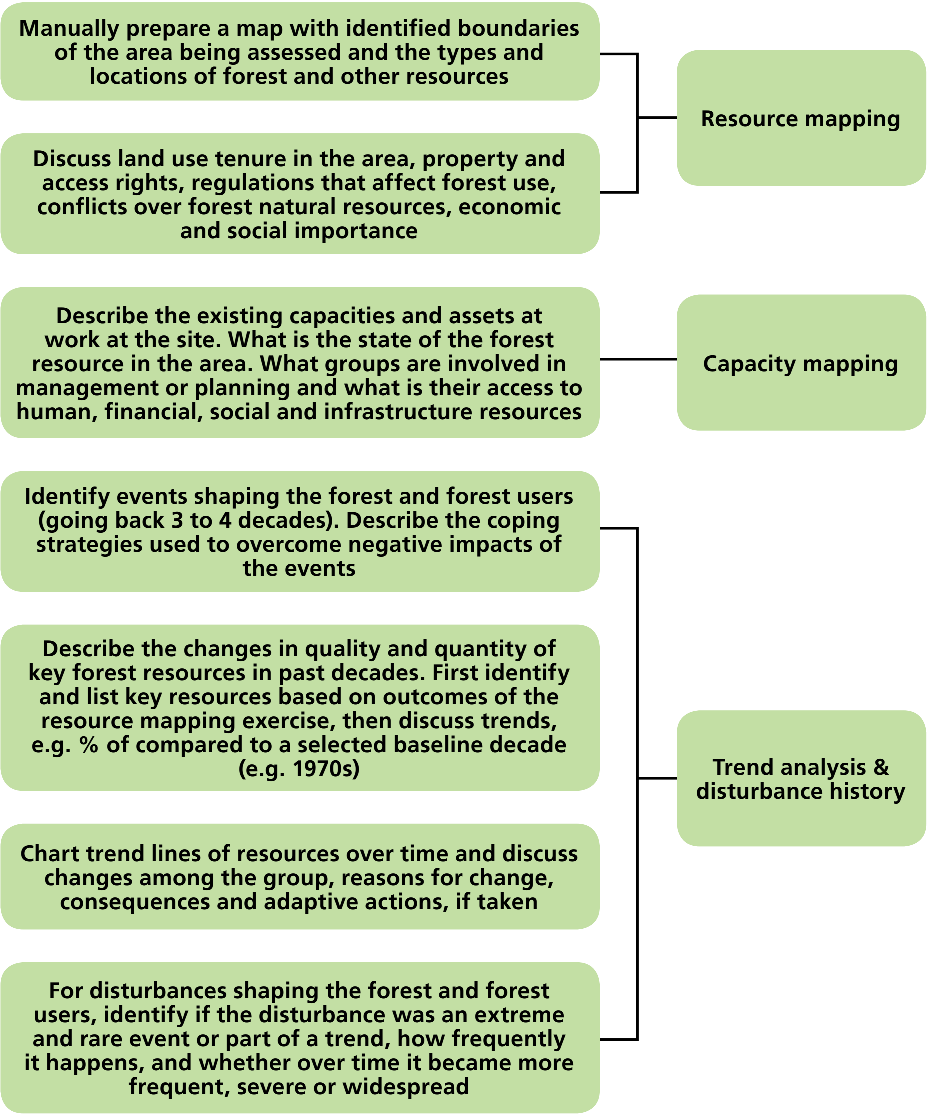
The methodology was designed to facilitate exchanges of knowledge on the current effects of climate variability between researchers and local people as a means of enabling community development of adaptation plans. The steps in the process shown in Figure 7 were modified for this document so that they refer to forest-oriented information.

The process involves seven steps that in total lead to an eighth step to develop an adaptation plan. Each step is called a tool by Ampomah and Devisscher and collectively, the tools make up the toolkit. Several of the tools produce information that can be physically mapped to indicate where events or features are located.

Initially the approach is used to develop a description of the physical, human, governmental and climatic characteristics of the area. Factors shaping the forest, forest sector and forest communities (e.g. extreme events, trends in forest change) are identified and the sensitivity and exposure of each to climate hazards is rated. This then leads to a ranking of the forest and forest community to each hazard. A discussion step takes place to elucidate the consequences if a vulnerable feature is affected by a hazard. Finally, adaptive capacity is addressed, in which the ability to reduce vulnerability is addressed. A computer program, the Adaptation Decision Explorer, is available to help with the evaluation of adaptation options.

Forest and cloud formation in East Kalimantan ©Christoforus Terry

FIGURE 7
Major steps in the vulnerability assessment methodology presented by the United Nations Institute for Training and Research (UNITAR)



Manually prepare a map with identified boundaries of the area being assessed and the types and locations of forest and other resources

Discuss land use tenure in the area, property and access rights, regulations that affect forest use, conflicts over forest natural resources, economic and social importance

Describe the existing capacities and assets at work at the site. What is the state of the forest resource in the area. What groups are involved in management or planning and what is their access to human, financial, social and infrastructure resources

Identify events shaping the forest and forest users (going back 3 to 4 decades). Describe the coping strategies used to overcome negative impacts of the events

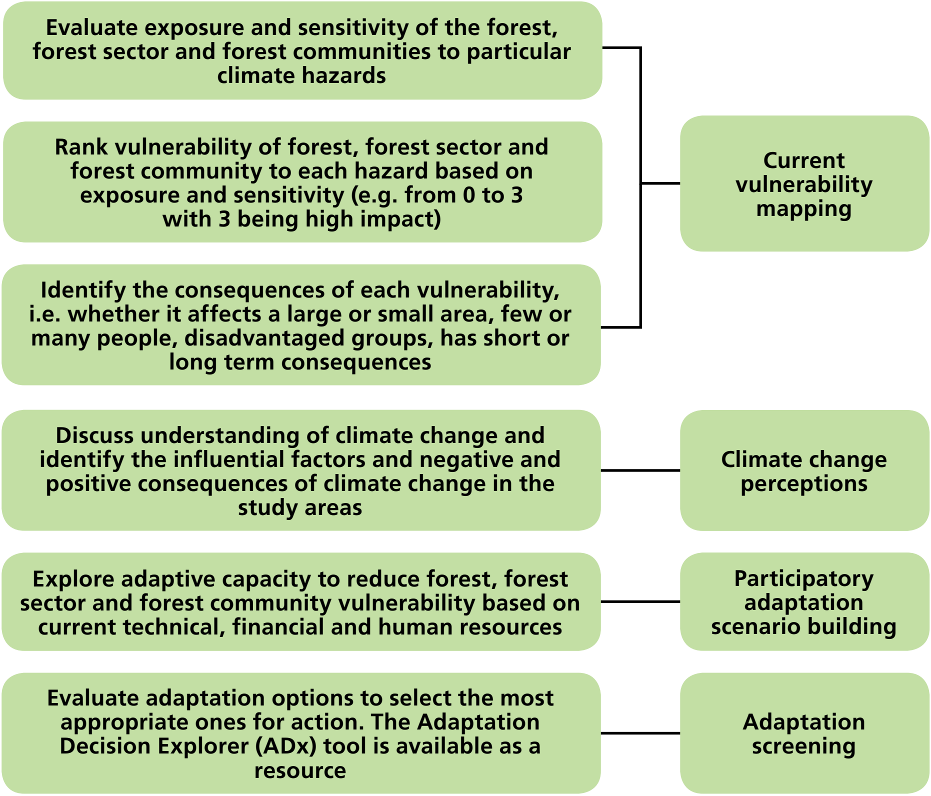
Describe the changes in quality and quantity of key forest resources in past decades. First identify and list key resources based on outcomes of the resource mapping exercise, then discuss trends, e.g. % of compared to a selected baseline decade (e.g. 1970s)

Chart trend lines of resources over time and discuss changes among the group, reasons for change, consequences and adaptive actions, if taken

For disturbances shaping the forest and forest users, identify if the disturbance was an extreme and rare event or part of a trend, how frequently it happens, and whether over time it became more frequent, severe or widespread

Figure continues

Figure continued



Source: Ampomah and Devisscher, 2013

Assessment of vulnerability to climate change of forest-dependent communities in Cameroon

This study (Bele *et al.*, 2013) reports on an evaluation carried out of the vulnerability to climate change of two forest-dependent communities in Cameroon. The approach (Figure 8) was contextual and examined current and historical changes in climate. Using a variety of participatory techniques, the project team evoked points of view about local forest and forest uses from community members.

The approach consisted of four phases: preparatory activities; participatory research; surveys; data analysis and presentation of results. Key members of the communities selected for participation in the study were involved early on in planning the assessment. Care was taken to meet with and obtain buy-in from stakeholders inside the communities and from local authorities, before commencing the study. Different genders and ethnic groups participated individually and later collectively in consensus-building sessions.

The techniques used were able to demonstrate that the communities are already experiencing adverse effects from climate change, with substantial impacts on livelihoods and resources that community members rely on. Further, the approach allowed participants to identify what factors were causing problems for the communities (e.g. drought, shifts in seasonality of natural events, unpredictable rainfall, and extreme rain and wind events). The approach allowed for identification and evaluation of the effectiveness of current coping and adaptation strategies, and the participants provided suggestions for further adaptations and methods for facilitating their implementation.

FIGURE 8
Approach for assessing vulnerability to climate change in forest-dependent communities in Cameroon

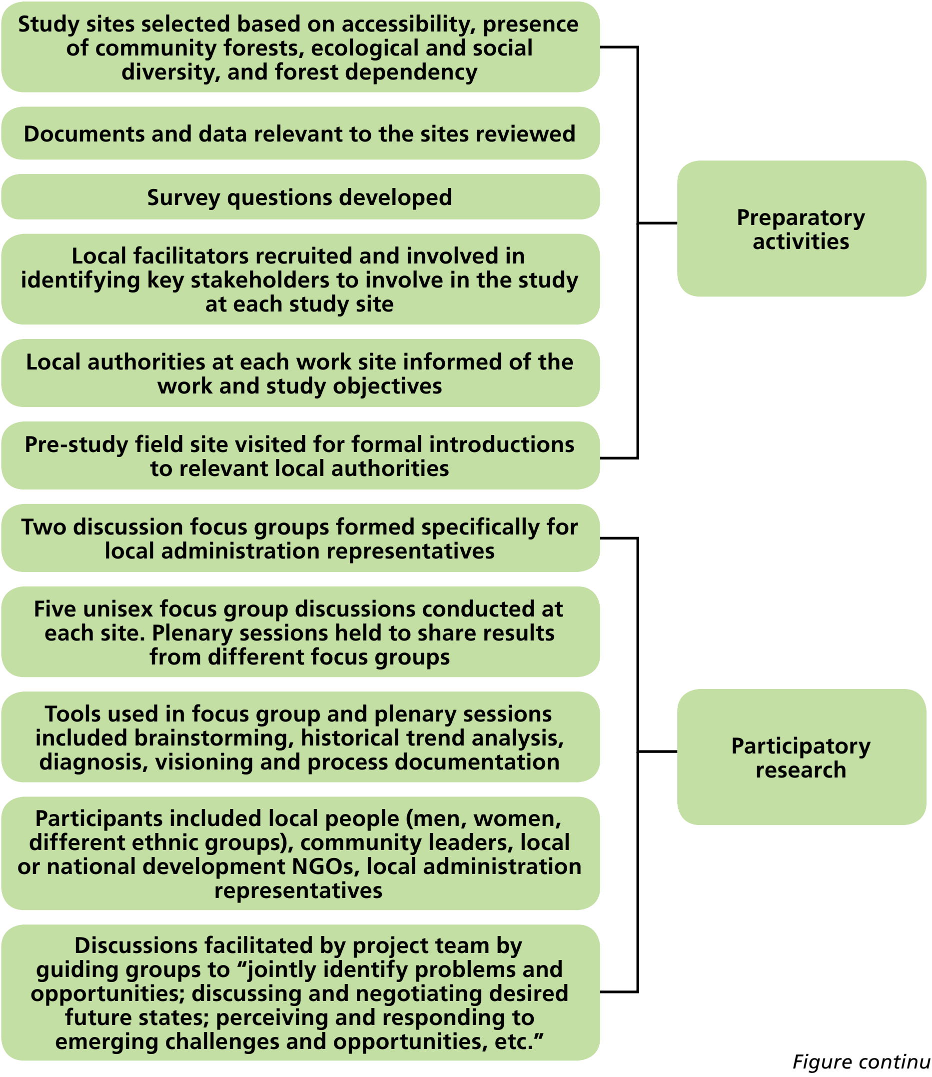
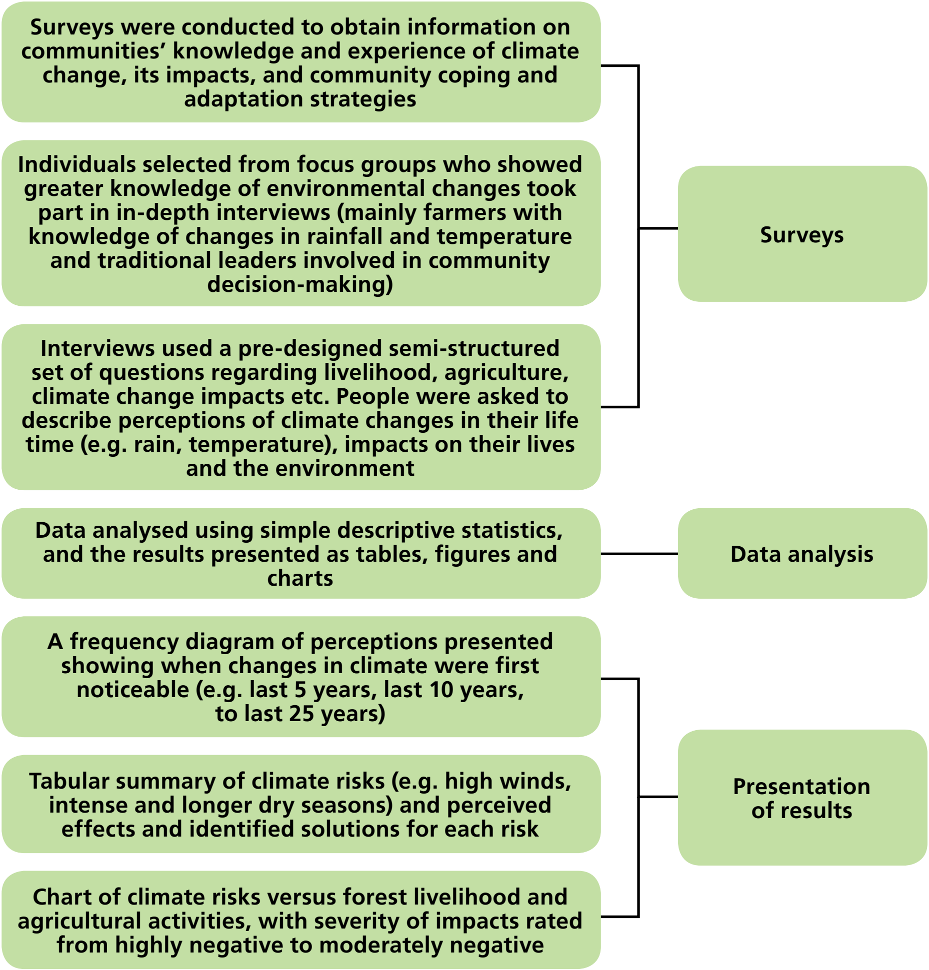


Figure continues

Figure continued



Surveys were conducted to obtain information on communities' knowledge and experience of climate change, its impacts, and community coping and adaptation strategies

Individuals selected from focus groups who showed greater knowledge of environmental changes took part in in-depth interviews (mainly farmers with knowledge of changes in rainfall and temperature and traditional leaders involved in community decision-making)

Interviews used a pre-designed semi-structured set of questions regarding livelihood, agriculture, climate change impacts etc. People were asked to describe perceptions of climate changes in their life time (e.g. rain, temperature), impacts on their lives and the environment

Data analysed using simple descriptive statistics, and the results presented as tables, figures and charts

A frequency diagram of perceptions presented showing when changes in climate were first noticeable (e.g. last 5 years, last 10 years, to last 25 years)

Tabular summary of climate risks (e.g. high winds, intense and longer dry seasons) and perceived effects and identified solutions for each risk

Chart of climate risks versus forest livelihood and agricultural activities, with severity of impacts rated from highly negative to moderately negative

Source: Bele *et al.*, 2013

7.3 COMBINED METHODOLOGIES FOR FORESTS AND FOREST-DEPENDENT COMMUNITIES

Vulnerability mapping to integrate contextual and outcome vulnerability

The approach used by O'Brien *et al.* (2004) studied the example of Indian agriculture to demonstrate a method for assessing regional vulnerability to climate change. The method combined several aspects of social, economic and biophysical vulnerability into a single numerical index (Figure 9). The approach uses vulnerability mapping – literally, the creation of maps based on differences in vulnerability estimated across the area. This was combined with local case studies, in order to explore whether there were finer-scaled differences in vulnerability and to see if the vulnerability mapping was verified at the local level.

The authors of the study consider the general methodology suitable for use in other national or regional areas to differentiate vulnerability for sectors beyond agriculture. Through the use of local case studies, the approach was able to identify policy interventions that were capable of increasing community adaptive capacity.

The study encompasses a number of different approaches and applies them in creative ways to reach conclusions about vulnerability, adaptive capacity and sensitivity to climate change. In particular, the study:

- Features both a contextual component, by examining present-day vulnerability, and an outcome approach, by projecting vulnerability for a future climate scenario (a 2x CO_2 scenario modelled using the Hadley Centre's regionally downscaled HadRM2 climate model for the years 2041–2059.
- It employs a modelling approach normally associated with outcome vulnerability assessments, which in this case is applied to evaluate outcome and contextual vulnerability.
- In addition to modelling, the authors also use several participatory approaches to obtain first-hand information from local experts and community members.
- The study also combines multiple factors of social, economic and biophysical vulnerability that are elements of a contextual vulnerability assessment (see Figure 2) but uses them to evaluate both current and future vulnerabilities.
- Finally, the study relies heavily on an indexing procedure so that disparate social, economic and biophysical factors can be combined into a single composite measure of vulnerability.

In sum, this study applies a large number of methodologies and uses them in ways that demonstrate the flexibility with which they can be used to meet the goals of vulnerability assessment.

FIGURE 9

A combined contextual and outcome vulnerability assessment conducted using modelling and participatory techniques

Part 1
Modelling of a Combined Contextual and Outcome Assessment

Create a climate change vulnerability profile based on indices for exposure, sensitivity, adaptive capacity

Evaluate adaptive capacity by identifying major biophysical, socio-economic and technological factors influencing agricultural production

Transform information on factors to indices for: biophysical factors, soil depth and available groundwater; socio-economic factors, human (literacy) and social capital (gender equality) and economic factors (non-agricultural economic activity); and technological factors, irrigation and other infrastructure.

Combine indices for different measures of adaptive capacity into a single index value. Create a map delineating areas of higher to lower adaptive capacity

Construct a climate-sensitivity index and associated map based on historical and future (2041–2059) climates, combining climate sensitivity and exposure for monsoon rainfall dependency and dryness. Future climate was downscaled to regional output based on the HasRM2 General Circulation Models using a 2x CO_2 scenario.

Calculate and map current sensitivity to 2x CO_2 climate by summing indices values for adaptive capacity with climate sensitivity under future exposure.

Part 2
Contextual Assessment using a Participatory Approach

After distinguishing districts of high and low vulnerability, conduct community-level case studies targeting sub-units of high and low vulnerability within areas covered by the modeling assessment

Select villages for local-level study based on secondary statistics of socio-economic and climatic conditions and on discussions with local experts from governmental organizations

Interview government officials in the district to identify if agriculturally relevant policy reforms had been introduced

Conduct household surveys in a participatory exercise to assess whether agricultural reforms influenced farmers’ and agricultural labourers’ livelihoods and ability to cope with calamities such as drought

Document historical examples of and factors affecting village-specific climate sensitivity and adaptive capacity

Evaluate reasons for differences and similarities between contextual case studies and outcome modeling studies and apply that information to potential adaptation measures being considered

Source: O’Brien *et al.* (2004)

A dense swarm of locusts as seen during spraying operations with an FAO-contracted helicopter in Madagascar.

©FAO/YASUYOSHI CHIBA

8 Moving from vulnerability assessment to implementing adaptive measures

Adaptation options may develop differently depending on the initial framing of a vulnerability assessment and the approach with which vulnerability is assessed. For that reason, taking the goals of adaptation into account can have downstream effects when planning what to assess for vulnerability and the approach to take when conducting a vulnerability assessment.

For example, an outcome vulnerability assessment evaluating how a tree species may respond to increasing drought exposure has a narrow focus and will most likely involve a quantitative approach. While this gives the assessment considerable power to point towards adaptations that address the problem of drought exposure, the focus on that single species and type of exposure means that the vulnerability assessment will be unable to discern whether the adaptations that might be proposed are those that are most urgently needed.

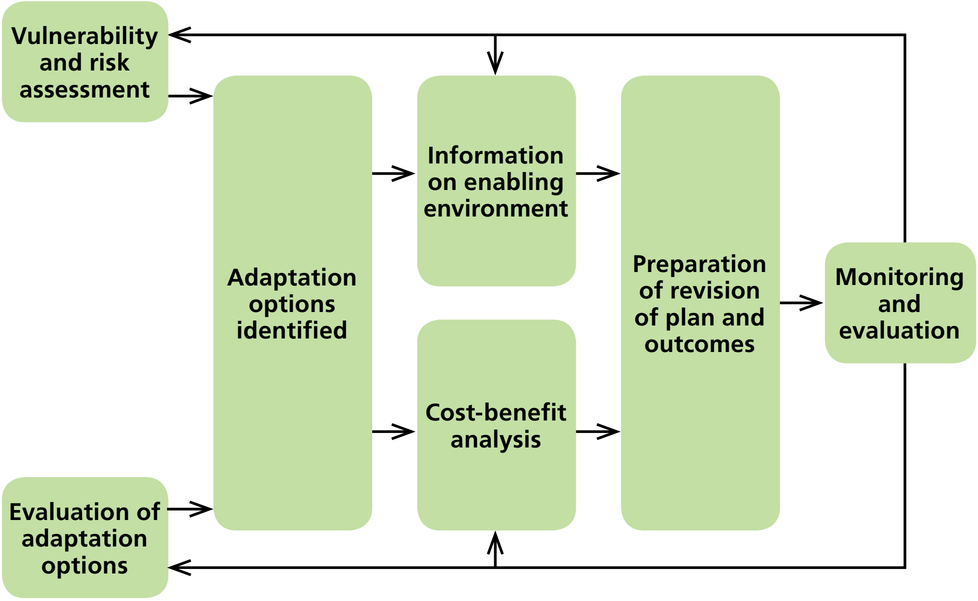
In comparison, a contextual vulnerability assessment evaluates the combined influence of climate and other interacting factors on vulnerability, usually with a focus on current or near-term vulnerability. The approach is qualitative and addresses multidimensional problems. Thus, a contextual vulnerability approach can permit comparison of vulnerability and can potentially rank vulnerabilities according to importance and risk of damage. However, the near-term focus of a contextual assessment will mean that adaptations that address longer-term needs may not be addressed.

The differences in the types of adaptations that will be suggested from contextual and outcome assessments are not right or wrong, they are simply different. Therefore, when embarking on a vulnerability assessment, a project team should recognize that the approach they choose to proceed with will affect the nature of the adaptation measures identified.

Involving key individuals in planning and carrying out a vulnerability assessment will facilitate implementing adaptations (United Nations Development Programme, 2010). In the case of an outcome vulnerability assessment of biological aspects of forests, this could mean involving policymakers and decision makers from government and non-governmental organizations in the process. An assessment of forest-dependent communities should include community leaders, organizations that work in and with communities, as well as community members from all local socio-economic, gender, generational and ethnic groups (Turnbull and Turvill, 2012).

FIGURE 10

A flow-chart showing steps to move from the assessment of vulnerability to integrating adaptation options into plans and strategies



Source: FAO, 2013

This document, with its focus on vulnerability assessment, provides a bridge into the topic of adaptation development and implementation. The topic of adaptation has received a great deal of attention in its own right (e.g. Füssel, 2007; Lim *et al.*, 2005; Turnbull and Turvill, 2012; United Nations Development Programme, 2010; UNFCCC, 2011). This large body of published work should be consulted for additional information on approaches and techniques to identify and prioritize adaptation measures. An example is provided in Figure 10.

One approach to evaluating adaptation options that has been used in a variety of forms is called a validity quadrant. The validity quadrant is an approach that can be used with either a contextual or an outcome vulnerability assessment and for vulnerability assessments that are quantitative or qualitative. It can be particularly useful in assisting community members to evaluate actions they might consider when addressing risks to community assets, activities and local forests (Turnbull and Turvill, 2012).

The validity quadrant consists of four cells, which rank an activity's effectiveness to reduce vulnerability and achieve a desired result on the one hand, while ranking whether the actions are sustainable in the long term on the other. This validity quadrant approach is derived from a general approach that ranks whether an option is valid – on the x-axis of the quadrant, and whether the option is reliable – on the quadrant's y-axis. An example of a validity quadrant that might be applied to a forest or in some cases to a forest-dependent community is shown in Table 4. The feasibility of implementing adaptation options that are highly effective and have high sustainability can be considered first.

TABLE 4

An example of a validity quadrant used to rank potential actions to take to address vulnerability to disturbances

Highly effective, Low sustainability	Highly effective, High sustainability
Poorly effective, Low sustainability	Poorly effective, High sustainability

An area in Thailand's northeast following a bushfire. Once heavily forested, northeast Thailand has lost about 3/4 of its tree cover over the last 25 years, triggering serious problems of erosion, environmental damage, and unemployment and general poverty.

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9 Conclusions

The need to undertake forest vulnerability assessments and to use those results to adapt forests to climate change is not declining. Even in the best-case scenarios for greenhouse gas emissions reductions, climate in coming decades will continue to change, and the effects of climate change will be expressed more frequently and with more extreme conditions. Applying climate change vulnerability assessments to forests and forest-dependent communities can lay the groundwork for the management of species and activities at risk, so that harmful effects on forest-dependent communities are reduced.

A forest vulnerability assessment needs to identify the environmental conditions that reduce species' biophysical fitness. Identifying vulnerabilities brought about by climate change can reveal threats to what have historically been considered "perpetual benefits" provided by the natural processes that flow from robust and diverse forest ecosystems.

For forest-dependent communities, a vulnerability assessment can reveal threats to obtaining subsistence supplies of food, fuel, goods that can be sold, and employment. A vulnerability assessment can provide an avenue for people in forest-dependent communities to articulate their knowledge of how forests respond to climate. Moreover, participatory processes that are often recommended for conducting vulnerability assessments of communities have a twofold purpose. First, they express the knowledge already held by the community, in a way that helps to reveal insights about vulnerability to climate. Second, they provide the assessment project team with those same insights, so that they might be used to benefit the participating community and those in other jurisdictions. In exchange, the project team shares knowledge from other sources about how climate can affect forests.

The ultimate goal of a vulnerability assessment is to enable those who live in forest-dependent communities or who have a role in forest management to use their knowledge to reduce vulnerabilities to climate. This is of growing importance because people will be increasingly vulnerable to losing the benefits they derive from healthy forests. The application of a methodology to assess vulnerability can help to lessen harmful impacts of climate on forests and forest-users and help prioritize where to direct resources to adapt forests and communities to changing environmental conditions.

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