Climate Resilience Indicator Literature Review

Prepared as part of "Using Columbia Basin State of the Basin Indicators to Measure Climate Adaptation"

Jennifer Ellis

December 2014

Columbia Basin trust

cbt.org

Acknowledgements

This project was funded by Columbia Basin Trust (the Trust) and Natural Resources Canada (NRCan) and conducted by members of the Trust's Communities Adapting to Climate Change Initiative and the Columbia Basin Rural Development Institute.

Project team members:

- **Adrian Leslie – Columbia Basin Rural Development Institute**
- **Ingrid Liepa – Communities Adapting to Climate Change Initiative**
- **Kate Mahoney – Communities Adapting to Climate Change Initiative**
- **Lauren Rethoret – Columbia Basin Rural Development Institute**
- **Jeff Zukiwsky – Communities Adapting to Climate Change Initiative**

The project team gratefully acknowledges the guidance of the Project Advisory and Steering Committee:

- **Gundula Brigl, Regional Manager, Emergency Management BC**
- **Deborah Carlson, Staff Counsel, West Coast Environmental Law**
- **Jenny Fraser, BC Ministry of Environment, Climate Action Secretariat**
- **Tim Hicks, Manager, Water and Environment, Columbia Basin Trust**
- **David Lapp, Manager, Professional Practice, Engineers Canada**
- **Cathy Leblanc, BC Ministry of Communities, Sport and Cultural Development**
- **Terri MacDonald, Regional Innovation Chair in Rural Economic Development, Columbia Basin Rural Development Institute, Selkirk College**
- **Kathy Moore, Rossland City Councillor**
- **Trevor Murdock, Climate Scientist and Program Lead, Regional Climate Impacts, Pacific Climate Impacts Consortium**
- **Thomas White, BC Ministry of Environment, Climate Action Secretariat**

Columbia Basin trust

COLUMBIA BASIN RDI RURAL DEVELOPMENT INSTITUTE

Natural Resources Canada Ressources naturelles Canada

Canada

Table of Contents

I: Introduction

Objective

This literature review was prepared as part of a larger project entitled *Using Columbia Basin State of the Basin Indicators to Measure Climate Adaptation,* undertaken by Columbia Basin Trust's Communities Adapting to Climate Change Initiative in cooperation with the Columbia Basin Rural Development Institute at Selkirk College, and with support and guidance of a Project Advisory and Steering Committee.

A primary objective of the literature review was to document and describe types of indicators currently in use or proposed for tracking climate change, impacts and adaptation. The review explores the complexities associated with measuring adaptation, issues associated with attribution, and identifies approaches that may be appropriate for the Columbia Basin Trust region (the Basin). It also informed the development of a model, framework and criteria for selection of climate change, climate impact and climate adaptation indicators for the *State of Climate Adaptation and Resilience in the Columbia Basin indicator suite*.

The complete project report and summary report can be downloaded at www.cbt.org/climatechange.

Overview of Indicators

Definition and Types

The European Environment Agency (EEA), an agency of the European Union, is one of the world's leading authorities on climate change indicators. The EEA defines an indicator as:

> *"A measure, generally quantitative, that can be used to illustrate and communicate complex environmental phenomena, simply, including trends and progress over time – and thus helps provide insight into the state of the environment."* (EEA, 2005).

Five types of indicators are examined in this paper. CACCI defines the first three types of indicators as follows:

1) *Climate change indicators* measure changes in climate over time using data on key trends relating to temperature and precipitation.

2) *Climate impact indicators*
    a. *Environmental impact indicators* measure the impacts of changes in climate on biophysical systems.
    b. *Community impact indicators* measure the impact of changes in climate on human systems and infrastructure.

3) *Climate adaptation indicators* measure community response to climate impacts through implementation of capacity and adaptation actions.

Vulnerability and resilience indicators are also considered as critical constructs relating to climate change. While CACCI chose not to define vulnerability and resilience indicators, various definitions can be found in the literature. CACCI has defined the concepts of vulnerability and resilience as follows:

1) *Vulnerability* is the degree to which human or ecological systems are susceptible to and unable to cope with, adverse climate impacts.

2) *Resilience* is the ability of human or ecological systems to absorb disturbances while retaining the same basic structure and ways of functioning, as well as the capacity of those systems to cope with, adapt to and recover fully or partially from stress and change.

The five types of indicators can be qualitative, quantitative or binary according to the type of data they utilize.

Quantitative indicators (e.g. the average annual temperature, the number of projects developed in response to a policy, or the number of bridges constructed) are often preferred for monitoring and evaluation. Where quantitative data is not available, and the issue is still considered important for monitoring purposes, qualitative or binary indicators may be utilized.

Qualitative indicators provide narrative or summary information regarding an item of concern (e.g. the state of salmon on the B.C. coast or the development of a policy framework). Adaptation indicators, because they relate to processes, are more likely to be qualitative than climate change or climate impact indicators.

Binary indicators have a yes/no answer. Several indicators appropriate for climate adaptation could be binary, e.g. early warning systems in place (yes/no) (Lamhauge *et al.*, 2011).

Indicator Uses

Indicators are used to measure progress towards a desired goal. They are preferably quantitative and serve four basic purposes: simplification, quantification, standardization and communication (Natural England, 2010).

Indicators related to climate change help to assess climate change trends and progression, and are used to communicate climate change, climate impacts and the need for and effectiveness of adaptation measures to the general public. They provide support for science-based decision making in the development of mitigation and adaptation strategies (EPA, 2012). Indicators related to climate change can help evaluate the effectiveness of these measures and progress toward overall goals. They are used to monitor implementation and evaluate after implementation. The Canadian Council of Ministers of the Environment (2003) observed that indicators are:

> *"important tools for tracking the social, economic and environmental effects of changes in our climate."*

Indicators may be critical for providing an early warning signal to decision makers and the public with respect to climate change (Erhard *et al.*, 2003).

According to the EEA, different types of climate change indicators have different purposes. The EEA (2012) defines these purposes as follows[1]:

Table 1: The Purposes of Indicators relating to Climate Change

Type of Indicator	Main Purpose
Climate change indicators	Understanding the causes of impacts of climate change
Climate impact indicators	Understanding the consequences of climate change and determining vulnerability to climate change
Vulnerability and climate adaptation indicators	Monitoring and understanding vulnerability; identifying adaptation needs; evaluating adaptation strategies and action

While indicators are an important element of the toolbox for climate change adaptation, mitigation, and monitoring and evaluation efforts, it is important to stress that indicators only provide an overview of change — they do not explain how or why that change came about (Lamhauge *et al.*, 2011). Indicators cannot address all of the changes that could occur as a result of climate change, nor can they report on the effectiveness of all climate adaptation measures (Cannell *et al.*, 2003).

Schönthaler *et al.*, (2011) emphasize that climate change indicators are part of monitoring and evaluation, but do not replace a formal program or project evaluation. Indicators are chosen on the basis of specific criteria that often include data availability and representativeness, although they may also drive the collection of new types of data not previously collected. As such, they provide valuable information on trends and changes in key factors over time, yet cannot communicate the whole story.

Status of Development and Interrelationships

Indicators relating to climate change are at different stages of development and usage (EEA, 2012). Climate change indicators and climate impact indicators are at a more advanced stage of development. Vulnerability, resilience and climate adaptation indicators are still in the early stages of development.

Different countries and organizations around the world are also at different stages of indicator development. In general, climate change indicators and climate impact indicators have been developed together. Vulnerability and climate adaptation indicators have been developed and are treated in isolation from each other, and separate from climate change indicators and climate impact indicators. A similar convention was followed in this review.

Nonetheless, there are overlaps among the different types of indicators. For example, some climate adaptation indicators related to outcomes are the same as climate impact indicators because they both measure the state of a natural system or vulnerable population. Likewise, there are two schools of thought with respect to measuring success in adaptation. One school seeks to measure success through what this review refers to as adaptation indicators, measuring whether climate change policies were developed, implemented, and their impact. The other defines reduction in vulnerability as success in adaptation, taking the view that adaptation and vulnerability indicators are the same (GIZ, 2013). While this review treats the five types of indicators as separate, these interrelationships should be kept in mind.

1 The EEA does not include resilience indicators in its framework and therefore they are not included in the table.

Although it is not yet a common practice, there may be value in presenting the five types of indicators (or just the first three types – climate change, climate impact and climate adaptation indicators) as an integrated suite of indicators. This approach is being used by some agencies in the United States, where indicators of climate changes, impacts, vulnerabilities, opportunities, resilience and preparedness are being developed together (Janetos *et al*, 2012; Buizer *et al.*, 2013). Germany has also taken this approach in using the drivers-pressures-state-impacts-response (DPSIR) model that will be discussed below (Schönthaler *et al.*, 2011), This model simplifies matters by referring to indicators as either impact indicators or response indicators.[2]

Organization of the Review

Section II of this paper focuses on the five types of indicators outlined above. Since most organizations develop and discuss climate change indicators and climate impact indicators together in one broad category of climate change indicators, they will be discussed together. Vulnerability, resilience and climate adaptation indicators are usually treated separately in the literature and are presented in their own sections below.[3]

The order in which the information is presented in Section II varies slightly among the indicators. Given the larger body of experience in using climate change and climate impact indicators, some approaches utilized in other jurisdictions will be presented first, followed by a brief summary of challenges that have occurred. Since there are fewer accepted suites of vulnerability or adaptation indicators, a summary of the key challenges associated with developing these types of indicators is presented first, followed by a summary of key thinking on moving forward, and finally by examples of proposed indicator suites and some indicators already in use. Resilience indicators are presented last, providing an overview of the general state of resilience indicator research and approaches to measuring resilience.

Section III focuses on approaches to selecting indicators, potential criteria for selecting indicators, and classification frameworks for indicators based on how they meet the selection criteria. It also touches on approaches to interpreting and presenting indicators. Section IV shares the conclusions of the review.

---

2 Germany's more integrated system of indicators is presented separately at the end of this paper.

3 Resilience indicators were added in a subsequent draft of this literature review and therefore are presented in a slightly different format that reflects their late addition and the more nascent stage of development of the climate resilience indicator literature.

II: Indicators

Climate Change Indicators and Climate Impact indicators

There is considerable global experience using climate change indicators and climate impact indicators—usually referred to jointly as climate change indicators—and comprehensive indicator suites exist at a national level in the United States (U.S.), the United Kingdom (U.K.) and Canada, at an international level in the European Union, and at a state or provincial level in places such as California, British Columbia (B.C.) and New Brunswick. Many of these indicator suites have been in use for several years or more.

CACCI has historically separated climate change data in the Canadian Columba Basin (the Basin) into climate changes and climate impacts. The former tells us only about changes in the climate such as changes in temperature and precipitation, while the latter addresses resulting changes in watersheds and ecosystems.

This section covers approaches to selecting and categorizing climate change indicators and climate impact indicators, reviews some of the more comprehensive indicator suites available, and discusses challenges associated with using climate change indicators and climate impact indicators.

Approaches Utilized

There are a wide array of approaches in the literature to selecting and categorizing climate change indicators and climate impact indicators. Nevertheless, there are some common features to the indicator suites and established best practices, largely because there is more experience in the development and use of these indicators.

Categorization of Indicators Together

Many organizations that study climate change and develop indicators do not distinguish clearly between climate change indicators and climate impact indicators, and tend to classify both climate change indicators and climate impact indicators into one category called climate change indicators (EPA, 2012; MWLAP, 2003; Cannel *et al.*, 2003). Some organizations do distinguish between the types of indicators using sub-categories. For example, the Province of B.C. refers to what CACCI would call climate change indicators using the sub-category of climate change drivers (MWLAP, 2003), while the U.S. Environmental Protection Agency (EPA) places these indicators in the sub-category of weather and climate (EPA, 2012), and the EEA places them in the sub-category of changes in the climate system.

There is limited consistency in the naming of sub-categories. For example, the Province of B.C. uses ‘climate change drivers’ to refer to changes in temperature and precipitation, whereas the State of California uses ‘climate change drivers’ to refer to greenhouse gas emissions and atmospheric gas concentrations.

Inclusion of Emission and Gas Concentration Indicators

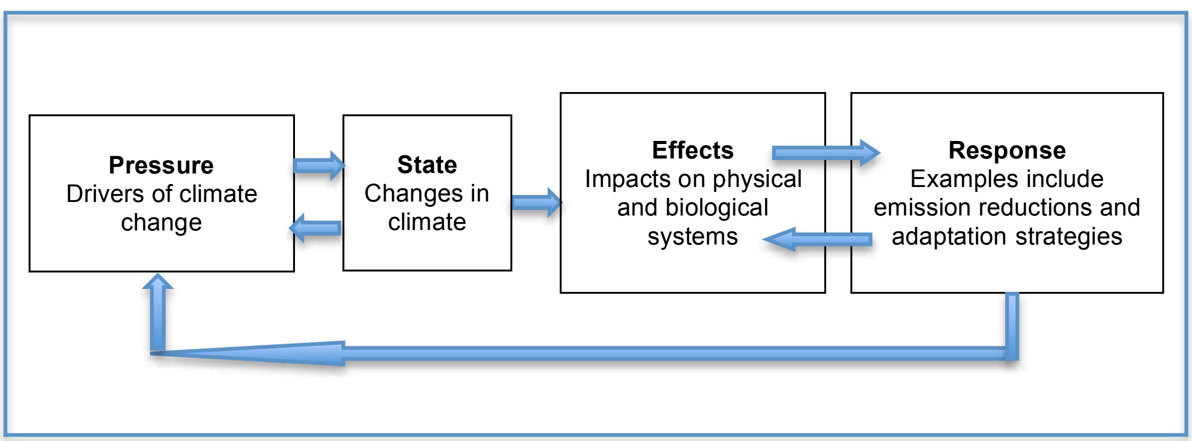
Many organizations incorporate indicators associated with greenhouse gas emission levels and atmospheric gas concentrations into their indicator suites. The U.K., for example, focuses only on indicators that detect changes in climate and the impacts of that change (Cannell *et al.*, 2003). According to U.K. Department of Environment, Food and Rural Affairs (DEFRA), it cannot be assumed that changes in climate are due to increased emissions of greenhouse gases in the atmosphere, thus it is more appropriate to concentrate on indicators that detect changes in climate rather than those related to potential causes (Cannell *et al.*, 2003).

Use of Pressure-State-Effects-Response Model

The California Environmental Protection Agency, Office of Environmental Hazard Assessment (Cal/EPA) uses a pressure-state-effects-response model from the Organization for Economic Development and Cooperation (OECD) to organize its climate change and climate impact indicators (Kadir *et al.*, 2013). In this model, human activities and natural phenomena exert pressures on the climate that alter the state of the climate, and the changes in state lead to adverse effects on human and ecological health. Responses are actions taken to alleviate the pressure or remediate the state.

In accordance with this model, pressure indicators include drivers of climate change such as greenhouse gas emissions, state indicators include changes in temperature and precipitation, effects indicators include impacts on physical and biological systems, and response indicators include both mitigation and adaptation strategies. This pressure-state-effects-response model is displayed in Figure 1.

Figure 1: Pressure-State-Effects Response Model (Kadir *et al.*, 2013)



This model is also utilized by U.K. DEFRA for its climate change indicators (Cannell *et al.*, 2003), in Germany for its overall suite of climate change indicators (Schönthaler *et al.*, 2011), and was the basis for the initial EEA list of candidate climate change indicators (Erhard, 2002). The pressure-state-effects-response model is also used more broadly in the European Union for the development of biodiversity indicator suites (Cannell *et al.*, 2003; UNFCC, 2010) and for the EEA's overall assessment framework (Erhard *et al.*, 2003).

Nonetheless, there are many approaches to using it and some inconsistency in its definitions and categories. For example, in the U.K. it is called the pressure-state-impact model (substituting impact for effects, and dropping responses) (Cannell *et al.*, 2003). In Germany and as part of the EEA overall assessment model, the category of socio-economic driving forces is added, making it the DPSIR model: socio-economic driving forces, pressures, state, impacts and policy responses) (Erhard *et al.*, 2003; Harley and Minnen, 2009; Schönthaler *et al.*, 2011). Some agencies drop effects and call it the pressure-state-response model, where responses are defined as the impacts of changes in climate and hydrology on the natural environment, human affairs, socio-economic activities and adaptation to these impacts (Cannell *et al.*, 2003).

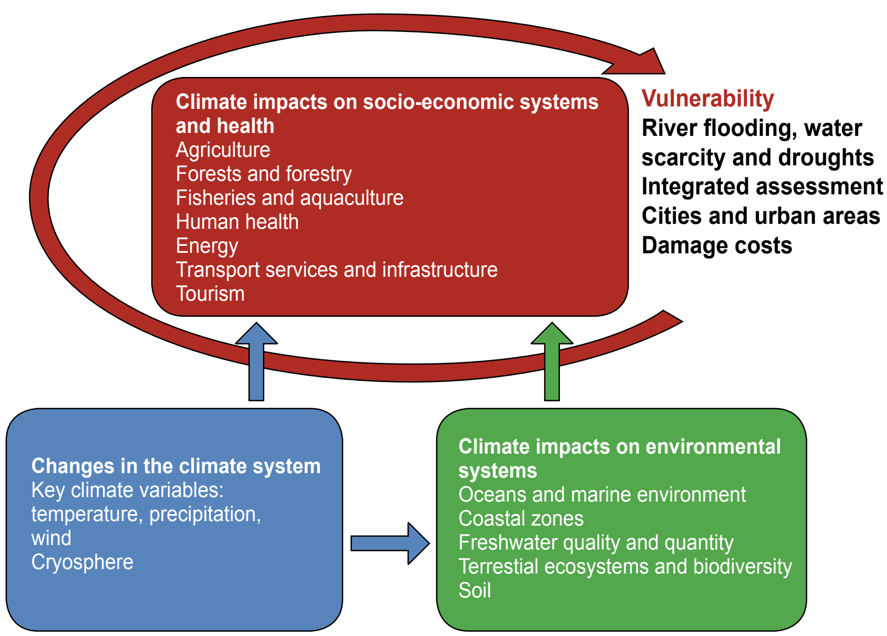
Despite the variations in nomenclature, this model is logical and incorporates responses to climate change by offering a place for adaptation indicators within a more comprehensive model. It should be noted that although the Cal/EPA and U.K. DEFRA utilize the pressure-state-effects-response model, neither have yet incorporated adaptation (response) indicators into their indicator suites. Only Germany has incorporated response indicators as part of its overall use of the DPSIR model (Schönthaler *et al.*, 2011).

Use of Other Models

Another potential indicator suite model to consider is the one used by the EEA (Füssel *et al.*, 2013). Like most other organizations in this review, the EEA lumps both climate change indicators and climate impact indicators under the single category of climate change indicators. However, the EEA does more to distinguish between indicators that address changes in the climate system and the impacts from those changes. The EEA has developed 40 climate change indicators in three categories: a) changes in the climate system, b) climate impacts on environmental systems, and c) climate impacts on socio-economic systems and health (Füssel *et al.*, 2013).

Another interesting element of the EEA model that makes it more comprehensive than others is its incorporation of some notion of vulnerability. The EEA model is shown graphically in Figure 2.

Figure 2: EEA Indicator Schemata (Füssel *et al.*, 2013)



Regional and Scale Components to Indicator Suites

There are both regional and scale components to the indicator suites selected by other organizations. Indicator suites intended for an entire country tend to be broader and more likely to take into account countrywide or global data. This is highlighted in the EPA and EEA indicator suites outlined in Table 2. Indicator suites also tend to be somewhat specialized for the specific species, natural features or geomorphology of the country or area in which they are to be applied. For example, indicator suites intended for coastal regions will have marine life and ocean temperature indicators.

In some suites the data for some indicators will be very regional and collected only for certain locales. This occurs for reasons that may include some or all of the following: data from one locale is considered representative of data for the larger area under consideration, historical data is only available for certain locations, collecting data for all locations is too costly, impacts are projected to be more extreme in certain locations, and/or certain locations are more vulnerable to particular climate impacts than others.

DEFRA chose to make their indicators very regional, only collecting data for certain indicators in certain locations due to the challenges of collecting data in all locations of the U.K. (Cannell *et al.*, 2003). They chose to collect data for certain indicators in locations thought to experience greater likelihood of extreme climate changes, or that were deemed particularly vulnerable to specific changes (Cannell *et al.*, 2003). The more regional nature of the U.K. indicators can be seen in Table 2 below.[4] DEFRA was more explicit about its method of only collecting data for certain indicators in certain locations by clearly specifying this in the name of its indicators, i.e. “River flows in NE and SW Britain”. Other organizations, such as the EEA, employ the same method of limiting data to specific locales, yet do not always clearly specify this in the indicator name (Füssel *et al.*, 2013).

With respect to scale, the EEA goes a further step by presenting its indicator results by region: northern Europe, northwestern Europe, central and eastern Europe, Mediterranean region, and the European average. It also notes whether each indicator has experienced adverse or beneficial observed change (EEA, 2012).

Use of Narrative, Snapshot and Proxy Data

To develop a comprehensive suite of climate change indicators, some organizations, such as the EEA, are electing to include indicators in their climate change indicator suite for which they do not currently have data, do not have clear quantitative data or do not have trend data. This goes against the traditional method of selecting indicators with good historical data or the potential to collect high quality data. Instead, the EEA chose to develop a comprehensive set of indicators that address climate changes and potential impacts deemed important. The EEA fills gaps in data using snapshot observations of variables, studies of individual events, proxy data (i.e. from locations outside the European Union) and narrative summaries in which the best data available is discussed to draw some general conclusions (Füssel et al., 2013). The Province of B.C. has also used a similar

4 Due to space limitations, the exact location for which data was collected for some of the indicators was not included in the table.

approach for indicators such as salmon, human health and mountain pine beetle range, providing only narrative summaries or some snapshot observations (MWLAP, 2003).

An important rationale for this approach is the need for a comprehensive indicator suite that does not omit key variables related to climate change. Focusing only on variables for which data is readily available could result in the use of less relevant indicators. There is an important balancing point between relevance and data quality as criteria for selecting indicators, which is discussed further in the indicator selection criteria section below. Another rationale for taking this approach is that data, or data models for some indicators, could become available in the future. Including an indicator in a suite supports development of a 'complete' suite and will, ideally, spur the necessary data collection or development of data analysis models to enable effective measurement in the future.

The use of narrative, snapshot or proxy data must be undertaken with care to ensure that it does not result in flawed conclusions (Füssel *et al.*, 2013).

Inclusion of Projections

Indicators can be used to provide a snapshot of the current state, a comparison with historical data to reveal trends, or to show future modeled projections. A key element of the EEA indicator analysis process is providing quantitative projection data for as many of its climate change indicators as possible, while recognizing that it will be highly uncertain for some projections (Füssel *et al.*, 2013).

Use of Composite Indicators

Use of composite indicators is particularly common for biodiversity or ecosystem indicators. For example, in the U.K., indicators have been developed for three separate taxa - butterflies, moths and ground beetles. A single composite indicator, based on a substantial core of common butterfly, moth and carabid beetle species, has been constructed (ECN, nd).

Development of Sector Specific Indicator Indices

Some organizations and researchers have developed more specialized climate impact indicator suites for certain sectors. For example, Newson *et al.*, (2008) have developed a set of 17 indicators to measure the impact of climate change on migratory species. It includes four indicators for birds, four for marine mammals, two for sea turtles, one for fish, three for land mammals and three for bats. While Döll and Zhang (2010) use a set of five indicators to model the impact of climate change on freshwater ecosystems—focusing on ecologically relevant river flow alterations, they noted 32 potential indicators of flow magnitude, frequency, duration and timing and rate of change.

Selected Indicator Suites

Some of the more comprehensive indicator suites from Europe, Canada and the United States can be found in Table 2. Some of these indicator suites have a large number of indicators, so examples are provided for each category. For example, the indicator suite developed by Erhard *et al.*, (2003) for the EEA includes 49 indicators in nine different categories. Other indicator suites are less comprehensive and have not been included. For example, the Province of New Brunswick uses 12 indicators and NASA uses five. Germany has developed a more integrated suite of indicators that links impact and response (adaptation) indicators, which is described in a subsequent section on Integrated Indicator Suites.

Table 2: Climate Change Indicators and Climate Impact Indicators

Key: i) * means too many indicators to list in a section; ii) N means indicator is based on narrative data)

U.S. Environmental Protection Agency (EPA, 2012)	Province of B.C. Climate Change Indicators (MWLAP, 2002)	California Environmental Protection Agency (Kadir et al., 2013)	U.K. Department for Environment, Food and Rural Affairs (DEFRA, 2003)
Greenhouse Gas Indicators • U.S. greenhouse gas emissions • Global greenhouse gas emissions • Atmospheric concentrations of greenhouse gases • Climate forcing (how substances such as greenhouse gases affect the amount of energy absorbed by the atmosphere) *Weather and Climate* • U.S. and global temperature • High and low temperatures • U.S. and global precipitation • Heavy precipitation • Drought • Tropical cyclone activity *Oceans* • Ocean heat • Sea surface temperature • Sea level • Ocean acidity *Snow and Ice* • Arctic sea ice • Glaciers • Lake ice • Snowfall • Snow cover • Snowpack *Society and Ecosystems* • Streamflow • Ragweed pollen season • Length of growing season • Leaf and bloom dates • Bird wintering ranges • Heat-related deaths	*Climate Change Drivers* • Average temperature • Maximum and minimum temperature • Precipitation • Snow (measured as snow water equivalent – the weight of water in a column of snow and snow depth) *Climate Change and Freshwater Ecosystems* • Glaciers (glacier retreat) • Freezing and thawing (date of first lake and river ice melt) • Timing and volume of river ice • River temperature • Salmon in the river (migration success at certain locations) (N) *Climate Change and Marine Ecosystems* • Sea level • Sea surface temperature • Salmon at sea (N) • Seabird survival (N) *Climate Change and Terrestrial Ecosystems* • Growing degree days • Mountain pine beetle range (N) *Climate Change and Human Communities* • Heating and cooling requirements • Human health (N)	*Climate Change Drivers (Pressures)* • Greenhouse gas emissions • Atmospheric greenhouse gas concentrations • Atmospheric black carbon concentrations • Acidification of coastal waters *Changes in Climate (State)* • Annual air temperature • Extreme heat events • Winter chill • Freezing level elevation • Annual precipitation *Impacts on Physical Systems (Effects)* • Annual Sierra Nevada snowmelt runoff • Snow-water content • Glacier change • Sea level rise • Lake water temperature • Delta water temperature • Coastal ocean temperature • Oxygen concentrations in the California current *Impacts on Biological Systems (Effects)** On humans • Mosquito-borne diseases • Heat-related mortality and morbidity • Exposure to urban heat islands On vegetation • Tree mortality • Large wildfires • Subalpine forest density • Vegetation distribution shifts On animals • Migratory bird arrivals • Small mammal range shifts	*Climate, Hydrology, Sea Level and Air Pollution* • Air temperature in central England • Seasonality of precipitation • Precipitation gradient across U.K. • Predominance of westerly weather • Dry and wet soil conditions • River flows in N.W. and S.E. Britain • Frequency of low and high river flows • Groundwater storage in the chalk • Sea level rise • Risk of tidal flooding in London • Atmospheric ozone levels in summer *Insurance, Energy, Tourism and Fire* • Domestic property insurance claims • Supply of gas to households • Domestic holiday tourism • Scottish skiing industry (# passes) • Number of outdoor fires *Health* • Incidence of Lyme disease in humans • Seasonal pattern of human mortality *Agriculture and Forestry** • Use of irrigation water for agriculture • Proportion of potato crop area irrigated • Warm weather crops: grapes • Date of leaf emergence in spring • Health of beech trees *Insects and Birds** • Date of insect appearance and activity • Insect abundance • Arrival date of swallow • Egg-laying dates of birds *Marine and Freshwaters* • Marine plankton • Appearance of ice on Lake Windermere

European Environment Agency (Füssel et al., 2013)	European Environment Agency (Füssel et al., 2013) (CONT)	Canadian Council of Ministers of the Environment (CCME, 2003)	European Topic Centre on Air and Climate Change (Erhard et al., 2003)
Changes in the Climate System Key Climate Variables • Global & European mean temperature • Temperature extremes • Mean precipitation & precipitation extremes • Storms *Cryosphere* • Snow cover • Greenland ice sheet • Glaciers • Permafrost • Arctic and Baltic sea ice • Lake and river ice *Climate impacts on environmental system* Oceans and marine environment* • Ocean acidification • Ocean heat content • Sea surface temperature • Distribution of marine species Coastal zones • Global and European sea-level rise • Storm surges Freshwater quantity and quality • Mean river flow • River floods • River flow droughts • Water temperature of rivers and lakes • Lake and river ice Terrestrial ecosystems and biodiversity* • Plant and fungi phenology • Animal phenology • Distribution of plant species • Distribution/abundance of animal species Soil • Soil organic carbon • Soil erosion • Soil moisture	*Climate Impacts on Socio-Economic Systems and Health* Agriculture • Growing season for agricultural crops • Agrophenology • Water-limited crop productivity • Water requirement for irrigation Forests and forestry • Forest growth • Forest fires Fisheries and aquaculture • Fisheries and aquaculture (N) Human health • Floods and health (coastal and river) • Extreme temperatures and health • Air pollution by ozone and health • Vector-borne diseases (Some N) Energy • Heating degree days Transport services and infrastructure • Transport services and infrastructure (N) Tourism • Tourism (N) Damage costs • Direct losses from weather disasters	*Canada's Changing Climate* • Temperature • Highs and lows • Precipitation • Snow and rain • Sea surface temperature *Nature* • Sea level rise • Sea ice • River and lake ice • Glaciers • Polar bears • Plant development *People* • Traditional ways of life • Drought • Great Lakes-St. Lawrence water levels • Frost and frost-free season • Heating and cooling • Extreme weather	*Climate and Atmosphere** • Temperature and precipitation • Atmospheric CO_2 & other GHG concentrations • Storms Lightning frequency *Cryosphere** • Mountain glaciers • Snow cover • Lake ice, river ice & Baltic sea ice • Permafrost • Soils and Land Resources • Net Carbon Uptake • Soil Moisture Availability *Agriculture and Forestry** • Crop suitability • Forest growth • Shifts in the tree line • Pests and diseases *Ecosystems and Biodiversity** • Growing season • Changes in species behavioural patterns • Changes in ecosystem composition/ biodiversity • Ecosystem fires *Hydrology and Water Resources** • Global and regional annual river discharges • Lake temperatures • Frequency of low and high river flows *Marine Environment and Coastal Zones** • Sea surface temperatures • Sea level rise *Economy and Infrastructure** • Energy consumption for space heating • Tourism/number of skiing tourists • Sales of seasonal products *Human Health** • Distribution of vector-borne diseases • Death attributable to heat

For comparison, Table 3 presents the CACCI model for thinking about climate change as outlined in *From Dialogue to Action* (CBT, 2012). The items listed are not indicators per se, rather areas in which CACCI has collected data in the past. Nevertheless, there is a fair degree of consistency between the CACCI model and some existing climate change indicator suites.

Table 3: CACCI Schemata for considering climate changes and impacts

CACCI Model from Dialogue to Action (CBT, 2012)
Climate Changes • Average annual temperature • Very hot days • Warm spells • Growing-degree days • Growing season length • Heating-degree days • Summer and winter precipitation • Rain and snow at low elevations • Extreme precipitation events • Variability of temperature and precipitation *Impacts on the Environment* • Glacial runoff • Lake water temperatures • Streamflows • Freeze/thaw cycles • Rain-on-snow and rain-on-frozen-ground events • Timing and scale of flooding • Droughts • Diseases and pathogens • Frequency and severity of wildfires • Landslide and avalanche frequency • Biodiversity risks

Challenges in Measuring Climate Change and Climate Impacts

Using indicators to measure climate change and climate impacts creates a range of challenges. Some challenges are the same as those that arise with using indicators to measure climate change vulnerability and climate adaptation, including long timeframes, challenges in attribution and lack of resources. These challenges will be outlined in more detail in the section on climate adaptation indicators.

The best data with the longest data series are generally available for climate change indicators and some climate impact indicators related to ecosystems (Füssel *et al.*, 2013). Yet for many indicators the historical data series are short (Füssel *et al.*, 2013). Moreover, in the area of socio-economic systems and health, there are issues related to data availability, the adequacy of data models and attribution to climate change (Füssel *et al.*, 2013). There may be lots of data but it is not assembled in a standard form over large areas (Füssel *et al.*, 2013).

Due to challenges in data collection, modeling and attribution, some organizations will use more narrative data for their indicators, which stretches the common definition of an indicator. Other organizations choose not to include certain indicators in their indicator suites. For example, the

EEA does not include indicators for climate impacts on industry and manufacturing, insurance, most infrastructure, livestock production, cultural heritage and migration of people due to lack of data, challenges in quantifying, and difficulty linking changes in these factors to climate change (Füssel *et al.*, 2013).

The challenges associated with data collection and modeling linked to climate change indicators underscore the importance of providing an adequate explanation of uncertainty when presenting climate change indicators (Füssel *et al.*, 2013).

Key Lessons

Given the range of different potential needs, scales of measurement and regional differences, it is unlikely that any one set of climate change indicators and climate impact indicators will be universally applicable. However, there are a significant number of comprehensive climate change and climate change impact indicator suites available worldwide. While they range dramatically in the number of indicators they incorporate, they can provide a useful starting point for indicator suite development or refinement.

Vulnerability Indicators

Vulnerability indicators are generally at an earlier stage of development than climate change indicators, climate impact indicators and climate adaptation indicators. Moreover, there are additional challenges in developing vulnerability indicators that are less applicable to the other types of indicators addressed in this paper. In 2008, Harley *et al.*, (2008) stressed that there are not any widely accepted and usable vulnerability indicators. Although additional work has occurred since then, vulnerability indicators remain at incipient stages of development. Yet, according to Schauser *et al.*, (2010), a small number of vulnerability indicators are in use in the U.S., U.K. and Australia.

This section outlines what vulnerability indicators are, provides an overview of their uses, outlines the broad types of vulnerability indicators, discusses the challenges of measuring vulnerability, provides proposed approaches to developing vulnerability indicators and finally, offers examples of vulnerability indicators currently in use.

Definition of Vulnerability and Vulnerability Indicators

The first step in developing vulnerability indicators is defining vulnerability. All of the papers on vulnerability indicators consulted for this literature review (Harley *et al.*, 2008:10; CESR, 2010; Schauser *et al.*, 2010; EEA, 2012; Miller *et al.*, 2013) define vulnerability in accordance with the International Panel on Climate Change (IPCC) definition in which vulnerability is defined as the extent to which a system (such as a region, community, species, component of infrastructure, economic sector or group of people) is “susceptible and unable to cope with the adverse effects of climate change, including climate variability and extremes.” Vulnerability is a function of three core factors:

1. The character, magnitude and rate of change of climate change impacts to which the system is exposed (exposure);

2. The sensitivity of the system (degree to which a system could be affected adversely or beneficially by climate change), and
3. The adaptive capacity of a system (the ability of a system to adjust to climate change, to moderate potential damages, to take advantage of opportunities or to cope with the consequences).

However, Schauser *et al.*, (2010) point out that while many organizations use the IPCC definition as a starting point, this definition has limitations and is difficult to operationalize because the precise relationship among the three components is not defined, the terms are not always accurately defined and there is considerable overlap between adaptive capacity and sensitivity. In particular, there is considerable debate with regard to what constitutes adaptive capacity (Schauser *et al.*, 2010). It is important to note that some vulnerability indicator researchers refer to sensitivity as susceptibility and adaptive capacity as resilience, and define vulnerability as an exposure-susceptibility-resilience construct (Balica *et al.*, 2011).

Vulnerability indicators are essentially quantitative measures of relative vulnerability, of populations, ecosystems, regions, economic sectors or nations (Eriksen and Kelly, 2007).

Uses for Vulnerability Indicators

Vulnerability indicators may be most useful in a) identifying particularly threatened regions, communities, species, economic sectors or infrastructure, b) raising awareness, and c) creating a list of priority areas for adaptation and/or to develop and implement measures to reduce risk (Harley et a*l., 20*08).

They are intended to help compare relative vulnerability of one place, group, system or sector to another (Eriksen and Kelly, 2007). They could, potentially, be used to influence funding allocation for climate adaptation, with greater funding going to more vulnerable areas, sectors or groups (Schauser *et al., 201*0). Vulnerability indicators may also be used to measure progress towards reducing vulnerability (Schauser *et al., 201*0) and could help in understanding factors that contribute to vulnerability, thereby improving our ability to develop adaptation measures (Eriksen and Kelly, 2007).

Vulnerability indicators may also be essential in defining a baseline against which the other indicators are measured. For example, the number of municipalities adopting climate change plans—a potential process adaptation indicator (as outlined below)—may only be relevant in comparison with the number municipalities vulnerable to climate change (Lamhauge *et al.*, 2011). Thus vulnerability indicators may be helpful in measuring the effectiveness of adaptation (Schauser *et al.*, 2010), and used as a type of adaptation indicator because decreased vulnerability is often viewed as a reflection of successful adaptation. The World Bank Group proposes using only indicators of vulnerability, exposure and adaptive capacity as a means of evaluating adaptation-related outcomes and impacts (IEG, nd).

Broad types of Vulnerability Indicators

There are three broad types of vulnerability indicators:

Global/National Indices

The first approach is to develop general global or national scale vulnerability indices — such as the vulnerability-resilience index, or the Index of Human Insecurity, the GAIN index or the Global Distribution of Vulnerability Index (Glass, 2013; Miller *et al.*, 2013). These indices generally incorporate a wide variety of indicators (up to fifty), such as water resources per capita, energy imports as a percentage of consumption, food import dependency, implementation capacity and human and civic resources (Miller *et al.*, 2013). They are then weighted and aggregated in some way, and an overall rating or index of vulnerability (generally on a country basis) is developed.

Specific/Local Indicators

A second approach is to develop sector-specific and local vulnerability indicators (Schauser *et al.*, 2010; Miller *et al.*, 2013). Some of these indicators are based on the aggregation of exposure, sensitivity and adaptive capacity sub-indicators, while others are presented as more of an indicator suite, without aggregation of the data. For example, vulnerability indicators have been developed for urban areas for heat waves, fluvial floods, wildfires, water scarcity, urban drainage floods and sea level-rise on a national or regional level (Schauser *et al.*, 2010). Miller *et al.*, (2013) examined vulnerability indicator suites developed for specific areas, for agriculture, water resources, forestry and coastal zones.

Sub-Indexes

A third approach focuses on separating the social, economic and physical aspects of vulnerability and developing different indices or sub-indexes for each that can be presented in a series of overlays to provide a more composite view of vulnerability. Cutter *et al.*, (2003) developed the Social Vulnerability Index that considers 42 socio-economic variables (e.g. age, race, ethnicity, education, family structure and so on) reduced to a single index that can be used with biophysical assessments of vulnerability. Wongbusarakum and Loper (2011) also focused only on social vulnerability and identified ten indicators — one of exposure, one of sensitivity and eight of adaptive capacity (e.g. current household livelihood and income diversity, awareness of household vulnerability to climate hazards) to determine whether certain communities or groups are vulnerable to climate change — for use with other indicators of vulnerability. Sometimes these sub-indexes are developed jointly as in the case of a multi-scale coastal vulnerability index that includes a coastal characteristics sub-index, a coastal forcing sub-index and a socio-economic sub-index (Balica *et al.*, 2011).

Challenges in Measuring Vulnerability

Despite the potential uses of vulnerability indicators, vulnerability is particularly hard to measure because it is dynamic and related to a large number of environmental, social, economic and political factors (Harley *et al.*, 2008). Developing vulnerability indicators can be a challenge because vulnerability is more of a conceptual construct than other types of climate change indicators (Schauser *et al.*, 2010; Miller *et al.*, 2013). Vulnerability indicators must somehow incorporate approaches to defining and measuring exposure, adaptive capacity and sensitivity, which are also conceptual constructs. This is problematic from a variety of perspectives, as discussed below.

Data Challenges

Historical, projected or even current data is rarely available for adaptive capacity or sensitivity (Schauser *et al.*, 2010). As a result, proxy data is generally required and, generally speaking, a single type of proxy data is insufficient. Thus, sub-indicators or inputs, such as gross domestic product, technological resources, distribution of resources, human and social capital, GDP, employment ratio, access to risk-spreading options (e.g. insurance) and environmental capacity are often utilized (Harley *et al.*, 2008). The data for some sub-indicators may be unavailable, unsound and generally static, and the relationship between this generic information and sensitivity and adaptive capacity has often not been clearly demonstrated in the literature (Eriksen and Kelly, 2007; Schauser *et al.*, 2010). CESR (2010) observed that because of the lack of data, quantification was possible only for a very small number of the vulnerability indicators that it would have liked to utilize for water resources.

Schauser *et al.*, (2010) examined vulnerability indicators developed for urban areas addressing heat waves, fluvial floods, wildfires, water scarcity, urban drainage, floods and sea level-rise on a national or regional level, and found that the existing indicators are often missing data for at least one, and sometimes two, of the three components of vulnerability: exposure, adaptive capacity and/or sensitivity (Schauser *et al.*, 2010). For example, according to Schauser *et al.*, (2010), many organizations have developed indicators for health problems associated with higher temperatures and heat waves. While all of these indicators are strong on the exposure front (i.e. tracking or forecasting a particular type of weather over a particular time frame), and can be strong on the sensitivity front (i.e. identifying particular groups or areas at risk), they struggle on the adaptive capacity front. Even on the sensitivity front, there are challenges. Data for some aspects of sensitivity is often hard to find and, if available, it is often very general or focused only on the biophysical aspects of sensitivity. For example, in a survey of coastal vulnerability indices, Balica *et al.*, (2011) found that while many considered physical vulnerability, only more complex indices considered economic and social vulnerability. If the indicator or index considers vulnerable populations at all, vulnerable population groups are often defined as those who are elderly, disabled, single parent households, minorities or low income. Although these are generally accepted components of social vulnerability, there is no clear evidence in the literature that these particular groups are particularly vulnerable to the specific climate impacts under consideration, and there are many disagreements with regard to the selection of specific indicators to represent these broader concepts (Schauser *et al.*, 2010; Fischer *et al.*, 2013).

Aggregation Difficulties

Sub-indicator data is best aggregated using a logically sound approach, yet there are currently no accepted methodological approaches for doing so (Schauser *et al.*, 2010). Aggregation of the independent sub-indicators is done in a multitude of different ways. Generally the data is normalized to summable or comparable units (e.g. percentages, per capita or density functions), which may then be weighted (often by experts) and added or multiplied to develop a weighted average score (Schauser *et al.*, 2010; Balica *et al.*, 2011). Other times component analysis is utilized to reduce the number of sub-indicators to a smaller number of independent components that account for the majority of the variance, which are then added with equal weights to produce a summary score (Schauser *et al.*, 2010). Some researchers favour weighting, while others do not, claiming that it can distort the data and hide assumptions (Balica *et al.*, 2011). Similarly, Adger (2004) argued that construction of composite indexes by averaging may not be the best approach and favours a scoring approach within categories or the use of disaggregated indices.

An example is the GAIN index, which aggregates 14 indicators of readiness for each country, such as rule of law and political stability, and 36 indicators of vulnerability such as number of threatened species, dependency on natural resources and maternal mortality rates (Glass, 2013). The vulnerability score is then subtracted from the readiness score (Glass, 2013).

Beckmann (2012) presented an approach to developing an index of adaptive capacity that involves *three* levels of aggregation: the first from an array of indicators, including GDP per capita and number of doctors, to produce six determinants of adaptive capacity — equity, knowledge, technology, infrastructure, flexibility and economic power, to a second level of aggregation to produce three components of adaptive capacity — awareness, ability and action, to a third level of aggregation of a single index of adaptive capacity.

The number of assumptions and amount of data required for these types of indices is significant, and the chances of error increase with the degree of complexity and aggregation. The issue of aggregation is further complicated when data aggregation methods are left unspecified, which makes validation and replication very challenging (Schauser *et al.*, 2010). A number of the indices examined for this review did not describe their data aggregation methods.

Challenging Language

The language of vulnerability indicators can be difficult, both in reference to exposure, sensitivity and adaptive capacity, and in how individual indicators are described. Indicators that are aggregated composites of many sub-indicators are often called indices, indexes or sometimes sub-indexes (if they are a component of a larger index). Indicators used as inputs into larger indicators or indices can be called indicators, sub-indicators, factors or variables.

Overall, there are serious conceptual, methodological, data and application gaps that affect vulnerability indicator development (Schauser *et al.*, 2010). The lack of a clear conceptual framework for the selection of indicators has hampered previous efforts (Eriksen and Kelly, 2007). Global or national scale vulnerability indices have been criticized for their conceptual, methodological and empirical flaws and are not considered to be useful as benchmarks of international climate policy (Miller *et al.*, 2013). In addition, these indices cannot account for localized variability in geography, economics or vulnerable populations (Glass, 2013). Indeed, as Miller *et al.*, (2013) report, due to the complexity of the vulnerability concept, even accepted methods for vulnerability assessment (without the use of indicators) have been slow to develop.

Moving Forward

To facilitate vulnerability indicator development, researchers, such as Schauser *et al.*, (2010) and Miller *et al.*, (2013) and Balica *et al.*, (2011), have attempted to address key challenges by narrowing and defining the focus. All three suggest focusing on more specific and localized indicators. Miller *et al.*, (2013) argued that focusing on local sector-specific indicators is essential due to the heterogeneity of the biophysical environment and socio-economic context that determine vulnerability. These indicators may be presented as either aggregates of many sub-indicators or as a disaggregated collection of exposure, sensitivity and adaptive capacity indicators relating to one topic.

Schauser *et al.*, (2010) proposed a wide array of possible approaches to further operationalizing the vulnerability construct by:

- Focusing only on vulnerable human populations, and potentially focusing on human health only (rather than on economic or ecological damages);
- Clarifying the scale for which the indicator is being developed (relates to the purpose of the indicator);
- Concentrating primarily on exposure and sensitivity, for which better data is available;
- Breaking sensitivity into spatial (where will the impact be), bio-physical (what land or infrastructure is sensitive) and social (what populations are sensitive) sensitivity; and,
- Keeping aggregation methodology as simple and transparent as possible, including the use of stepwise and intermediate levels of aggregation, so results can easily be understood and analyzed.

Balica *et al.*, (2011) echoed this need to be focused and stressed that while it is tempting to use all available data in the development of an index, sub-indicators or variables are often highly correlated with each other and it is sometimes more appropriate to focus on fewer sub-indicators.

Miller *et al.*, (2013) proposed that vulnerability assessment requires a dynamic point of view—that static proxy variables such as annual GDP (often used in the global vulnerability indices) are often insufficient because they do not account for changing adaptive capacity over a period of time due to changes in perception, knowledge and experiences.

Fischer *et al.*, (2013) provide a helpful schemata by suggesting that the following questions be asked in association with each component of vulnerability:

> *Exposure*: What environmental changes or events associated with climate change may adversely affect resources that human communities rely on or derive value from? Which human communities rely on or derive value from resources that are likely to be affected? (e.g. chance of increased flooding due to severe storms, chance of longer more intense wildfire season due

to increased temperature, loss of commercially valuable species due to a shift in vegetative communities).

Sensitivity: How many climate-related changes in local resources affect human communities' use of those resources and vice versa? Which segments of human communities will be disproportionately affected and why? (e.g. is there economic reliance on biophysical conditions that could change, is there cultural reliance on certain species or landscapes, are there ways of living that leave certain groups exposed to climate impacts, is the economy diversified)

Adaptive Capacity: What capabilities do human communities have for adapting and mitigating climate change-related impacts? What opportunities exist for human communities to learn to become more capable of adapting? (e.g. availability and distribution of resources, ability to apply, generate and apply new knowledge, ability to make decisions and act collectively).

Approaches to Developing Indicators

This section provides examples of approaches to developing local and specific vulnerability indicators. It highlights the types of information inputs that could be required and the complexity of trying to measure vulnerability through the use of indicators. Schauser *et al.*, (2010) and Miller *et al.*, (2013) differ in their approach to categorizing potential vulnerability indicators. Schauser *et al.*, (2010) classifies them based on climate impact, while Miller *et al.*, (2013) classify them based on sector. Table 4 outlines their approaches to classifying potential vulnerability indicators.

Table 4: Vulnerability Indicator Classification Approaches

Schauser *et al.*, (2010)	**Miller *et al.*, (2013)**
• Higher temperatures, heat wave and health problems • Decreased precipitation, water scarcity and drought • Wildfires • Heavy precipitation and fluvial floods • Intensive precipitation and urban drainage • Sea level-rise and storm-surge driven flooding • Saltwater intrusion into aquifers • Mass movements and erosion • Wind storms • Vector-borne diseases	• Agriculture • Coastal zones • Water supply • Forests

Schauser *et al.*, (2010) observed that little research has been done for some categories of indicators, including water scarcity and drought, urban drainage, and wildfires. For others, more research has been undertaken, yet serious limitations remain. For example, in the case of heavy precipitation and fluvial floods, current indicator efforts focus on identifying vulnerable groups or geographical components to identify vulnerable building structures, and there is a fair bit of information available on exposure and sensitivity (Schauser *et al.*, 2010). Likewise, some work has been done with regard to sea level rise and storm surge-driven flooding, but the proposed indicators focus primarily on geomorphological and biophysical characteristics, while only a few consider socio-economic factors—mostly coastal population density (Schauser *et al.*, 2010).

Schauser *et al.*, (2010) outline their approach to developing indicators in Table 5, which shows the components of a vulnerability indicator for heat waves. This methodology illustrates their suggested approach of dividing up sensitivity (and adaptive capacity) based on spatial information, biophysical information and social information.

Table 5: Vulnerability Indicator for Heat Waves

	Exposure	**Sensitivity**		
	Climatic Information	**Spatial Information**	**Bio-physical Information**	**Social Information**
Generic	• Max summer temperature	• Urban areas	• Residential areas	• Population density
Specific	• Heat days • Tropical nights	• Impervious area	• Location of hot-spots (hospitals, old-age homes) • Condition and age of dwellings	• Population above 65 years (and living alone) • Population with renal sickness • Population working outside
Adaptive Capacity:				
Generic			• Blue green areas	• GDP • Access to information via Internet
Specific				• Household income • Access to air conditioning • Installation of cooling centres

Based on research of information important to assessing vulnerability in agriculture on a local scale, Miller *et al.*, (2013) developed the following schemata (Table 6) showing the potential inputs or indicators required to illustrate this vulnerability. Note the large number of components being measured. Since the schemata refers to the individual components as indicators, they are likely intended to be presented in disaggregate form.

Table 6: Summary of Possible Local Vulnerability Indicators in Agricultural Sectors

Components	Possible indicators	
Exposure	Precipitation variability Temperature variability Extreme events (drought, flood, cyclone)	
Sensitivity	Coastal farm	Salt water intrusion and destruction of farm land (low lying farm areas; coastal spring destruction and diseases)
	Small, rural agrarian communities	Mangrove habitats/wet tropic
	Population	Vulnerable age of population
Adaptive capacity	Economic	Dependency on rain-fed agriculture or resources Income, non-agricultural income Nominal income, real wage, real expenditure, medical expenditure, disposable income Domestic price and world price (or openness) Physical assets (animals, vehicles, machines, house and land) Diversification of occupation and crops Immigration option
	Social	Community network Collective action (religion-based activities observed from marriage to funerals)
	Infrastructure	Buildings and road Access to water Irrigation system Public health Transportation system
	Individual knowledge	Awareness of climate-driven risk based on past threats Level of education/cost of education
	Institutional	Government social interventions (education, policy, credit for low-income farmers, immigration policy)

CESR (2010) took a different approach when developing suites of potential vulnerability indicators for water resources. It argued that exposure indicators are not dependent on socio-economic factors and therefore could be developed more generally for a certain topic or climate impact, while indicators for the other components of vulnerability (sensitivity and adaptive capacity) would differ for each economic sector, location and user group. CESR's construct for vulnerability to water scarcity is outlined in Table 7. Note that CESR (2010) also incorporated impact indicators and an overall measure of vulnerability into their vulnerability indicator suite.

Table 7: Indicators for Water Scarcity

Component	Possible Indicators
Exposure to water scarcity is the degree to which a system is exposed to available long-term average water quantity.	Average precipitation, average river discharge, average soil moisture, groundwater level
Sensitivity to water scarcity is determined by the influence of the stress factor (e.g. climate change) on the functioning of the system. In some basins a reduction of 10 per cent rainfall results in a 30 per cent reduction in water availability while in other basins, reduction in rainfall only has a marginal impact on stream flow. Indicators for sensitivity relate to both supply and demand of water. Systems where water demand is high are more sensitive to water scarcity than systems where water demand is low.	Change in water demand in the future, compared to some base period. This demand could be further disaggregated according to different users and sectors: domestic, agriculture, industry, energy production, tourism
Impacts of water scarcity. Occurs when availability exceeds water demand. The difference between long-term water supply and water demand will result in a water "gap", which will negatively influence socio-ecological systems. These influences we will label (potential) "impacts".	Loss of industrial and agricultural production, of jobs, income and livelihoods; desertification and land degradation
Adaptive capacity to water scarcity is determined by the ability/possibility of regions or sectors to close the gap between water demand and supply. It could be achieved by enhancing the societal ability to increase water supply, decreasing water demand or some combination of both. Adaptive capacity is a very challenging concept and difficult to make operational as indicator. Therefore we will adapt a more practical approach, looking at the capacity to implement measures necessary for the reduction of the identified vulnerability, and at cultural, technological, financial and institutional barriers that hamper this implementation.	No indicators
Vulnerability to water scarcity is determined by the gap between water supply and demand and is expressed as a per cent change of current and expected future water (in-)sufficiency in comparison with a baseline.	Water Stress (measured as the ratio of total water availability to total water withdrawals); Water Exploitation Index (calculated as the mean annual total demand for freshwater divided by the long-term average freshwater resources); Falkenmark Index (measures renewable water recourses per capita)

Actual Indicators

Some examples of current vulnerability indicators and approaches to managing the three components of vulnerability are provided below. These examples from Schauser *et al.*, (2010) highlight the different approaches and data utilized to measure the same type of vulnerability, the data gaps that exist for each indicator and the amount of data that has to be analyzed and aggregated to generate a single result for an indicator.

Heat Vulnerability Indicators

Two examples of heat vulnerability indicators are provided to highlight the different types of information that could be utilized to measure the same indicator.

1) Cumulative Heat Vulnerability Index (U.S.)
    a. *Scale:* national
    b. *Exposure data:* none
    c. *Sensitivity data:* race, age greater than or equal to 65, living alone and aged greater than or equal to 65, diabetes, area without vegetation

    d. *Adaptive capacity data:* poor, education level, living alone, without central or any air conditioning

*Aggregated using principal component analysis

2) Heat-related Risk Assessment (Manchester, England)
    a. *Scale:* city
    b. *Exposure data:* daily maximum and minimum temperatures
    c. *Sensitivity data:* urban morphology types, age greater than 75, age younger than 4, population health, residence dependency
    d. *Adaptive capacity data:* none

*Normalized in classes, aggregated by unweighted addition

Wildfire Indicator

1) Vulnerability indicators for bush fire (Sydney)
    a. *Scale:* unclear
    b. *Exposure data:* present January maximum temperature, present days >30 C, annual rainfall average and 10th percentile, change in average DJF (December-January-February), maximum temperature, rainfall in 2030
    c. *Sensitivity data:* land use, vegetation cover, primary production, slope, aspect, population, road density
    d. *Adaptive capacity data:* internet access, home loan, home ownership, household income, council expenses, >12 years education, non-English speaker

*Aggregation by summation of components values for each element, scoring, weighting based on expert values and summation of the elements values for each vulnerability indicator (number of indicators is unspecified).

Schauser *et al.*, (2010) provided many more examples of indicators currently in use—and the data inputs associated with them—for water scarcity and drought, floods, urban drainage, saltwater intrusion into aquifers, mass movements, wind storms and vector-borne diseases.

Flood Vulnerability Index

The coastal city flood vulnerability index developed by Balica *et al.*, (2011) further highlights the complexity of vulnerability indicators. This index consists of four components reflecting the four different systems at play in determining vulnerability: i) a hydro-geological component (which reflects the physical system), ii) a social component, iii) an economic component (which together reflect the socio-economic system), and iv) a politico-administrative component (which reflects the institutional system). The index is outlined in Table 8. Balica *et al.*, (2011) used this index to calculate the vulnerability of several coastal cities around the world. Quantitative results were aggregated by component and then the component results were aggregated to produce a total relative rating of vulnerability for each city. Note that Balica *et al.*, (2011) replace sensitivity with susceptibility and adaptive capacity with resilience.

Table 8: Flood Vulnerability Components and Factors

	Vulnerability Factors		
Coastal flood vulnerability components	**Exposure**	**Susceptibility**	**Resilience**
Hydro-geological	Sea-level rise (how much increase in one year) Storm surge (rapid rise in water level) Number of cyclones in last 10 years River discharge (maximum discharge in last ten years) Foreshore slope (average slope of foreshore beach) Soil subsidence (how much the area is decreasing) Km of coastline along city	-	-
Social	Population close to coastline (number of people exposed to hazard) Cultural heritage (number of historical buildings, museums in danger)	Per cent of disabled persons (per cent of population with any kind of disability and people less than 12 or over 65)	Shelters (Number of shelters per km^2 including hospitals) Awareness and preparedness (are people aware and prepared; have they experienced a flood in the last 10 years)
Economic	Growing coastal population (per cent growth in last ten years)	-	Km of drainage (km of canalization in city) Recovery time (amount of time needed by city to recover to functional operation after flood)
Politico-administrative	Uncontrolled planning zones (per cent of surrounding coastal area 10 km from shoreline that is uncontrolled)	Flood hazard maps (existence)	Institutional organizations (existence of institutional organizations) Flood protection (existence of structures to prevent flooding including storage capacity and berms)

Perception-Based Vulnerability Indicators

Finally, a simpler approach to assessing vulnerability could be considered. Under the UNDP Vulnerability Reduction Assessment process, vulnerability is measured based on community perceptions of vulnerability and capacity to adapt. Local people are asked four questions on vulnerabilities associated with locally relevant issues in a survey administered during a community meeting. The survey is administered several times over a certain period to provide an indication of relative changes in vulnerability, usually as part of a climate adaptation project (Crane Droesch, 2008).

Other Indicators

Indicators with potential applicability to measuring vulnerability have been developed in other fields of study such as disaster management or development. Examples include the UNDP Disaster Risk Index and the Disaster Deficit Index (Sanahuja, 2011). These indicators, and the data aggregation methods used by these indices, could have some relevance for measuring vulnerability to climate change.

Key Lessons

Most vulnerability indicators are composite indicators and the complex nature of the vulnerability construct makes development of these indicators highly challenging. Although some vulnerability indicators are beginning to be developed and used in various jurisdictions around the world, they are not a simple undertaking. The methodological uncertainties associated with aggregation are significant and require a large number of value judgments. Ultimately there may be value in considering disaggregated measures of vulnerability based on consultative, stakeholder-driven processes, rather than technical analysis resulting in a single number or ranking (Sanahuja, 2011).

Considerable overlap exists between vulnerability indicators and adaptation indicators, and some organizations are focusing on vulnerability as a means of assessing adaptation success where reduced vulnerability = successful adaptation. Sanahuja (2011) argued that vulnerability and resilience are just two different sides of the same coin. If the aim of adaptation is to achieve resilience, then decreased vulnerability is a marker of success.

Climate Adaptation Indicators

As with vulnerability indicators, climate adaptation indicators are still in early stages of development. Many countries include monitoring and evaluation as an integral part of the adaptation cycle, and are increasingly acknowledging the need to develop indicators as part of this monitoring and evaluation (UNFCC Secretariat, 2010). Nonetheless, a few comprehensive adaptation indicator suites are currently available. Because the development of adaptation indicators is in its infancy, there is limited experience or consensus on good practice in other jurisdictions from which to draw (Harley *et al.*, 2008). Ford *et al.*, (2013) observed that very little research has focused on how to monitor and evaluate adaptation, and GIZ (a German organization for International Cooperation) (2013) observed that there is currently no one way to approach monitoring and evaluation of adaptation.

Many countries are beginning to address the development of adaptation indicators. The U.S., Kenya, Morocco, Tunisia, Northern Ireland, Wales and Scotland have all identified the need to develop adaptation indicators or are in the process of doing so (Sniffer, 2012; Buizer *et al.*, 2013; GIZ, 2013). Most of these countries are in early stages of either creating an indicator development process or establishing draft indicators. Germany, Finland, the Philippines and the U.K. are considered to be among the furthest along in adaptation indicator development (UNFCC Secretariat, 2010; GIZ, 2013). Germany, for example, is developing adaptation indicators to reflect its Adaptation Strategy, but is not expected to complete the project until 2014 (EEA, 2012). It has selected an indicator development system and a structure for its indicators, and is in the process of selecting indicators (GIZ, 2013). The U.K. has developed a set of basic process adaptation indicators and draft adaptation indicators. The Philippines incorporated a small number of adaptation indicators into its National Climate Change Action Plan and has plans to develop more (CCC, 2012; GIZ, 2013). Finland has a very basic set of process indicators (UNFCC Secretariat, 2010).

Unlike vulnerability indicators, which range in scale from national to very local, and climate change and climate impact indicators, which have been developed on multiple scales, most of the experience of developing adaptation indicators is at the national level. Many in the adaptation field believe this is the scale at which adaptation actions are best developed and delivered.

It is likely there will be some overlap between climate impact indicators and climate adaptation indicators and that some climate impact indicators may be useful in measuring climate adaptation. However there may be problems of attribution when using some of the climate impact indicators to measure climate adaptation, so a separate set of climate adaptation indicators is likely necessary (Natural England, 2010).

Uses of Adaptation Indicators

This section reviews uses for adaptation indicators, types of adaptation indicators, challenges in measuring adaptation, potential approaches to moving forward with the development of indicator suites, and examples of potential indicators.

The goal of adaptation indicators is to indicate whether climate adaptation policy and adaptation measures were implemented and if these efforts were successful in reducing vulnerability (Harley and Minnen, 2009; Ford *et al.*, 2013). Harley *et al.*, (2008) list the following reasons for developing adaptation indicators:

- Targeting, justifying and monitoring adaptation funding and programs;
- Evaluating adaptation policy interventions;
- Informing future adaptation policy development;
- Comparing adaptation achievements across regions or countries;
- Communicating adaptation to the general public;
- Informing political climate change negotiations in the international arena;
- Sharing information on good practice in adaptation to climate change; and,
- Measuring progress and effectiveness of resource commitments.

The specific goals of developing indicators, (i.e. whether they are to evaluate programs, compare achievements across countries or communicate with the public), will affect the nature of the indicators selected.

Two Main Types of Adaptation Indicators

1. *Process indicators* monitor and measure:

    - Development of adaptation policies and building of adaptive capacity (Harley and Minnen, 2009; Harley and Minnen, nd); and

    - Implementation and delivery of adaptation measures (Harley *et al.*, 2008; Harley and Minnen, 2009).

Some organizations (such as the UNFCC, 2010) call process indicators output indicators. They can be further broken down into input indicators and output indicators. Input indicators refer to the amount of effort, time and money applied toward some end, and output indicators refer to the number of policies, products or events that result from the actions (Lamhauge *et al.*, 2011).

2. *Outcome indicators* measure:
    - Effectiveness of adaptation policies and actions (Harley *et al.*, 2008: Harley and Minnen, 2009)
    - Progress towards pre-defined goals (Natural England, 2010). Natural England (2010) argues that these goals should be quantified.

These indicators may be referred to as impact indicators in some publications (i.e. UNFCC, 2010, Lamhauge *et al.*, 2011), while others define outcome indicators as measuring short- to medium-term outcomes, and impact indicators as measuring long-term outcomes. Where possible, outcome indicators should be linked with relevant climate impact indicators (Harley and Minnen, 2009).

Harley and Minnen (nd) highlight the difference between process and outcome climate adaptation indicators in Table 9:

Table 9: Process versus Outcome Indicators

Sector	Building adaptive capacity: Process-based indicators
Agriculture	Research into farming techniques that accommodate climate change
Biodiversity	Integration of adaptation into conservation management plans
Health	Establishment of coordinating authorities and networks
Water	Development of flood management policies/plans
	Delivering adaptation actions: Process-based indicators
Agriculture	Introduction of drought and heat-resistant crops
Biodiversity	Extension, connection and establishment of buffer zones around protected areas
Health	Provision of climate control equipment for vulnerable people
Water	Construction of flood protection schemes
	Delivering adaptation actions: Outcome-based indicators
Agriculture	Increase in crop yields
Biodiversity	Reduction in degraded ecosystems
Health	Reduction in deaths during heat waves
Water	Reduction in losses due to floods

In practice, classifying indicators as process versus outcome indicators can be challenging as there is no clear agreement in the literature on how this classification should be approached. Some organizations would classify clearing of fuel from an interface area to reduce wildfire impact on communities as a process indicator, while others would consider it an outcome indicator. Yet others would not bother to classify it as one or the other. Sanahuja (2011) suggested it might be best to consider the indicators as being on a continuum. Rather than creating completely distinctive categories, Sanahuja (2011) proposed a continuum from progress indicators (which would include action, processes, outputs and lower outcomes) to impact indicators (which would include major changes). This continuum approach could just as easily be used for process to outcome indicators.

Since process indicators measure the planning and delivery of adaptation, they may fall somewhat short in measuring achievement of adaptation. Indeed, there is no guarantee that successful development and implementation of an adaptation policy means effective adaptation is taking place (Harley *et al.*, 2008). Process indicators tend to be less quantified (Natural England, 2010).

Since outcome indicators measure downstream effects on ecosystems and communities, it may be possible to use indicators (or data) utilized in indicator suites related more generally to sustainability. Since process indicators are linked to the development or implementation of specific adaptation policies, they are more specialized and generally must be developed and measured specifically for an adaptation program or plan. On the other hand, there are greater challenges in attribution associated with outcome indicators than with process indicators: i.e. did the change in the ecosystem, community or economic sector occur as a result of an adaptation action, or some other event or policy?

Harley *et al.*, (2008) expects a combination of process-based and outcome-based indicators will be required to measure progress towards adaptation. As climate adaptation is still in early stages, process indicators are likely to be most important in the short term, with outcome indicators becoming more relevant in the long term (Harley and Minnen, 2009). Ford *et al.*, (2013) similarly suggest process indicators may be most important in the short term given that the full extent of climate impacts may not occur for decades and data for some outcome indicators may not be available for many years.

Process and outcome indicators can be further broken down into:

- General indicators focused on general broad-scale adaptation action such as the development of a national climate adaptation plan;
- Sector-specific indicators focused on performance within a particular sector; and
- Crosscutting or headline indicators measuring action in more than one sector or on more than one level (Beckmann, 2012).

Challenges in Measuring Climate Adaptation

Measuring climate adaptation through the use of indicators is very complex and there are numerous challenges as detailed below,

The timeframe, uncertainty and reverse logic of adaptation

Adaptation is expected to occur over long time scales, and changes in some potential indicators may therefore occur very slowly (Prowse and Snilstveit, 2009; UNFCC, 2010). Timelines for climate change may require commitments to collecting indicator data over 20 to 50 years or more (Lamhauge *et al.*, 2011). The success of adaptation may not be known for years (Ford *et al.*, 2013). There is also uncertainty regarding expected climate impacts and, consequently, uncertainty with regard to how much adaptation is enough (Natural England, 2010) and in what direction adaptation is needed (Ford *et al.*, 2013). A reverse logic applies to some climate adaptation measures where the measure is deemed successful if no impacts, costs or changes occur (UNFCC, 2010). For example, how does one measure an avoided event (such as preventing loss of species from an ecosystem) against no fixed baseline at some unclear point in the distant future? Said another way, how would one know how many and what species might have been lost in the absence of the intervention (Natural England, 2010)? Similarly, how does one measure future infrastructure costs avoided by considering climate impacts now and designing infrastructure in accordance with potential future climate changes (Lamhauge *et al.*, 2011)? A lack of linearity in some climate impacts and adaptations means some adaptation measures may reduce short-term vulnerability and increase long-term vulnerability, or vice versa (Lamhauge *et al.*, 2011; Ford *et al.*, 2013).

Messiness and complexity of adaptation

Unlike climate change mitigation where measuring carbon dioxide emissions has an agreed upon global metric, there are multiple potential metrics—and no agreed upon metrics—for measuring climate adaptation; they will vary from jurisdiction to jurisdiction depending on the specific vulnerabilities of that region (UNFCC, 2010; Ford *et al.*, 2013). Adaptation is also 'messy' and involves attempts to make changes to human systems at multiple scales by multiple actors in multiple sectors over different timescales (Natural England, 2010; Ford *et al.*, 2013). Indicators that work well on a provincial level may not work as effectively on a regional or local scale (Natural England, 2010). Many climate adaptation measures are institutional or governance-related, which can be challenging to measure in a robust manner (Prowse and Snilstveit, 2009). In addition, selecting indicators for an evaluation usually requires an accepted causal theory of change, i.e. if we do this, this will happen. This causal theory of change can be lacking or unclear for climate adaptation measures (Prowse and Snilstveit, 2009). This issue is linked to, yet separate from, the challenges in attribution discussed below.

Lack of baseline data

Climate adaptation actions and interventions have already been implemented in many jurisdictions in the absence of indicator-based monitoring and evaluation frameworks, and baseline data for many potential indicators was not collected prior to those actions (Prowse and Snilstveit, 2009). In addition, because of the reverse nature of avoiding climate impacts through climate adaptation, there is no way to collect baseline data for some avoided costs. Lamhauge *et al.*, (2011) refer to this as a "counter-factual" baseline.

Challenges in attribution

Since climate adaptation does not occur in a vacuum neither can progress toward adaptation be measured in a vacuum. For each adaptation action, there will be other accompanying drivers, stressors or external factors that will influence the original vulnerability either positively or negatively, or enhance the effectiveness of the adaptation measure positively or negatively (Sanahuja, 2011). These include changes in the global economy, such as increases in energy costs, or other policy measures, such as increased fuel taxes or changes in water policy, undertaken for reasons other than adapting to climate change (Harley and Minnen, 2009). Even on an individual level, choices made with respect to farming practices, for example, may reflect consideration of current or future climate changes, yet could also be influenced by many other factors (Lamhauge *et al.*, 2011). To say that changes in farm practices are attributable to climate change education or policy may not be accurate. This is sometimes referred to as the 'attribution gap' (Lamhauge *et al.*, 2011) and is further complicated by the practice of mainstreaming climate adaptation measures into other larger policies, actions and practices (Harley *et al.*, 2008). It may be impossible to isolate the outcomes of one single adaptation measure. If the goal of using indicators is to monitor the status of the overall system/region and observe trends, then attributing changes in indicators to a particular action or adaptation measure may not be required (Harley *et al.*, 2008; UNFCC, 2010). However, if there is a cost to implementing the measures, it can be useful to know if they are effective so that resources can be allocated efficiently.

No defined yardsticks for success

There are no agreed-upon standards or definitions of successful adaptation, which relates to the uncertainty of how much adaptation is enough and how success may be viewed differently by academic, policy makers and communities (Harley *et al.*, 2008; Ford *et al.*, 2013). Many adaptation policies and programs lack measurable targets or clearly defined desired outcomes, which poses challenges for measurement (Sanahuja, 2011). Is the goal of adaptation to enhance resilience, reduce vulnerability, increase adaptive capacity, achieve specific adaptation goals, avoid impacts, or all of the above? Even though these concepts are related, each will drive a slightly different and distinctive evaluation approach and therefore different suites of indicators.

This section focuses on indicators that attempt to measure successful development, implementation and impact of climate change adaptation actions. Using vulnerability indicators to measure successful adaptation as reduced vulnerability, as discussed in the previous section, remains another potential approach. Due to the challenges associated with defining success and the potential for that success to look different in different jurisdictions or on different scales, it may be impossible to develop a set of indicators that will allow the comparison of outcomes of various adaptation projects, policies or programs (Sanahuja, 2011).

Lack of resources and coordination

Monitoring and evaluation is often the least funded area of adaptation practice (Sanahuja, 2011). Information sharing among agencies is often critical to the success of evaluation and monitoring programs, yet is one of the first things to be cut in challenging economic times. Agencies may also lack experience in using indicators to monitor programs related to the environment.

The attribution, timeframe and reverse logic challenges of measuring climate adaptation affect outcome indicators in particular (Ford *et al.*, 2013). This becomes problematic because outcome indicators or measures are generally the most important type of indicator in monitoring and evaluation (Ford *et al.*, 2013). The World Bank Group has stated that it is impossible to measure effectiveness of adaptation directly due to the long-term nature of climate change and the infrequency of extreme events (IED, nd). The World Bank Group has proposed instead to focus on process indicators and vulnerability indicators (IED, nd).

Moving Forward

Despite the challenges, many organizations agree on the need to develop adaptation indicators. Germany, the Philippines and the U.K. appear to have developed the most systematic approaches to developing adaptation indicators to date, and each is taking different approaches. All three are attempting to align indicators with their national climate adaptation strategies.

Clarifying the Purpose and Defining Success

Ford *et al.*, (2013) maintained that it is essential to define the characteristics of success in adaptation to develop appropriate indicators, especially outcome indicators. According to GIZ (2013) a crucial first step is clarifying the objective of the broader monitoring and evaluation system in which indicators are to be embedded. For example, are the indicators intended to monitor the implementation and success of a national climate strategy, or a local one? Are they being utilized to monitor the achievement of certain goals? Will they be used to assess increases or decreases in local, regional or national vulnerability?

This plays back into the two different schools of thought on measuring success in adaptation, the interrelationship between vulnerability and adaptation indicators, and the use of vulnerability indicators as adaptation indicators. The latter is based on the thinking that a decrease in vulnerability equals an increase in resilience, which equals success in adaptation. One school focuses on measuring progress towards successful end states, while the other measures movement away from undesirable states. Depending on the school, measures of success will vary in the degree to which they focus on prescriptive measures of adaptation, i.e. was a particular adaptation action implemented, or more open-ended measures of adaptation, i.e. whether vulnerability was reduced.

One advantage of the vulnerability reduction approach and the use of vulnerability indicators instead of adaptation indicators is that it reduces the need to attribute both causality and on-the-ground results to actual adaptation actions. If the objective is to measure whether the desired outcomes of certain adaptation actions have been achieved, it is important to define those desired outcomes and link them back to the actions through results chains or impact chains, which specify theorized cause and effect (GIZ, 2013). Although it may be impossible to set numerical goals for adaptation, it is possible to state desired adaptation outcomes such as the achievement of resilience qualitatively by relying on defined characteristics of resilience. Indicators can then measure increases or decreases in resilience over time (Natural England, 2010). For example, Natural England (2010) defined four characteristics of a resilient natural environment as the basis for developing a package of indicators: a diverse natural environment, reduction of non-climate anthropogenic pressures, flexible management and ecosystem function.

Added dimensions of success could include a) *coverage*, e.g. the number and types of people, groups, communities, sectors or ecosystems reached by an action, b) *sustainability*, e.g. the potential for an adaptation action to be sustained over time, and c) *replicability,* e.g. the extent to which an action can be achieved elsewhere or lessons learned can be shared (Sanahuja, 2011).

Types of Climate Adaptation Actions

Ford *et al.*, (2013) maintained the development of indicators is predicated on defining what adaptation looks like in practice and the types of actions encompassed. Accordingly, one approach could be to develop and classify indicators on the basis of types of climate adaptation actions.

For the purposes of evaluation, Lamhauge *et al.* (2011) divided climate adaptation actions into five categories. These categories are echoed by César *et al.*, (2013) and are based on an OECD report (OECD, 2010). Note that the OECD report also includes a sixth category of climate change funds, which are funds devoted to undertaking climate change mitigation and adaptation. Both Lamhauge *et al.* (2011) and César *et al.* (2013) chose to exclude this category or roll it into the other categories.

1) *Climate risk reduction/enhancing resilience to climate change*: activities that reduce vulnerability to climate change such as water conservation and flood prevention. These activities have the most direct impact on people's ability to adapt to climate change.

2) *Policy and administrative management for climate change*: activities that ensure climate change risks are taken into account in laws, planning, policies and negotiations.

3) *Education*, *training and awareness on climate change*: activities focused on changing people's behaviour and habits in accordance with current and projected climate conditions. Such activities do not directly reduce people's vulnerability, but equip them with information that help them adapt to current climate, consider future climate change in their decision-making, and prepare for extreme events.

4) *Climate change studies*, *scenarios and impact research*: activities that support risk reduction by supplying information needed to understand where training, policy and risk reduction activities are needed most.

5) *Co-ordination*: activities that support dialogue between stakeholders, dissemination of research, and enhance relevant communities of practice.

Separating climate adaptation actions into the categories above is one potential approach to framing and organizing indicators.

Dealing with Challenges

Additional approaches have been proposed to address the challenges of measuring adaptation outlined above, yet are still in the early stages of development and require more consideration.

One approach to addressing the attribution gap is to focus on process indicators, i.e. number of climate change workshops given to farmers, rather than outcome indicators, i.e. changes in farming practices. Nonetheless, only focusing on process indicators could result in impacts being overstated, i.e. if farmers do not adopt different farming practices, the workshops have had no impact (Lamhauge *et al.*, 2011).

Epidemiological and disaster preparedness intervention techniques—which also address reverse logic challenges (of avoided illnesses or deaths) in determining success—may be helpful in designing appropriate adaptation indicator suites and, in particular, outcome indicators (Ford *et* *al.*, 2013). Tracking factors like climate-related disaster losses, and mortality and morbidity over time—even though they cannot necessarily be directly linked to adaptation actions, can contribute evidence for the effectiveness (or ineffectiveness) of adaptation actions, especially when coupled with process indicators, or when used comparatively with other countries with similar climatic risks and socio-economic conditions, and different adaptation approaches (Ford *et al.*, 2013).

In the U.K., one proposed approach to dealing with data uncertainties or lack of data with respect to certain potentially useful indicators is to develop a star rating system for indicator data quality ranging from lowest quality and certainty to highest quality and certainty (Sniffer, 2013).

Incorporating the monitoring of adaptation into regular monitoring processes could help reduce the cost and resource challenges associated with developing and implementing indicators. This strategy has been proposed (Sanahuja, 2011) and has been strongly advocated in the U.K. (Sniffer, 2012). However, this approach must be undertaken with care as existing indicator suites or data collection systems may lack flexibility and may not be completely appropriate if they have been designed for other purposes (GIZ, 2013).

Potential Adaptation Indicators

This section introduces a range of potential adaptation indicators found in the literature. Best efforts have been made to classify them by sector and as either process or outcome indicators. This classification process was not without its challenges because, as discussed previously, there are different ways of thinking about whether an indicator is a process indicator or outcome indicator, and many of the organizations proposing or using adaptation indicators do not classify them at all. In addition, some indicators are double-barreled in that they refer to both the development of a policy and its implementation. As a result, while the classifications provided here were undertaken to provide some clarity, it may be more useful to consider these indicators as being on a continuum of process indicators to outcome indicators.

Sanahuja (2011) observed that indicators are generally case-specific and reflective of the type of effort with which they are associated. This is true of the indicators presented here. Some were developed to evaluate national adaptation policies and some were developed to evaluate specific programs. Some were developed for developing countries, while others were intended for developed countries. These differences are reflected in the nature of the indicator.

Germany has developed a more integrated suite of indicators linking both impact and response (adaptation) indicators, which is presented separately at the end of this section.

Process Indicators

Process indicators have been broken into the categories proposed by Harley and Minnen (2009):

- *Building of adaptive capacity/developing policy*: development of policies, undertaking of research and exchange of information; and,
- *Delivering of adaptation actions*: implementation of adaptation policies and plans.

Process indicators are also separated into general process indicators and sector-specific process indicators.

The current literature shows development of general process indicator suites as well as usage of only one or two suggested indicators. For example, Natural England (2010) offered a single process indicator: progress in assessing/planning for climate change (which would appear to fall under the building adaptive capacity category), while César *et al.*, (2013) suggested: number of vulnerable communities that have increased adaptive capacity to cope with climate change impacts (which fits into the delivery of adaptation actions category). Heidrich *et al.*, (nd) proposed a four-indicator suite measuring urban climate change preparedness: assessment of climate risks; planning strategies and processes; action plans and implemented projects; and, monitoring and reviewing.

In contrast, Table 10 summarizes more comprehensive general process indicator suites:

Table 10: General Process Indicators

Harley and Minnen, 2009	United Kingdom (UNFCC Secretariat, 2010)	Lamhauge *et al.* (2011)
Building Adaptive Capacity/Developing Policy		
• Research regarding expected climate change impacts and vulnerabilities • Research into non-climate stress factors • Use of scenarios to inform adaptation options • Development of relevant climate change policies, strategies and actions on a local, regional and provincial level • Amendment of existing policies, legislation etc. based on climate change • Identification of appropriate authorities or bodies to implement climate change adaptation measures • Engagement of stakeholders regarding climate change adaptation	• Potential threats and opportunities across estate and services starting to be assessed • Next steps to build on that assessment identified and agreed upon • Public commitment made to identify, communicate and manage climate-related risk • Local risk-based assessment of significant vulnerabilities and opportunities made • Comprehensive risk-based assessment undertaken and priority risks for services identified • Most effective adaptive responses identified and incorporated in council strategies, plans, partnerships and operations • Adaptive responses implemented in some priority areas • Climate impacts and risks embedded across council decision-making • Comprehensive adaptation action plan developed • Adaptive responses implemented in all priority areas	• Number of advisories on water use, crop planning, pest management etc. issued • Number of desk studies/synthesis reports available • Number of coordination meetings among local groups • Number of individuals in communities developing resilience strategies
Delivering Adaptation Actions		
• Evaluation of progress through the adaptive management cycle	• Comprehensive adaptation action plan across the local authority area implemented • Robust process for regular and continual monitoring and review exists to ensure progress with each measure and updating of objectives • Appropriate adaptive responses implemented	• Number of new adaptation initiatives implemented

Sector-specific process indicators were compiled from multiple sources and are listed in Table 11 below. Most of the proposed indicators from the documents reviewed are included in the table. Where the proposed indicator lists were lengthy, such as CCC (2012) and César *et al.*, (2013), a sample of indicators is provided as an example.

Table 11: Sector Specific Process Indicators

Building Adaptive Capacity/Developing Policy	**Source**
Agriculture	
o Research on farming techniques that can accommodate climate change	Harley and Minnen, 2009
o Provincial level agriculture and fishery sector vulnerability and risk assessment conducted nation wide o National and provincial agriculture and fisheries climate information and database established o Number of researches conducted on agriculture and fisheries adaptation measures and technologies developed	CCC, 2012
Ecosystems	
o Research into ecosystem-based adaptation o Integration of climate change considerations into regional ecosystem management plans	Harley and Minnen, 2009
o Amendment of biodiversity policy, legislation and agreements to reflect climate change	Harley and Minnen, nd
o Uptake of tree species climate change guidance	Beckmann, 2012
Water	
o Development of catchment-specific drought management policies/plans	Harley and Minnen, 2009
o Existing water resources management laws reviewed and harmonized o Number of site-specific water supply-demand (water balance) studies conducted	CCC, 2012
Health	
o Development of regional policies to address health impacts of climate change	Harley and Minnen, 2009
o Mapping of the eco-zones and changes in vector-borne disease	Sanahuja, 2011
Extreme Events	
o Development of disaster management plans	Harley and Minnen, 2009
Delivering Adaptation Actions	
Agriculture	
o Introduction of drought- and heat-resistant crops	Harley and Minnen, 2009
o Number of appropriate climate change adaptation technologies identified and implemented o Number and type of risk transfer (e.g. weather-based/index insurance) and social protection mechanisms developed for agriculture and fisheries o Number of farmers and fisherfolk communities trained on adaptation best practices and disaster risk reduction	CCC, 2012
Ecosystems and Biodiversity	
o Monitoring of climate change indicator species	Harley and Minnen, 2009
o Area of land under conservation agreements	Natural England 2010
o Assessment of species and habitat vulnerability o Implementation of measures to protect vulnerable species and habitats	Harley and Minnen, nd
o Number and types of climate change mitigation and adaptation measures implemented in key ecosystems o Hazard, vulnerability and adaptation maps produced for all ecosystems o Number and hectares of protected areas and key biodiversity areas protected o Number of staff in key government agencies trained and implementing integrated ecosystem-based management approaches	CCC, 2012

Building Adaptive Capacity/Developing Policy	Source
Water	
o Construction of flood protection schemes	Harley and Minnen, 2009
o Protocols and tools for water budgeting developed	Lamhauge *et al.*, 2011
o Number of water supply infrastructures assessed and climate-proofed o Number of modifications in the process and demands for water supply systems and users implemented o Number of staff from key institutions trained as pool of trainers/resources on integrated water resource management and climate change adaptation-mitigation	CCC, 2012
Health	
o Mapping and control of disease vector species (e.g. mosquitos)	Harley and Minnen, 2009
o Number of community-based public health surveillance systems implemented o Health emergency preparedness and response for climate change and disaster risks in place at the national and local levels	CCC, 2012
Extreme Events	
o Uptake of insurance to cover weather extremes	Harley and Minnen, 2009
o Local disaster management plans exist and put in place	Lamhauge *et al.*, 2011
o Disaster management committees in municipalities	Lamhauge *et al.*, 2011
o Number of communities implementing Climate Change Adaptation-Disaster Risk Reduction Management	CCC, 2012
o Redesign of forests for fire risk reduction	Beckmann, 2012
Infrastructure	
o Upgrade of transportation infrastructure	Harley and Minnen, 2009
o Number of critical local infrastructures assessed and retrofitted o Number of local governments implementing climate change adaptation-disaster risk reduction in the issuance of building permits and location clearances	CCC, 2012
Soil	
o Implementation of measures to reduce soil erosion and desertification	Harley and Minnen, 2009
Energy	
o Percentage increase in sustainable renewable generation capacity o Number of real estate developments adopting green building standards and design for environment concepts	CCC, 2012
Economy/Livelihoods	
o Clear national and local policies promoting the climate-smart industries and services formulated and implemented by 2012 o Number of livelihood opportunities and productive employment created from climate-smart industries and services in the rural areas and in highly vulnerable communities[5]	CCC, 2012

Outcome Indicators

The proposed outcome indicators presented in Table 12 are subject to two important considerations. First, as noted previously, some outcome indicators are very similar to process indicators for the delivery of adaptation measures. Second, some outcome indicators closely match some of the climate impact indicators reviewed in the previous section. Note that some organizations, such as Natural England, 2010 also provide detailed instructions on how to measure all of their indicators.

5 This could also be viewed as an outcome indicator.

Table 12: Outcome Indicators

Delivering Adaptation Outcomes	
Agriculture	
o Number of farmers and fishermen engaged in capacity development activities for climate change risk management[6] o Percentage change in adaptive capacity among demonstration villages (perception-based survey)	UNFCC Secretariat, 2010
o Number of households participating in improved agricultural practices[7]	Lamhauge *et al.*, 2011
o Improved agricultural yields o Agricultural productivity (yield per year) o Number of protected agricultural areas o Variability in yields or income over a multi-year period	César *et al.*, 2013
Ecosystems and Biodiversity	
o Extent of semi-natural habitat o Land cover dominance and plant diversity o Bird population indices o Landscape distinctiveness o Ecosystem fragmentation o Air quality o Plant diversity	Natural England, 2010
o Reduction of sources of stress and harm o Establishment of buffer zones around conservation areas o Establishment of networks of interconnected protected areas and intervening habitat	Harley and Minnen, nd
o Number of degraded ecosystems	Harley and Minnen, 2009
o Afforestation area o Survival rate of afforestation (per cent) o Forest coverage ratio (per cent) o Vegetation area (ha)	Lamhauge *et al.*, 2011
o Proportion of land covered by forest (does not include information regarding the type or quality of the forest). o Deforestation rate (per cent and trend) o Land degradation (per cent and trend) o Changes in threat status of species (per cent and trend) o Forest degradation (per cent of total in geographic area) o Forest biomass rate and trend (per cent) o Grassland degradation (per cent)	César *et al.*, 2013
Water	
o Good ecological status of water bodies o Surface and groundwater quality and quantity	Natural England, 2010
o Water consumption	Harley and Minnen, 2009
o Water supply-demand balance o Drought orders o Available water resources o Leakage	Harvey *et al.*, 2011
Health	
o Proportion of health-care facilities reporting climate-sensitive health risk data on a weekly basis (to enhance the effectiveness of early warning systems)	UNFCC Secretariat, 2010

6 This could also be viewed as an outcome indicator.
7 This could also be viewed as an outcome indicator.

Delivering Adaptation Outcomes	
o Human mortality and morbidity from extreme weather events	Harley and Minnen, nd
o Number of deaths during heat waves	Harley and Minnen, 2009
o Human comfort index o Hospital admissions for temperature-related causes	Harvey *et al.*, 2011
o Reduction in climate-related water-borne health risks	CCC, 2012
Extreme Events	
o Economic loss due to floods	Harley and Minnen, 2009
o Area affected by fires (km^2 per year) o Early warning systems in place (yes/no)	César *et al.*, 2013
o Number of people impacted by flooding o Duration of flooding o Value of flood damage o Early warning systems in place	Lamhauge *et al.*, 2011
Infrastructure and Urban Areas	
o Area of functioning floodplain o Area of green infrastructure within urban areas o Heat island effect (temperature differential between urban areas and countryside)	Natural England, 2010
o Construction of climate-proof infrastructure[8]	Lamhauge *et al.*, 2011
o Rehabilitated water reservoirs effectively adapted to climate change[9]	César *et al.*, 2013
o Transport disruptions due to infrastructure damage o Infrastructure assets in flood risk areas with 'significant' risk of flooding o Interruptions to electricity supply o Insurance claims for weather-related causes	Harvey *et al.*, 2011
Soil	
o Nitrogen deposition o Soil organic matter and soil organic carbon content	Natural England, 2010
Economy/Livelihoods	
o Number of households that seek out, test, adapt and adopt ideas and practices that strengthen their livelihoods	Lamhauge *et al.*, 2011
o Income o Quality of life index o Number of individuals with resilient employment opportunities	César *et al.*, 2013

Integrated Indicator Suites

Germany has produced a more integrated indicator suite that combines both impact indicators and response indicators as guided by its drivers-pressures-state-impact-response (DPSIR) model. Table 13 includes six of its fourteen action areas (Schönthaler *et al.*, 2011).[10] This suite is, to some extent, a simpler approach that recognizes the overlap between climate impact indicators and adaptation outcome indicators.

8 This could also be viewed as an outcome indicator.
9 This could also be viewed as an outcome indicator.
10 The other action areas are: fisheries, energy, financial services, transportation and transport infrastructure, tourism, planning, and civil protection.

Table 13: Germany's Integrated Indicator Suite

Impact Indicators	Response Indicators
Action Field: Human Health	
Heat exposure	Heat warning system
Heat wave mortality	Success of heat warning systems
Contamination with pollen of common ragwort	Information on common ragwort
Sensitization to common ragwort	Pollen information service
Pollen exposure	
Allergy issues	
Risks from oak processionary moth infestation	
Vector-borne diseases	
Contamination by cyanobacteria of bathing waters	
Action Field: Building Sector	
Thermal load in urban environments	Recreation areas
Summer heat island effect in Berlin	Heat requirements of federal real estate
Neighbourhood noise	Space heating requirements in domestic situations
	Finding for climate-adapted construction work
Action Field: Water Regime, Water Management, Costal and Marine Protection	
Groundwater level	Disconnecting residential areas from the public sewage system
Salinity of groundwater	Adaptation of the municipal scale of fees for waste water disposal
Mean run-off	Specific water consumption per capita
Floodwater run-off	Investment into adaptation measures
Low water	Structural quality of water bodies
Water temperature of lakes	
Duration of the summer stagnation period	
Start of the spring algae blooms	
Sediment input to rivers	
Action Field: Soil	
Soil water storage in agricultural soils	Humus reserves of agricultural soils
Soil temperature	Size of grasslands
	Conservation status of organic soils
	Organic soils under cultivation
Action Field: Agriculture	
Shifts in agrophenological stages	Agricultural advice
Quality of wine	Adaptation of management rhythms
Changes in yield	Cultivation and seed multiplication of warmth-loving crops
Insured hail-storm damage in agriculture	Developments with regard to the number of crop species for which varieties are registered
Warning messages for damaging pest events	Varieties of grain maize categorized by maturity groups
Pest infestation messages	Cultivation of thermophilic red-wine varieties
Loss of plant genetic resources	Range of services for pest management
Mortality of productive livestock	Inland output of pesticides
	Intensity in the application of pesticides
	Agricultural irrigation
	Development in wheat prices
Action Field: Woodland and Forestry	
Changes in the tree species composition in designated forest nature reserves	Forestry-related information on the theme of adaption
Endangered spruce stands	Area of mixed woodlands
Incremental growth of timber	Investment into forest conversion
Infested timber – extent of casual use	Forest conversion of endangered spruce stands
Extent of timber infested by spruce bark beetle	Conservation of forest genetic resources
Forest fire hazard and forests/woodlands affected by fire	Pest control in forests
Forest dieback	Humus reserves and other water retention in woodland soils

An integrated approach to climate-related indicators is under development in the U.K., and a few examples of integrated indicator suites have already been developed for some sectors. This approach, developed by Harvey *et al.*, (2011), attempts to connect climate impact indicators with non-climate drivers and adaptation indicators. An example of the indicator suite for the health and well-being sector is presented in Table 14.

Table 14: Proposed Health and Well-being Indicators in U.K.

Category	Indicator Title
Major Impact Indicator	
Temperature effects on mortality, morbidity, human comfort	Excess summer mortality during heat waves (England & Wales)
	Excess winter mortality of men and women aged over 65
Non-climate drivers	
Population aged over 65 (contextual)	Number of women aged 65 or over
Urban heat island (controllable)	Intensity of the urban heat island effect
Adaptation Indicators	
Awareness of heat wave response	Awareness of the heat wave health plan

This approach is interesting in that it incorporates non-climate drivers, which could be considered a partial measure of vulnerability. For example, the non-climate driver indicator listed for the built environment sector is the number of buildings/properties/ households/commercial premises in flood-prone areas. These integrated indicators are also presented in Miller *et al.*, (2012) who observed that the interconnectedness of climate change might necessitate an integrated indicator approach. It is challenging to assess adaptation and preparedness without first understanding vulnerability and non-climate drivers of and barriers to adaptation.

Key Lessons

Many organizations are beginning to move forward with climate adaptation indicators. There is a wide array of potential examples to select from and they are generally less complicated than vulnerability indicators. Significant challenges still exist, and clearly defining what constitutes success is a critical first step in developing a climate adaptation indicator suite. Linking climate impact and climate adaptation indicators — and potentially also vulnerability indicators — in a more integrated suite should be considered.

Resilience Indicators

Opinions are divided on whether it is better to focus on vulnerability or resilience when developing indicators and explaining climate impacts and adaptation to communities. Vulnerability is considered negative, yet potentially a greater motivation to action, whereas resilience is considered more positive, though harder to understand and perhaps less motivating. Ibarrarán *et al*., (2008:4) propose a focus on resilience over vulnerability, claiming that:

Vulnerability is a deficit concept; researchers and analysts are examining what is wrong, with at least an implicit conclusion that these vulnerability-contributing factors need correction.

They maintain that a focus on resilience will more correctly guide policy makers to improving situations. Malone (2009) observed that climate change research initially focused on vulnerability and is now shifting to a more resilience-based approach because "it (resilience) is a positive concept that can be more integrated with general development goals."

If resilience is considered the inverse of vulnerability, then it follows that focusing on resilience means focusing on vulnerability and that emphasizing the positive (i.e. resilience) may be of value. On the other hand, it is possible that emphasizing vulnerability may spur more policy action on the part of decision-makers.

Carpenter *et al*. (2001) note that resilience is not always positive; systems that decrease social welfare, such as polluted water supplies and dictatorships, can be highly resilient.

Defining and Operationalizing Resilience

Resilience is defined and operationalized in a number of different ways. There are common features to the definitions and also subtle differences that should be considered in the development of resilience indicators. Resilience is generally defined as being able to respond to, cope with and recover from climate variations and impacts, i.e. remaining in or returning to the old state (Ibarrarán *et al*., 2008; Malone, 2009; EC-FAO, nd). However, some researchers also include the notion of positive change, i.e. developing a new state in response to climate impacts (Ibarrarán *et al*., 2008; Malone, 2009).

Work on resilience indicators in the field of climate change is limited and, according to Sivell *et al*., (2008), as of 2008 there were no indicators of resilience to climate change. From an indicator perspective, there appears to be four broad approaches to defining and operationalizing resilience:

1. Vulnerability approach;
2. Adaptive capacity approach;
3. Formal capitals approach; and
4. Components or determinants of resilience approach.

Vulnerability Approach

Resilience is sometimes defined and operationalized as the opposite of vulnerability (Malone, 2009), which is considered to be a combination of exposure, sensitivity and adaptive capacity. There is disagreement on this definition and, in practice, some components of vulnerability are usually dropped when developing resilience indicators.

Sivell *et al*., (2008) discuss both resilience and resistance to climate impacts. Where resistance involves completely blocking the effects of a particular event, resilience is about how quickly and easily a community recovers from an event and reduces the damage associated with the event.

Resilience includes coping strategies, awareness, plans to respond (adaptive capacity) and prior adaptation actions to reduce the impacts of an event. Sivell *et al*., (2008:12) therefore define resistance and resilience jointly as the counterpoint to vulnerability:

Vulnerability is reduced through improving both resistance and resilience — resistance reduces the number of impacts that are likely to significantly affect you, while resilience reduces the extent of the damage caused by impacts that do affect you.

According to Ibarrarán *et al*., (2008) resilience includes components of sensitivity and coping/adaptive capacity, which are also components of vulnerability, and adaptation, which is not a component of vulnerability. Resilience does not include exposure, which is the third component of vulnerability. Ibarrarán *et al*., (2008) suggest that resilience is not simply the inverse of vulnerability in light of the IPCC definitions:

Resilience is the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability of extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

McAslan (2011) also suggests that vulnerability and resilience are not necessarily the inverse of each other. The vulnerability of a community is determined by the intersection of the natural, built and socio-economic environment. While some communities are at higher risk of being exposed to certain natural events, these communities can be well-organized with significant social and institutional capital. Accordingly, high vulnerability does not necessarily indicate low resilience. Although it is not explicitly stated, McAslan (2011), like Ibarrarán *et al*., (2008), seems to be dropping the notion of exposure (that is part of vulnerability) when considering resilience.

If one takes resilience to be the inverse of vulnerability then all of the approaches outlined to developing vulnerability indicators in this literature review are relevant to the development of resilience indicators.

Adaptive Capacity Approach

A second approach to operationalizing resilience is presented by Malone (2009:6) who suggests for analytic and practical purposes that resilience be equated with adaptive capacity, where adaptive capacity is defined as follows:

In practical terms, adaptive capacity is the ability to design and implement effective adaptation strategies, or to react to evolving hazards and stresses so as to reduce the likelihood of the occurrence and/or the magnitude of harmful outcomes resulting from climate-related hazards. The adaptation process requires the capacity to learn from previous experiences to cope with current climate, and to apply these lessons to cope with future climate, including surprises.

Although they do not explicitly equate resilience and adaptive capacity, Swanson *et al*., (2009) also seem to take this view in using the words resilience and adaptive capacity somewhat interchangeably in developing indicators of adaptive capacity for farming on the Canadian prairies, and referring to both as the inverse of vulnerability. Elasha *et al*., (2005) also seem to suggest that assessing adaptive capacity is the equivalent of assessing community resilience. Berkes and Jolly (2001) collect data and measure communities' adaptive capacity even though socio-ecological resilience is their primary focus.

If resilience is considered to be akin to adaptive capacity, a wide range of research on measuring adaptive capacity and climate change becomes relevant for consideration. However, this approach, while making resilience much easier to measure, does constrain resilience to being the inverse of a component of vulnerability, not the entire construct.

On the other hand, Carpenter *et al*., (2001) explore the relationship between adaptive capacity and resilience, noting that the two terms are often utilized in conjunction with each other. They point out that resilience has three properties:

- The amount of change the system can undergo (and the amount of external force the system can sustain) and still remain within the same controls on function and structure;
- The degree to which the system is capable of self-organization; and
- The degree to which the system can build capacity to learn and to adapt.

According to Carpenter *et al*., (2001), adaptive capacity only incorporates the learning component of resilience. If one chooses to go with the adaptive capacity approach to measuring resilience, many approaches to measuring adaptive capacity can be found in the literature.

Formal Capitals Approach

A third approach to resilience outlined by Malone (2009) comes from the sustainable development research community. Rather than focusing on sensitivity, exposure and adaptive capacity (the IPCC definition of vulnerability), it considers vulnerability as a lack of capabilities or physical, financial, social, human and natural "capitals". Resilience becomes the opposite of vulnerability and is considered to be the possession of these capabilities or capitals. These capitals are defined as "livelihood capitals" and similar capitals are used or proposed in many studies measuring resilience (Sadik and Rahman, nd; Elasha *et al*., 2005; Malone, 2009).

Components or Determinants of Resilience Approach

A fourth and final approach to operationalizing resilience is to conceptualize it as a combination of desirable components or determinants of resilience. This is similar to the capitals approach, except there is no set group of capitals that researchers work with. The components or determinants of resilience are defined specifically for each local area and indicators are selected based on the determinants.

Examples of Resilience Indicators

The literature suggests that there is more flexibility in creating resilience indicators than vulnerability indicators. With that flexibility comes a wide range of approaches and no widely accepted approach as yet. This section provides examples of indicators that fall into the four main approaches outlined above.

Despite the difference in approaches there are some common features to all of the resilience indicators considered. As Sivell *et al*. (2008) have observed, no single indicator or even three or four individual indicators could adequately measure a region's resilience on either a relative or absolute scale. Moreover, resilience can likely only be measured in a relative manner (Sivell *et al*., 2008). Guibert (nd) echoes this and maintains that resilience indicators are not a way to measure resilience, but rather constitute simplified proxies of relevant factors that allow for comparative assessment and monitoring of change over time.

Vulnerability Approach Indicators

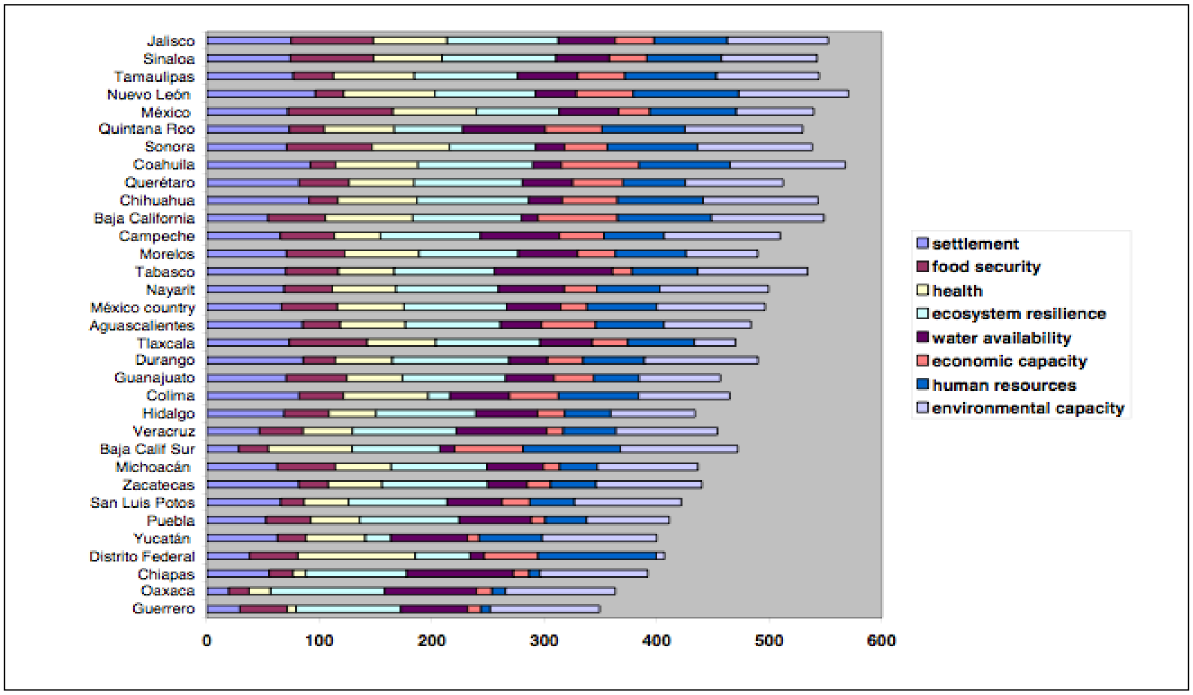
Ibarrarán *et al*., (2008) integrate their resilience and vulnerability indicators into a Vulnerability-Resilience Indicators Model (VRIM) that focuses only on sensitivity and adaptive capacity. Exposure, the authors claim, is implicit and assumed. The components of the VRIM developed for Mexico are illustrated in Table 15:

Table 15: Vulnerability-Resilience Indicators Model (VRIM) for Mexico

Component	Sector	Indicators
Sensitivity	Settlement/infrastructure sensitivity	Population at flood risk from sea level rise
		Population without access to clean water/sanitation
	Food security	Cereals production/crop land area
		Protein consumption/capita
	Ecosystem sensitivity	Per cent of land irrigated
		Fertilizer use/cropland area
	Human health sensitivity	Completed fertility
		Life expectancy
	Water resource sensitivity	Renewable supply and inflow and water withdrawal
		Precipitation
Coping and Adaptive Capacity	Economic capacity	GDP (market)/capita
		Income equity measure
	Human and civic resources	Dependency ratio
		Literacy
	Environmental capacity	Population density
		Air pollution/state area
		Per cent of land unmanaged

These are then presented in disaggregate form by province summed by sector as illustrated in Figure 3.

Figure 3: Mexico's States Ranked for Resilience



Adaptive Capacity Approach Indicators

As outlined above, Malone (2009) proposed that the similarity between resilience and adaptive capacity might allow for the use of adaptive capacity measurement approaches in measuring resilience. It is important to note that the two examples of adaptive capacity approach indicators provided here also use the determinants approach, but in this case the determinants of adaptive capacity are equated to resilience. The determinants of resilience approach is slightly different and is outlined in a subsequent section

Malone (2009) identifies eight determinants of adaptive capacity as follows:

1) The range of available technological options for adaptation;

2) The availability of resources and their distribution across the population;

3) The structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed;

4) The stock of human capital, including education and personal security;

5) The stock of social capital, including the definition of property rights;

6) The system's access to risk-spreading processes;

7) The ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers themselves; and

8) The public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

In this approach, each factor is scored with a value of zero through five to develop an index of adaptive capacity.

Swanson *et al*., (2009) also chose the adaptive capacity route to developing indicators of adaptive capacity/resilience, identifying six determinants of adaptive capacity as outlined in Table 16.

Table 16: Determinants of Adaptive Capacity

Determinant	Rationale
Economic resources	Greater economic resources increases adaptive capacity
	Lack of financial resources limits adaptation options
Technology	Lack of technology limits range of potential adaptation options
	Less technologically advanced regions are less likely to develop and/or implement technological adaptations
Information, skills and management	Lack of informed, skilled and trained personnel reduces adaptive capacity
	Greater access to information increases likelihood of timely and appropriate adaptation
Infrastructure	Greater variety of infrastructure can enhance adaptive capacity, since it provides more options
	Characteristics and location of infrastructure also affect adaptive capacity
Institutions and networks	Well-developed social institutions help to reduce impacts of climate-related risks and therefore increase adaptive capacity
	Policies and regulations may constrain or enhance adaptive capacity
Equity	Equitable distribution of resources increases adaptive capacity
	Both availability of and entitlement to resources are important

Swanson *et al*., (2009) then picked four indicators for each determinant for which they felt data could be summarized. Given that there is no guidance in the literature on weighting, the equal number of indicators per determinant reflected their view that each determinant is equally important. The indicators selected by Swanson *et al*., (2009) to measure adaptive capacity in agriculture in the Canadian prairies are outlined in Table 17. A single aggregated value for each determinant was calculated as the average of the normalized indicator values. A single overall adaptive capacity index for each census division under consideration was calculated as the average of the aggregated determinant values.

Table 17: Indicators of Adaptive Capacity

Determinant	Aspect	Indicator
Economic resources	Income generation relative to capital investment	Ratio of gross farm receipts to total capital investment. Higher is better.
	Income generation relative to summary expenses	Ratio of income to expenses. Higher is better.
	Off-farm earnings	Off-farm earnings as a per cent of total family income where families have at least one farm operator. Higher is better.
	Diversity of employment opportunities	Ratio of off-farm contribution of time to on-farm contribution of time. Not available with current dataset. Alternative was the ratio of employment in other industries within CD. Lower is better.
Technology	Water-access technology	Ratio of value of irrigation equipment to value of all other farm equipment. Higher is better.
	Computer technology	Ratio of farms reporting use of computer to all other farms. Higher is better.
	Technological flexibility	Ratio of value in tractors under 100 hp to total value of all other tractors. Lower is better.
	Technological exposure	Ratio of technologically demanding to less demanding farm types. Higher is better.
Information, skills and management	Enterprise information management	Ratio of farms reporting computer livestock and crop record keeping to all other farms. Higher is better.
	Sustainable soil resource management practices	Ratio of area of no-till or zero-till seeding to tilled area. Higher is better.
	Sustainable environmental management practices	Ratio of farms reporting windbreaks and shelter belts to all other farms. Higher is better.
	Human resources management	Ratio of total farms reporting paid agricultural labour to all other farms. Higher is better.
Infrastructure	Soil resources	Proportion of area in dependable agricultural land. Higher is better.
	Surface water resources	Ratio of surface water area to total land area. Higher is better.
	Groundwater resources	Number and/or yield of wells. Higher is better.
	Transportation network	Ratio of high-capacity to low-capacity roads. Higher is better.
Institutions and networks	Informal operating arrangements	Ratio of total farms reporting formal agreements to total number of farms reporting sole proprietorships and partnerships without written agreement minus miscellaneous category. Lower is better.
	E-mail use	Ratio of total farms reporting e-mail use to all other farms. Higher is better.
	Internet access	Ratio of total farms reporting internet use to all other farms. Higher is better.
	Opportunity to access agricultural education institutions	Distance between centroids of each Census Division and the nearest regionally significant agricultural education institution. Lower is better.
Equity	Employment opportunities	Unemployment rate from Statistics Canada's 2001 Census of Population 20 per cent Sample Data for Population of 15 years and over. Lower is better.
	Opportunity to access health and social services	Ratio of labour force in health and social-service occupations to all other occupations. Statistics Canada 2001 Census of Population 20 per cent Sample data for Population. Higher is better.
	Distribution of income – general population	Rating by Alessandro's work as published in Catalogue no.21-006-X1E (Rural/urban divide is not changing; income disparities persist)
	Distribution of income – agricultural producers	Ratio of farms reporting sales in excess of $250,000 to all other farms. Lower is better.

Capitals Approach Indicators

In studies of livelihood resilience to climate change, Sadik and Rahman (nd) and Elasha *et al.*, (2005) defined livelihood resilience to climate change as the combination of five groups of livelihood capitals:

- *Natural capital*: land, water and biological resources;
- *Physical capital*: infrastructure and other products created through economic production;
- *Financial capital*: stocks of money or other savings and loans in liquid form and easily disposable assets;
- *Social capital*: markets, social networks, governance, trade or professional associations; and
- *Human capital*: skills, knowledge, quality of labour available, household size and health.

Measurement of capitals is referred to as the ‘sustainable livelihood approach’ to assessing community resilience to climate change. It is important to note that the sustainable livelihood method also includes specific approaches to indicator development through consultation with affected communities.

In their study in the Sunderban region, Sadik and Rahman (nd) selected 60 indicators classified as reflecting one of three dimensions—sustainability, productivity or risk—to measure the five groups of livelihood capital (twelve for each capital). In their study in the Sudan, Elasha *et al*., (2005) added a fourth dimension of equity.

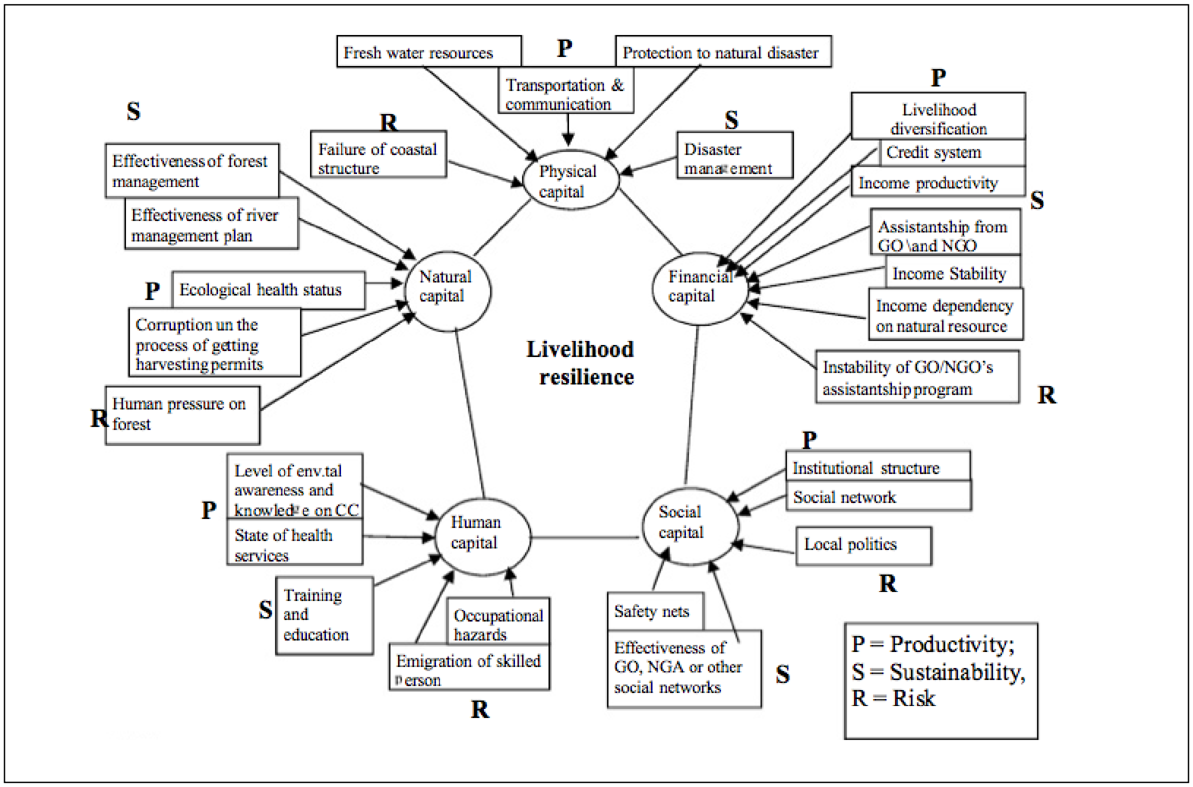
The indicators selected by Sadik and Rahman (nd) for two of their capitals are outlined in Table 18.

Table 18: Indicators of Livelihood Resilience using Capitals Approach

Natural Capital		
Dimension	**Criteria**	**Indicator**
Productivity	Forest health status	Propagation of salinity front
		Percentage of Sunduri typed forest
	Effectiveness of river management in Sundarban	Integration of river management in forest river management plan
		Measures taken to combat salinity intrusion
Sustainability	Effectiveness of forest management	Corruption of forest department staff
		Improvement of forest health
		Production increase
		Per cent of harvesters follows harvesting rules
Risk	Corruption in the process of getting harvesting permits	Taka needed to bribe for each permit (proportion to legal amount)
	Pressure on the forest	Spreading of top dying disease
		No of incident of forest fire by human
		No of incident of use of poison for fishing
Human Capital		
Productivity	Training and education	Training programs launched each year
		Per cent of population having training
		Per cent of population having primary education
		Rate of school enrolment
	State of health services	Serving population ratio-doctor (population per doctor)
		Distance of hospital
Sustainability	Level of environmental awareness and knowledge on climate change risk	Knowledge on climate change awareness program launched in community each year
		Level of adopted coping mechanism
Risk	Out-migration of skilled manpower	Rate of out migration of skilled people (%)
	Occupational hazard	Attack of royal Bengal tiger
		Attack of sea pirates

In consultation with the affected communities, Sadik and Rahman (nd) selected similar indicators for each of the other three capitals. The end result was the resilience indicator conceptual framework in Figure 4.

Figure 4: Livelihood Resilience Indicator Framework for the Sunderban Region



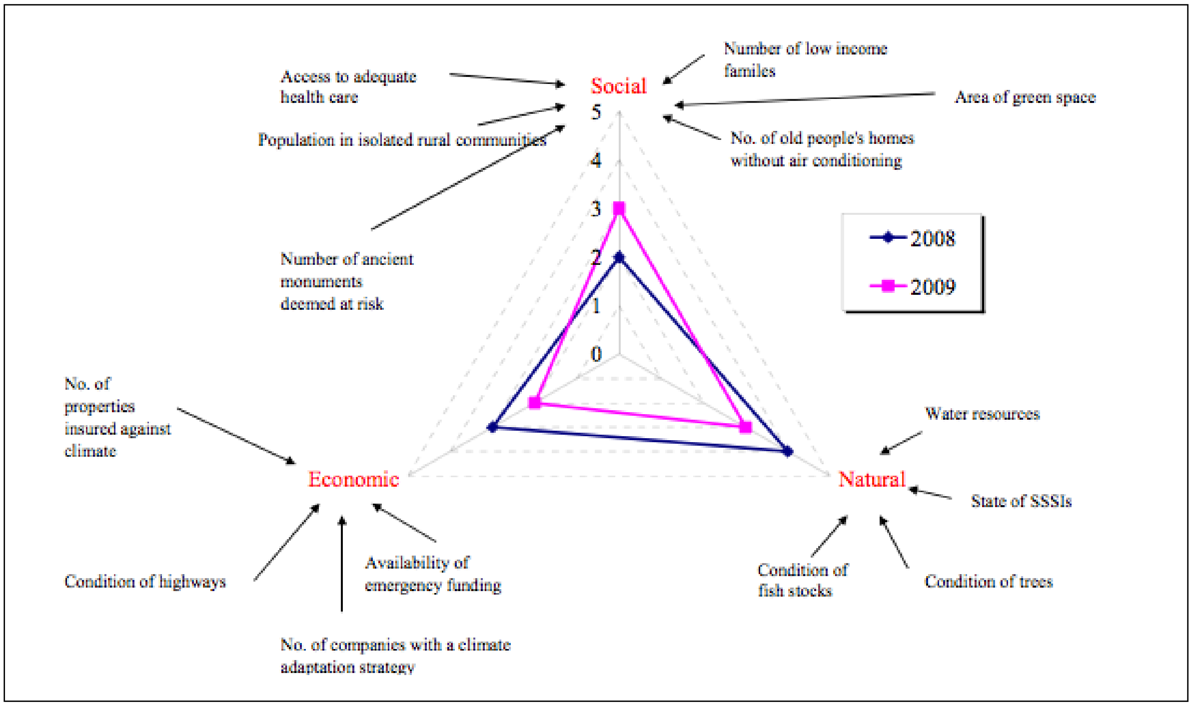
The results for each dimension of each of the capitals are then summed and averaged and weighted, presumably to develop an overall score (although this is not explicitly stated).

Components or Determinants of Resilience Approach Indicators

The components or determinants of resilience approach to developing indicators is a catch-all category that incorporates all resilience indicators that do not fall specifically under one of the three approaches outlined above. The basic approach in this category is to define components or determinants of resilience specific to a particular area or sector, and then develop an indicator or indicators for those determinants.

Working in southeast England, Sivell *et al*., (2008) proposed a set of three compound indicators measuring three components—social, economic and environmental sustainability—using pre-existing indicators to score each of the three components from one to five. The results are presented in aggregate form as a radar diagram to show overall resilience, as shown in Figure 5.

Figure 5: Resilience of the South East to Climate Change Radar Diagram



Sivell *et al*., (2008) go on to present a wide range of potential indicators that could be utilized to indicate resilience for each of the three components. While they note that more components can be incorporated, three components were viewed as optimal. They also provide a summary of how to weight, score and aggregate the indicators. The diagram above highlights how the indicators could be displayed graphically in the form of radar diagrams and does not include the final indicators selected as part of Sivell *et al*.'s work. The final set of indicators selected to illustrate resilience (chosen from an existing set of sustainability indicators) are shown in Table 19.

Table 19: Resilience Indicators for South East England

Component	Indicator
Social	Percentage of new build and retrofit homes meeting Ecohomes Very Good standard or equivalent code for sustainable homes
	Life expectancy
	The extent to which older people receive the support they need to live independently at home
	Percentage of rural households at set distance from key services
	Access to natural green space
Economic	Real GVA per capita growth
	Number of income support claimants in the 20 per cent most deprived areas
	The percentage of total south east business turnover attributable to new (new to market) and significantly improved products
	The expenditure on research & development as a proportion of GVA
	Working age population qualified to at least level 4 or higher
Natural	Properties at risk from flooding
	Number of planning permissions granted contrary to the advice of the Environment Agency on flood defense grounds
	New development with sustainable drainage installed
	Area of land covered by higher level and entry level environmental stewardship schemes
	Per capita consumption of water

Sivell *et al*., (2008) observe that these are the best options from the existing set of sustainability indicators, implying that potentially better indicators could be found and that they were restricting their attention to the current set.

Focusing on urban climate resilience with a specific attention on Asian cities and working through US Aid/Asia and the Asian Cities Climate Change Resilience Network, Guibert (nd) proposed a framework for climate resilience indicators that focuses on three components:

- *Systems*: infrastructure and ecosystems;
- *Agents*: organizations, social groups and individuals; and
- *Institutions*: rules and social conventions that constrain or enable vulnerable agents to access systems.

Guibert then proposes twelve indicators for each component as illustrated in Table 20 for systems relating to water supply, public health and mangroves.

Table 20: Indicators of Urban Climate Resilience in Asian Cities

	Water Supply	**Public Health**	**Mangroves**
Systems	Source capacity / ten-year projected demand	Preventive health budget as per cent of sector spending	Area replanted
	Leakage rate	Number of clinics/hospitals flooded (five-year average)	Seedling survival rate
	Storage as per cent of daily use	Hospital beds/population	Total area healthy mangroves
	Days/year of supply failure	Penetration of hh level precautionary measures	Annual shoreline erosion (five-year average)

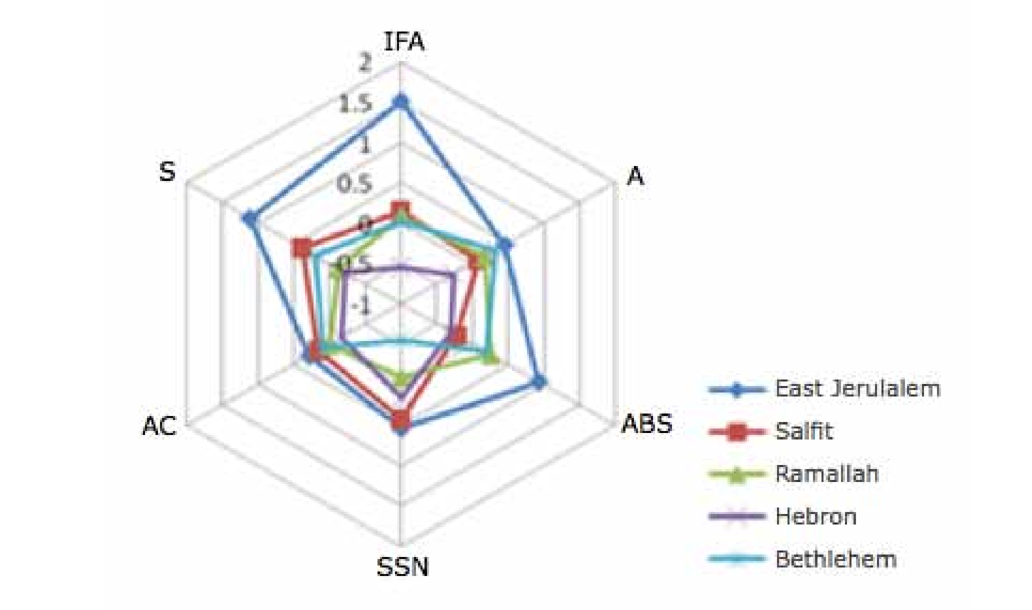
No information was provided on how these indicators are presented or aggregated.

There is also research on other resilience indicators not specific to climate change, particularly in the disaster management literature. While the focus for these indicators is slightly different, the frameworks and aggregation methods are worth examining for use in developing climate change resilience indicators, and many of the measures of resilience in disaster management are quite similar to those that could be utilized for climate resilience. While some focus primarily on socio-economic resilience, others include ecological and infrastructure resilience.

For example, the European Commission and Food and Agriculture Organization (nd) developed a more general measure of community resilience with six components for use in evaluating food security: social safety nets, access to basic services, assets, income and food access, stability and adaptive capacity. Four to six indicators were identified and aggregated for each component to produce a radar diagram of resilience similar to the one developed by Sivell *et al*., (2008), as shown in Figure 6.

Similarly, in developing resilience indicators for natural disasters, Cutter (nd) incorporated 40 indicators for six different components of resilience including ecological, social, economic, infrastructure, institutional capacity (mitigation), and community competence. These indicators are aggregated using multivariate analysis to produce an overall resilience score for different communities.

Figure 6: Components of Resilience in Five West Bank Governorates



Key Lessons

There are many potential approaches to developing resilience indicators and, because the definition of resilience is more general and involves fewer constructs than the definition of vulnerability, there is more latitude for flexibility in approaches. However, as with vulnerability indicators, resilience indicators are challenging composite indicators that rely on many different sub-indicators to provide an overall picture of the resilience of a region.

III: Indicator Selection and Interpretation

Using Criteria to Select Indicators

The Indicator Selection Process

In Germany, one of the most advanced countries in developing a full suite of all five types of indicators, the general process for indicator selection was to:

- Define the themes of particular importance to indication and reporting;
- Research potential indicators and data sources associated with those themes (sometimes indicators are developed by scrutinizing available data, sometimes they are developed based on what was hoped to be measured);
- Consider existing indicators;
- Determine key criteria for indicator selection; and
- Carry out criteria-based prioritization in mini-group sessions (Schönthaler *et al.*, 2011).

Many organizations and agencies that have developed climate adaptation and resilience indicators have taken similar approaches, albeit with slight variations. In Germany, the prioritization process was mostly undertaken via group sessions with experts. In some cases, draft indicator lists were mailed to experts for initial input prior to workshops to review indicators. In the U.K., a broader base of stakeholders who both use and develop indicators were involved in an initial workshop to help define success in adaptation and identify indicator needs and concerns (Sniffer, 2012). In Germany, representatives from all departments of the federal government were involved in the selection process (Schönthaler *et al.*, 2011). It has been observed that the credibility and utility of the indicators can strongly be improved by ensuring robust engagement of relevant expertise in their development (Sniffer, 2012)

Potential Criteria

The types of criteria used to select climate change indicators are many and varied, and fall under four general categories:

Data Criteria

1. *Measurability*: is the indicator easily measurable, and can it be measured quantitatively (Natural England, 2010)?

2. *Data availability and cost*: does appropriate and reliable data already exist and is it collected on regular intervals at different scales, or can it easily be gathered, and is collecting the data affordable (Cannell *et al.*, 2003; Natural England, 2010; UNFCC, 2010)?

3. *Data reliability*: is the data, or can the data be, collected and analyzed using scientifically valid data methods that can support sound conclusions (Erhard *et al.*, 2003; Kadir *et al.*, 2013)? Is there agreement on the data validity, data collection methods and statistical methods (Erhard *et al.*, 2003)?

4. *Historical data*: is there historical data that can be analyzed for trends (Cannell *et al.*, 2003; Natural England, 2010)? Does the historical data have an appropriate length of time series in relation to the response time of the indicator (Erhard *et al.*, 2003)?

5. *Continuity/consistency*: can consistent comparable data for the indicator be collected over time (Natural England, 2010)? Are data available over an unbroken time series (Sanahuja, 2011)? The frequency with which data is available and the data collection cycle are also key factors to consider (Miller *et al.*, 2012).

6. *Scalability/site specificity/coverage/spatial representation*: can the indicator be measured on different scales? (UNFCC, 2010), Can it be measured realistically for the entire geographic area under consideration? Do the data allow for international comparability (Erhard *et al.*, 2003)? Will aggregating the indicator to a national or regional level result in the loss of information regarding hot spots (Harley *et al.*, 2008)? Is the indicator relevant across the entire geographic area? DEFRA in the U.K. found that it could not possibly measure all of the indicators that it was interested in across all of the U.K. and thus choose to measure certain indicators only in

locations where extremes were expected to be experienced, or in areas particularly vulnerable to climate changes, such as coastal areas (Cannell *et al.*, 2003). In this way indicators became specific to an area, such as “rainfall in S.E. Britain.”

Usefulness Criteria

1. *Relevance/representativeness*: does the indicator measure what we need it to measure? Does it measure progress towards an objective? Does the indicator measure progress regarding an important or determining factor, rather than a less important one (UNFCC, 2010)? In the case of adaptation indicators, a key element will be defining adaptation goals or characteristics of resilient ecosystems or communities to be moving towards (Natural England, 2010).
2. *Sensitivity*: does the indicator distinguish meaningful differences in conditions (Kadir *et al.*, 2013; Natural England, 2010)? In particular, is the indicator sensitive to climate, and conversely is it insensitive, or relatively insensitive, to non-climate factors (Cannell *et al.*, 2003)? Because it could not include indicators or data for every region of the U.K., DEFRA (2003) focused on areas that would experience extremes or indicators that were particularly sensitive to climate change. Indicators that were too sensitive to non-climate factors were excluded (Cannell *et al.*, 2003), which can help address issues of attribution discussed above.
3. *Decision-support/need*s: does the indicator provide useful information for decision-making (Cannell *et al.*, 2003)? Does it meet the needs of stakeholders (Sniffer, 2012)? Determining the precise types of decisions to be supported is important. If the goal is to monitor and understand the sensitivity of certain systems to climate changes, detailed data from a few systems might suffice. If the goal is to inform specific adaptation actions in specific locations, then more comprehensive geographical coverage may be required (Füssel *et al.*, 2013).
4. *Broader applicability*: can the indicator be utilized to measure something else, such as progress toward sustainability, or biodiversity (Cannell *et al.*, 2003; Natural England, 2010; UNFCC, 2010)? Can it be incorporated into a larger integrated assessment tool (Erhard *et al.*, 2003)? Is the indicator already part of a larger indicator suite? This a cost-saving measure and also offers greater potential for accessing long-term good quality data.
5. *Consideration of extremes and means*: Erhard *et al.*, (2003) point out that both mean values and extreme events are critical to understanding what is happening in a changing climate, thus a suite of indicators relating to climate change should include indicators that measure both extremes and means.

Understandability and Acceptance Criteria

1. *Concreteness/specificity*: indicators must be transparent, not composite, and clearly defined (Natural England, 2010). Indicators that contain words or phrases such as “quality of life” (César *et al.*, 2013) need to be clearly defined or they will be difficult to measure and compare over time.
2. *Understandability/accessibility*: it is important for indicators, and the significance of changes in indicators, to be easily understood by scientists, decision-makers and the public (Cannell *et al.*,

2003; Erhard, *et al.*, 2003; Natural England, 2010). It is helpful if the indicator is immediately accessible and understandable by its name (Erhard, *et al.*, 2003). This is particularly important for climate adaptation indicators if they are to communicate meaningful information to people without an adaptation background (Sniffer, 2012).

3. *Public awareness/support/interest*: is the indicator acceptable to all stakeholders? Does it have public resonance? Is the public/target audience interested in it? (Cannell *et al.*, 2003; Erhard, *et al.*, 2003; Natural England, 2010).

Criteria Used by other Organizations

Harley *et al.*, (2008) state that indicators should be precise, robust, transparent, objective, simple, relevant and measurable at different spatial and temporal scales, clear and easy to understand. Table 21 lists the main criteria used by other organizations based on the general definitions above. Care must be taken in interpreting these criteria: while the organizations often adopt similar terminology, they sometimes use slightly different definitions for the terminology or do not provide clear definitions. Table 21 suggests that some combination of relevance, data quality, sensitivity to climate and understandability are key criteria in selecting indicators related to climate change.

Table 21: Criteria for Evaluating Indicators

(UNFCC, 2010)	**(Kadir *et al.*, 2013)**	**Natural England (2010)**	**Cannell *et al.*, (2003)**
• relevant • measurable • specific • achievable • time-bound (SMART)	• representativeness • data quality • sensitivity • decision support	• relevance (progress towards objective) • measurability • consistency/ continuity • easily understood	• data already collected reliably • long term data available • sensitivity to climate • easily understood • already part of suite of indicators
EEA (2012)	**CCME (2003)**	**Erhard *et al.*, (2003)**	**Schönthaler *et al.*, (2011)**
• relevance • data quality and accessibility • sensitivity to climate • easily understood and accepted • robustness/known uncertainty • coverage	• measuring important changes • reliable long term data • clear and direct sensitivity to climate • coverage/data available for most parts of country	• relevance for policy makers • coverage/spatial representation • easily understood/ transparent • analytical soundness and measurability • potential inclusion in integrated assessment	• relevance (particularly cause and effect relationships) • scientific validity • data availability • connection with other indicator systems • ease of reporting at local level

Selecting and Applying Criteria

It is important to consider the following in a) selecting criteria for the evaluation of potential indicators, and b) applying those criteria:

There can be a conflict in maximizing a large number of criteria. Sometimes a preference for the use of indicators that are easily measurable can lead to the use of indicators that are not as relevant to the intended outcomes of the project or program (Lamhauge *et al.*, 2011). Accordingly, it may be valuable to identify priority criteria and an overall vision for the indicator suite. For example, because certain indicators were seen as particularly relevant and there was potential for the data issues to be resolved over time, the EEA decided to include indicators for which long-time series data were not available and for which there were no clear means of measurement at this time.

Data should not be the only driver. The availability and quality of data, while very important for the development of robust indicators, should not be the only driver. Schauser *et al.*, (2010) strongly caution against allowing indicators to become "solely supply driven" or developed in a particular form because of data constraints.

Indicators may need to be flexible over time, due to the uncertain nature of climate impacts. Where the need for flexibility is known in advance, it should be noted (Natural England, 2010; Schönthaler *et al.*, 2011). It may also be important to evaluate indicator suites on a regular basis. In the U.K., DEFRA selected a suite of indicators in 1999, collected an initial set of data (or used historical data) and then re-evaluated those indicators for their relevance in 2003 (Cannell *et al.*, 2003). A detailed analysis was prepared for each indicator outlining whether or not the indicator worked and why, and whether to continue using it. In addition, as part of this re-evaluation, indicator suites from other countries were reviewed to determine whether to recommend them for addition (Cannell *et al.*, 2003). In Germany, transparency of the indicator selection process was critical, as "it must be possible to remove indicators from the system which may prove to be less relevant at some stage in the future, whilst it must also be possible to incorporate other indicators" (Schönthaler *et al.*, 2011:21).

It may be important to select indicators for which data is not currently available, or to highlight gaps. The EEA selected a large number of indicators knowing it would monitor only some of them initially (Cannell *et al.*, 2003). In Germany, the approach was to clearly identify gaps arising from lack of data and sub-themes of the national adaptation strategy for which indicators were not available (Schönthaler *et al.*, 2011).

It may be important to have a target or a range for the desired number of indicators. Some climate adaptation programs have detailed indicators corresponding to each component of an intervention while others focus on an aggregate assessment of change in climate vulnerability, such as public perception of vulnerability (Lamhauge *et al.*, 2011). It is important to be realistic about how much data the organization undertaking the indicator analysis can collect year after year.

Indicator names are important. It is important that the indicator name be immediately identifiable while at the same time effectively conveying the meaning of the indicator. For example, for an indicator of precipitation it should quickly be evident whether it measures the total amount of rainfall, number of rainy days, or rainfall intensity (Erhard *et al.*, 2003).

Classifying Indicators Based on Criteria

As part of the process of examining potential indicators against their selected criteria, the State of California (Kadir *et al.*, 2013) and the European Topic Centre on Air and Climate Change (Erhard *et* *al.*, 2003) classified potential indicators on how well they met certain criteria generally related to data availability. Their classification systems are provided in Table 22 and 23 below:

Table 22: State of California Classification System

(Kadir *et al.*, 2013)	
Type I	Adequate data are available, supported by on-going, systematic monitoring or collection
Type II	Full or partial data generated by on-going, systematic monitoring and/or collection are available, but either a complete cycle of data has not been collected, or further data analysis or management is needed
Type III	Conceptual indicators for which no on-going monitoring or data collection are in place.

Table 23: European Topic Centre Classification System

(Erhard *et al.*, 2003)	
Type I (short- term)	All criteria are already fulfilled or will be fulfilled within a short-term perspective (within 0-2 years).
Type II (medium-term)	Many criteria are fulfilled within a medium-term perspective. Some analysis or data mining will however be needed (within 3-5 years).
Type III (long-term)	Many criteria are fulfilled within only a long-term perspective (6 to 10 years). Both model evaluation and data collection and processing are needed for these indicators.
Type IV	Potential indicator Indicators that are potentially interesting within a medium/long-term perspective, but need more analysis (e.g. because of links to other environmental issues). Further, it is unclear whether data exist and are available and/or models exist to evaluate future conditions.
Type V (soft indicator)	Attractive indicators that are, however, not sensitive enough to climate change and/or for which not sufficient data are available.
Type VI (not suitable as indicator)	According to the information available, this indicator is not feasible for observing climate change.

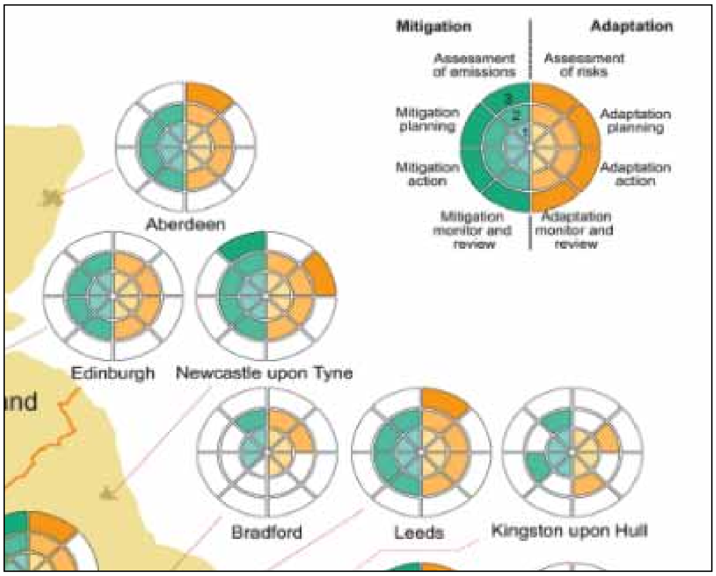
The European Topic Centre elected to maintain Type V and VI indicators on its list during the initial indicator evaluation process, even though they were likely to be excluded from the selected indicator suite for which data would be collected. Maintenance of a comprehensive list will allow for changes and re-assessment by experts. Types I to IV indicators were kept, even though data was not always available for Types III and IV indicators in the short- to medium-term.

A similar classification system was employed in Germany (Schönthaler *et al.*, 2011) where experts used set criteria to classify 126 potential indicators into four categories based on whether they could be implemented in 2014, or whether further data collection or methodological work would be required.

Interpretation and Use of Indicators

Once indicators have been selected and data gathered, interpreting and presenting the results is the next step. Indicators do not provide a single answer in respect of the overall increase in resilience of ecosystems or communities. What happens if some indicators show improvement while others show decline? How can this be interpreted in terms of increasing or decreasing adaptation? Some possible approaches are to devise an index of indicators, such as an overall resilience score. However, as outlined in the vulnerability indicator section, appropriately scoring and weighting the various indicators can be both subjective and challenging. Another approach is to present the indicator results graphically in disaggregate form, as Heidrich et al. (nd) did for Urban Climate Change Preparedness in the U.K. (see Figure 7). A public or expert grading of the indicators is yet another approach to determining what indicators mean and creating public resonance. While it is beyond the scope of this paper, these issues bear examination in further detail.

Figure 7: Urban Climate Preparedness in the U.K.



IV: Conclusions

This literature review explored the current state of research and experience associated with climate change indicators, climate impact indicators, vulnerability indicators and climate adaptation indicators in jurisdictions around the world. It also considered uses of and challenges associated with developing five types of indicators and potential criteria for indicator selection. Despite the challenges associated with the development of indicators relating to climate change, many countries and regions, particularly Germany, the U.K. and the European Union, are moving forward with development and implementation, offering many useful lessons and insights.

Climate change indicators and climate impact indicators are usually treated together. Several comprehensive indicator suites have been in use in a variety of countries for almost a decade. Significant challenges remain in acquiring data for many climate impact indicators, particularly those related to socio-economic and health impacts, which often requires the use of snapshot, proxy or narrative data. Scale issues must also be resolved.

Vulnerability indicators are in an earlier stage of development. They are the most challenging to develop due to the vulnerability construct's reliance on exposure, sensitivity and adaptive capacity. Measuring vulnerability to one potential climate impact, such as heat vulnerability or flood vulnerability, often requires consideration of climate data, socio-economic data and biophysical data.

As a result, many vulnerability indicators are composite indices with many sub-indicators or sub-indexes that must be aggregated to produce a final result. Developing appropriate methodologies for aggregation, identifying the appropriate data, and acquiring that data are all major challenges. Despite the difficulties, many potential vulnerability indicators have been developed and, due to their complexity, can potentially serve as a more comprehensive measure of a community, population, ecosystem or economic sector's preparedness for climate change than can single indicators. As a result, some organizations are focusing on vulnerability indicators instead of adaptation indicators to measure climate adaptation. This is based on the premise that reduced vulnerability is a measure of successful adaptation.

Climate adaptation indicators are also in early stages of development and can be divided broadly into process indicators and outcome indicators. Process indicators measure the development and implementation of climate adaptation actions and policies while outcome indicators measure the effects of and the effectiveness of those actions and policies. It is expected that a combination of these two indicators is necessary to measure climate adaptation. Given that climate adaptation efforts in many jurisdictions are also in early stages, process indicators might be most important in the short-term. Critical challenges associated with measuring climate adaptation include the long time scales associated with adaptation, lack of data, the reverse logic of many adaptation actions and attributing outcomes to adaptation actions due to the presence of multiple external factors influencing vulnerability. Many potential process and outcome indicators exist and defining the characteristics of success in adaptation is a core step in determining which indicators are most appropriate.

Resilience indicators were also studied. Resilience is often considered as the opposite of vulnerability. In developing these indicators, resilience is sometimes defined more narrowly to reflect just one component of vulnerability (adaptive capacity), or two components of vulnerability (sensitivity and adaptive capacity), or it is not defined in counterpoint to vulnerability at all. As a result, there are many different approaches to defining resilience and many different approaches to developing resilience indicators. As with vulnerability, resilience indicators are composite indicators and are more challenging to develop. There is no accepted approach to developing resilience indicators at this time.

There is a wide range of potential criteria for selecting indicators that fall under the categories of data criteria (data availability, reliability, cost and spatial representation), usefulness criteria (degree to which the indicator is relevant and sensitive to climate change and provides useful information) and understandability and acceptance criteria (the transparency, understandability and public acceptance of an indicator). Most organizations use some combination of relevance, data quality, sensitivity to climate and understandability in selecting indicators related to climate change. Once potential indicators have been selected using consistent criteria they can be classified into types based on whether appropriate data and modeling techniques are available immediately, expected in the medium-term or not available at all. Indicators for which no data or modeling techniques are available may still be kept on the list if they are particularly relevant. Once indicators are selected, approaches to interpreting indicators should be considered.

V: References

Balica, S. F., N. G. Write and F. van der Meulen (2011). A flood vulnerability index for coastal cities and its use in assessing climate change impacts, Natural Hazards. 64(1): 73-105.
http://link.springer.com/article/10.1007/s11069-012-0234-1#page-1
Accessed November 5, 2013.

Beckmann, Kate. (2012). Literature relevant for the Development of Adaptation Indicators: Scoping Review for the Scottish Context, Sniffer.
http://www.sniffer.org.uk/files/7213/4631/9842/Sniffer_ER23_Phase_1_final_report.pdf
Accessed November 20, 2013.

Berkes, F. and D. Jolly (2001). Adapting to Climate Change: Social-Ecological Resilience in a Canadian Western Arctic Community. Conservation Ecology (5(2):18.
http://www.ecology.ethz.ch/education/Resilience_Stuff/Berkes_and_Jolly_2001.pdf
Accessed January 30, 2014.

Buizer, James L., Paul Fleming, Sharon L. Hays, Kirstin Dow, Christopher B. Field, David Gustafson, Amy Luers, and Richard H. Moss, Report on Preparing the Nation for Change: Building a Sustained National Climate Assessment Process, National Climate Assessment and Development Advisory Committee, 2013.
http://origin.library.constantcontact.com/download/get/file/1102306387692-334/NCA-SASRWG%2520Report.pdf
Accessed November 6, 2013.

Canadian Council for Ministers of the Environment (CCME) (2003). Climate, Nature, People: Indicators of Canada's Changing Climate. Climate Change Indicators Task Group of the Canadian Council of Ministers of the Environment.
http://www.ccme.ca/assets/pdf/cc_ind_full_doc_e.pdf
Accessed October 23, 2013.

Cannell, Melvin, Tommy Brown, Tim Sparks, Terry Marsh, Terry Parr and Glen George (2003). Review of U.K. Climate Change Indicators. Department for Environment Food and Rural Affairs.
http://www.ecn.ac.uk/iccuk/
Accessed October 22, 2013.

Carpenter, S., B. Walker, J. M. Anderies and N. Abel (2001). From Metaphor to Measurement: Resilience of What to What? Ecosystems, 4(8):765-781.

Center for Environmental Systems Research (CESR) (2010). Background Document on Vulnerability indicators for the project Climate Adaptation – modeling water scenarios and sectoral impacts. European Commission, Directorate-General Environment.
http://climwatadapt.eu/vulnerabilityindicators
Accessed November 4, 2013.

César, Emelie, Gunilla Olund Winqvist, and Susanne von Walter (2013). Climate change adaptation indicators. A Logic framework assessment and indicator analysis of Sida's bilateral and regional contributions under the framework of the Climate Change Initiative. SIDA's Helpdesk for Environment and Climate Change.
http://sidaenvironmenthelpdesk.se/wordpress3/wp-content/uploads/2013/05/Final-Report-LFA-and-indicator-analysis-20130410.pdf
Accessed October 15, 2013.

Climate Change Commission (CCC) (2012). National Climate Change Action Plan 2012-2028. Office of the President of the Philippines, Climate Change Commission.
http://climate.gov.ph/index.php/documents/category/36-nccap-technical-document
Accessed November 6, 2013.

Crane Droesch, Andrew, Nickey //Gaseb, Pradeep Kurukilasuryia, Andre Mershon, Katiella Mai Moussa, Dale Rankine and Alejandro Santos (2008). A Guide to the Vulnerability Reduction Assessment, United Nations Development Programme Working Paper.
http://betterevaluation.org/sites/default/files/Attachment_CBA_VRA_Guide_Dec_08.pdf
Accessed November 12, 2013.

Cutter, S., B. Boruff, and W. Shirley (2003). Social Vulnerability to Environmental Hazards, Social Science Quarterly, 84(2): 242-261.

Cutter, S.L., C.T. Emrich and C.G. Burton (nd). Baseline Indicators for Disaster Resilient Communities. Hazards and Vulnerability Research Institute, University of South Carolina.
http://www.resilientus.org/wp-content/uploads/2013/03/Susan_Cutter_1248296816.pdf
Accessed January 30, 2014.

Department for Environment, Food and Agriculture (2012). UK Climate Change Risk Assessment (CCRA)
http://www.defra.gov.uk/environment/climate/government/risk-assessment/
Accessed October 23, 2013.

Deutsche Gesellschaft für Internationale Zusammenarbeit GIZ (2013). Recommendations for Adaptation M$E in Practice. Discussion Paper
https://gc21.giz.de/ibt/var/app/wp342deP/1443/wp-content/uploads/filebase/me/me-guides-manuals-reports/GIZ-2013_Recommendations_for_adaptation_MaE_in_practice.pdf
Accessed November 6, 2013.

Döll P. and J. Zhang (2010). "Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations," Hydrology and Earth System Sciences Discussions. Vol. 7: 1305-1342.
http://www.hydrol-earth-syst-sci-discuss.net/7/1305/2010/hessd-7-1305-2010.pdf
Accessed October 29, 2013.

Elasha, B.O., N.G. Elhassan, H. Ahmed and S. Zakieldin (2005) Sustainable livelihood approach for assessing community resilience to climate change: case studies from Sudan. Assessments of Impacts and Adaptations of Climate Change (AIACC) Working Paper No. 17.
http://www.iflea.org/pdf/AIACC_WP_No017.pdf
Accessed January 30, 2014.

Environmental Change Network (ECN) (nd). The ECN Data Centre Biodiversity Indicators.
http://data.ecn.ac.uk/indicators/composite.asp?graphtype=UK
Accessed October 29, 2013.

Environmental Protection Agency (EPA) (2012). Climate Change Indicators in the United States, 2012. United States Environmental Protection Agency.
http://www.epa.gov/climatechange/pdfs/climateindicators-full-2012.pdf
Accessed October 21, 2013.

Erhard, Markus, Jelle van Minnen, and Thomas Voight (2002). Proposed Set of Climate Change State and Impact Indicators in Europe. Technical Report. European Topic Centre on Air and Climate Change.
http://acm.eionet.europa.eu/reports/CC%20State%20Impact%20Indicators%20in%20Europe
Accessed October 23, 2013.

Erikson, S. H. and P. M. Kelly (2007). "Developing Credible Vulnerability Indicators for Climate Adaptation Policy Assessment", Mitigation and Adaptation Strategies for Global Change, Vol 12 (4): 495-524.

European Commission and Food and Agriculture Organization (EC-FAO) (nd). Measuring Resilience: A Concept Note on the Resilience Tool. http://www.fao.org/docrep/013/al920e/al920e00.pdf
Accessed January 30, 2014.

European Environmental Agency (EEA) (2005). EEA core set of indicators – Guide. European Environmental Agency.
http://www.eea.europa.eu/publications/technical_report_2005_1
Accessed October 23, 2013.

European Environmental Agency (EEA) (2012). Climate change, impacts and vulnerability in Europe 2012: An indicator-based report. European Environmental Agency, Copenhagen.
http://www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012
Accessed October 23, 2013.

Fischer, A Paige, Travis Paveglio, Mathew Carroll, Daniel Murphy and Hanna Brenkert-Smith (2013). "Assessing Social Vulnerability to Climate Change in Human Communities near Public Forests and Grasslands: A Framework for Resource Managers and Planners," Journal of Forestry. 111(5):357-365.

Ford, James. D., Lea Berrang-Ford, Alex Lesnikowski, Magda Barrera and S. Jody Heymann (2013). "How to Track Adaptation to Climate Change: A Typology of Approaches for National-Level Application," Ecology and Society. 18(3):40. http://dx.doi.org/10.5751/ES-05732-180340
Accessed November 5, 2013.

Füssel, Hans-Martin, Mikael Hildén and André Jol (2013). "What do we know about climate change and its impacts – conclusions from a comprehensive European-wise assessment," Impacts World 2013, International Conference on Climate Change Effects, Potsdam, May 27-30.
http://www.climate-impacts-2013.org/files/wism_fuessel.pdf
Accessed October 23, 2013.

Glass, Jacob (2013). Vulnerability View: GAIN Index Rates Climate Change Preparedness, New Security Beat, the blog of the Environmental Change and Security Program, Woodrow Wilson International Center for Scholars.
http://www.newsecuritybeat.org/2013/07/vulnerabilty-view-gain-index-rates-climate-change-preparedness/#.Unf0VI0Z-70
Accessed November 4, 2013.

Guibert, G. (nd) Indicators of Urban Climate Resilience. USAID/Asia, Asian Cities Climate Change Resilience Network, Institute for Social and Environmental Transition.
*sidaenvironmenthelpdesk.se/.../Final-Report-LFA-and-**indicator**-analysis-...*
Accessed January 30, 2014.

Harley, Mike, Lisa Horrocks and Nikki Hodgson (2008). Climate change vulnerability and adaptation indicators. European Topic Centre on Air and Climate Change Technical Paper 2008/9.
http://acm.eionet.europa.eu/docs/ETCACC_TP_2008_9_CCvuln_adapt_indicators.pdf
Accessed October 24, 2013.

Harley, Mike and Jelle van Minnen (nd). A conceptual framework for developing adaptation indicators. Presentation
http://eccaconf.eu/presentations/PDF/ECCA2013-9-6_4_1-Harley.pdf
Accessed November 5, 2013.

Harley, Mike and Jelle van Minnen (2009). Development of Adaptation Indicators: European Topic Centre on Air and Climate change Technical Paper 2009/6. European Topic Centre. http://acm.eionet.europa.eu/docs//ETCACC_TP_2009_6_Adaptation_Indicators.pdf
Accessed October 11, 2013.

Harvey, A., Hodgson, N., Benzie, M., Winne, S., Smithers, R., Dresner, S., Drummond, P., Coleman, C., Horrocks, L., and Harley, M. (2011). Provision of research to identify indicators for the Adaptation Sub Committee, Report to UK's Adaptation Sub Committee.
http://downloads.theccc.org.uk.s3.amazonaws.com/ASC%202nd%20Report/ED56687%20Final%20Report%20Issue%203_130711.pdf
Accessed November 20, 2013.

Heidrick, Oliver, Richard Dawson and Claire Walsh (nd). Climate Change Preparedness of UK Urban Areas. Centre for Earth Systems Engineering Research, Newcastle University.
http://www.ncl.ac.uk/ceser/researchprogramme/integratedsystemsdemonstrationscities/climatechangepreparednessofukurbanareas/
Accessed November 20, 2013.

Ibarrarán, M.E., E.L. Malone and A.L. Brenkert (2008). Climate change Vulnerability and Resilience: Current Status and Trends for Mexico. U.S. Department of Energy.
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18136.pdf
Accessed January 29, 2014.

Kadir, Tamara, Linda Mazur, Carmen Milanes, and Karen Randles. (2013). Indicators of Climate Change in California. California Environmental Protection Agency (Cal/EPA), Office of Environmental Health Hazard Assessment.
http://oehha.ca.gov/multimedia/epic/pdf/ClimateChangeIndicatorsReport2013.pdf
Accessed October 22, 2013.

Lamhauge, N., E. Lanzi and S. Agrawala (2012). Monitoring and Evaluation for Adaptation: Lessons from Development Co-operation Agencies. OECD Environment Working Papers, No. 38, OECD Publishing.
http://dx.doi.org/10.1787/5kg20mj6c2bw-en
Accessed October 15, 2013.

Malone, E.L. (2009). Vulnerability and Resilience in the Face of Climate Change: Current Research and Needs for Population Information. Population Action International: Washington DC.
http://populationaction.org/wp-content/uploads/2009/08/Malone_resilience.pdf (Accessed January 29, 2014).

McAslan, A. (2011). Community Resilience: Understanding the Concept and its Application. Torrens Resilience Institute, Adelaide, Australia. http://www.torrensresilience.org/images/pdfs/understanding%20community%20resilience.pdf
Accessed January 30, 2014.

Miller, Karen, Nikki Kent and Mike Harley (2012). Climate change adaptation-related indicators: Desk study of climate indicator work outside of Scotland. AEA Technology, Glengarnock Technology Centre.
http://www.sniffer.org.uk/files/7213/4631/9842/Sniffer_ER23_Phase_1_final_report.pdf
Accessed November 20, 2013.

Miller, Sebastián, Sang W. Yoon, and Bok-Keun Yu (2013). Vulnerability Indicators of Adaptation to Climate change and Policy Implications for IDB Projects. Inter-American Development Bank Policy Brief No. IDB-PB-184.
http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=37725582
Accessed November 4, 2013.

Ministry of Water, Land and Air Protection (MWLAP) (2002). Indicators of Climate Change for British Columbia. Province of British Columbia.
http://www.env.gov.bc.ca/cas/pdfs/indcc.pdf
Accessed October 21, 2013.

National Aeronautics and Space Administration (NASA) (nd). Global Climate Change: Vital Signs of the Planet: Key Indicators.
http://climate.nasa.gov/key_indicators
Accessed October 21, 2013.

Natural England (2010). Climate change adaptation indicators for the natural environment. Natural England Commissioned Report NECR038.
www.naturalengland.org.uk
Accessed October 15, 2013.

Newson, Stuart E., Sonia Mendes, Humphrey Q. P. Crick, Nicholas K. Dulvy, John D. R. Houghton, Graeme C. Hays, Anthony M Hutson, Colin D. MacLeod, Graham J. Pierce, and Robert A. Robinson (2008). "Indicators of the impact of climate change on migratory species," Endangered Species Research. Vol. 7: 101-113.
http://www.int-res.com/articles/esr2009/7/n007p101.pdf
Accessed October 29, 2013.

OECD (Organization for Economic Co-operation and Development) (2010). Evaluating Development Co-operation: Summary of Key Norms and Standards. Second Edition. Paris, OECD.

Prowse, M. and Snilstveit, B. (2010). 'Impact Evaluation and Interventions to Address Climate Change: A Scoping Study', The International Initiative for Impact Evaluation (3ie), New Delhi
http://www.gsdrc.org/go/display&type=Document&id=3926
Summary Accessed October 14, 2013.

Sadik, Shibly and Rezaur Rahman (nd). Indicator Framework for Assessing Livelihood Resilience to Climate Change for Vulnerable Communities Dependent on Sundarban Mangrove System. 4th South Asia Water Research Conference on "Interfacing Poverty, Livelihood and Climate Change in Water Resources Development: Lessons in South Asia" May 4-6, 2009, Kathmandu, Nepal.
http://www.academia.edu/662620/Indicator_Framework_for_Assessing_Livelihood_Resilience_to_Climate_Change_for_Vulnerable_Communities_Dependent_on_Sundarban_Mangrove_System
Accessed January 29, 2014.

Sanahuja, Harris E. (2011). A Framework for Monitoring and Evaluating Adaptation to Climate Change. Climate-Eval. Global Environment Facility. http://www.climate-eval.org/sites/default/files/studies/Climate-Eval%20Framework%20for%20Monitoring%20and%20Evaluation%20of%20Adaptation%20to%20Climate%20Change.pdf
Accessed November 20, 2013.

Schauser, Inke. Sonja Otto, Stefan Schneiderbauer, Alex Harvey, Nikki Hodgson, Holger Robrecht, Daniel Morchain, Joost-Jan Schrander, Maria Khovanskaia, Gamze Celikyilmaz-Ademir, Andrea Prutsch and Sabine McCallum (2010). Urban Regions: Vulnerabilities, Vulnerability Assessments by Indicators and Adaptation Options for Climate Change Impacts: Scoping Study. European Topic Centre for Air and Climate change Technical Paper 2010/12, December 2010.
http://acm.eionet.europa.eu/reports/docs/ETCACC_TP_2010_12_Urban_CC_Vuln_Adapt.pdf
Accessed November 1, 2013.

Schönthaler, Konstanze, Stefan von Andrian-Werburg, Daria Nickel, Sonja Pieck, Jenny Tröltzsch, Helmut Kuchenhoff, and Stephanie Rubenbauer (2011). Entwicklung eines Indikatorensystems für die Deutsche Anpassungsstrategie an den Klimawandel (DAS): English Summary. Umweltbundesamt.
http://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4230.pdf
Accessed November 6, 2013.

Sivell, P.M., S.J. Reeves, L. Baldachin and T.G. Brightman (2008). Climate Change Resilience Indicators: Client Project Report CPR117. Prepared for the South East Regional Assembly. http://startinternational.org/library/archive/files/climate_change_resilience_indicators_f0b781aa19.pdf
Accessed January 29, 2014.

Sniffer (2012). Climate Change Adaptation-Related Indicators. Final Report, July 2012. http://www.sniffer.org.uk/files/7213/4631/9842/Sniffer_ER23_Phase_1_final_report.pdf
Accessed November 20, 2013.

Swanson, D., J. Hilley, H.D. Venema and R. Grosshans (2009). Indicators of Adaptive Capacity to Climate Change for Agriculture in the Prairie Region of Canada: Comparison with Field Observations. The Prairie Climate Resilience Project. International Institute for Sustainable Development.
http://www.iisd.org/pdf/2009/pcr_adaptive_cap_ag.pdf
Accessed January 30, 2014.

UNFCCC Secretariat, 2010, 'Synthesis report on efforts undertaken to monitor and evaluate the implementation of adaptation projects, policies and programmes and the costs and effectiveness of completed projects, policies and programmes, and views on lessons learned, good practices, gaps and needs', UNFCCC, Bonn
http://www.gsdrc.org/go/display&type=Document&id=3947
Accessed October 14, 2013.

Wongbusarakum, Supin and Christy Loper (2011). Indicators to assess community-level social vulnerability to climate change: An addendum to SocMon and SEM-Pasifika regional socio-economic monitoring guidelines.
www.socmon.org/download.ashx?docid=64623
Accessed November 4, 2013.