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Climate impacts on human livelihoods: where uncertainty matters in projections of water availability

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Abstract.

Climate change will have adverse impacts on many different sectors of society, with manifold consequences for human livelihoods and well-being. However, a systematic method to quantify human well-being and livelihoods across sectors is so far unavailable, making it difficult to determine the extent of such impacts. Climate impact analyses are often limited to individual sectors (e.g. food or water) and employ sector-specific target-measures, while systematic linkages to general livelihood conditions remain unexplored. Further, recent multi-model assessments have shown that uncertainties in projections of climate impacts deriving from climate and impact models as well as greenhouse gas scenarios are substantial, posing an additional challenge in linking climate impacts with livelihood conditions. This article first presents a methodology to consistently measure Adequate Human livelihood conditions for wEll-being And Development (AHEAD). Based on a transdisciplinary sample of concepts addressing human well-being and livelihoods, the approach measures the adequacy of conditions of 16 elements. We implement the method at global scale, using results from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) to show how changes in water availability affect the fulfilment of AHEAD at national resolution. In addition, AHEAD allows identifying and differentiating uncertainty of climate and impact model projections. We show how the approach can help to put the substantial inter-model spread into the context of country-specific livelihood conditions by differentiating where the uncertainty about water scarcity is relevant with regard to livelihood conditions - and where it is not. The results indicate that in 34 countries, livelihood conditions are compromised by water scarcity. However, more often, AHEAD fulfilment is limited through other elements. The analysis shows that for 65 out of 111 countries, the water-specific uncertainty ranges of the model output are outside relevant thresholds for AHEAD, and therefore do not contribute to the overall uncertainty about climate change impacts on livelihoods. In 46 of the countries in the analysis, water-specific uncertainty is relevant to AHEAD. The AHEAD method presented here, together with first results, forms an important step towards making scientific results more applicable for policy-decisions.

1 Introduction

Processes of global change are closely linked to human well-being and livelihood conditions. Global and regional impacts of climate change are expected to affect important societal sectors and have the potential to significantly reduce human welfare (Hare et al., 2011; Schneider et al., 2007; O'Brien et al., 2004). The linkages of various processes of global change to aspects of human well-being and livelihoods have been recognized in different contexts, including climate impacts (O'Brien et al., 2004), sustainable development (Dietz et al., 2009) and ecosystem services (MEA, 2005). While many approaches to define human well-being and livelihoods exist at various degrees of sophistication (O'Riordan, 2013; Alkire, 2002), an operable framework to assess and measure human well-being and livelihoods conditions in the context of climate change research does not exist so far. Yet, such a framework can provide an important means to assess the consequences of climate change for human welfare and societal systems, allowing to relate impacts of climate change to other development aspects and to compare impacts across sectors.

Uncertainty has proved to be a major impediment in climate-related policy decisions. Considerable uncertainty is associated with global models of climate and other biophysical processes, deriving from a range of factors (Schneider and Kuntz-Duriseti, 2002). Different types of uncertainty can be distinguished, some of which can be approached though further research or model improvement (epistemic uncertainty). Other aspects, such as uncertainty from scenarios, cannot be fully eliminated (aleatory uncertainty) (Dessai and Hulme, 2004). Uncertainty is an integral part of scientific analyses, however, in public perception it is often interpreted as ignorance or a lack of robustness (Sigel et al., 2010). To overcome barriers in the translation of scientific results into the policy process, uncertainty needs to be adequately framed (Smith and Stern, 2011). The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014) provides an important step towards explicitly and systematically addressing uncertainty deriving from climate impact models and emission scenarios and providing a consistent overview of the range of modelling results. While model improvements may reduce uncertainties to some extent, projections of future changes will always remain subject to aleatory uncertainties, as for example development pathways are not knowable. On the one hand, model- and scenario-related uncertainties can be made visible and quantified, as has been done with recent ISI-MIP results. On the other hand, methods to address the *relevance* of the uncertainty range for specific contexts can help in approaching the topic (Smith and Stern, 2011).

The central objectives of the present paper are two-fold, namely (I) to provide a method which addresses climate impacts in a wider context of human well-being and livelihood needs and (II) to show how this method can address the relevance of uncertainties within such assessments. While uncertainty itself is not reduced through the approach, its relevance for the system under consideration can be determined by viewing the uncertainty range in relation to a specific context. We first outline a novel methodology to measure *Adequate Human livelihood conditions for wEll-being*

And Development, further referred to as AHEAD. Based on a transdisciplinary sample of concepts, the approach provides an integrated quantification of livelihood conditions, which allows assessing climate impacts in a comparable way. After an initial implementation of the approach on a global scale, we show how climate as well as population change may affect overall fulfilment of AHEAD. For a fist implementation of the approach, we focus on the example of water scarcity which has been identified as a major challenge of the future (Grey et al., 2013).

Recently, Schewe et al. (2014) analysed the range of ISI-MIP models to determine developments of water scarcity over the course of the next century. Results show significant uncertainty associated with the output of global water models, which is often even larger than the uncertainty deriving from climate models. We show how the AHEAD approach can provide a framework to view these uncertainties in a context.

Section 2 outlines the background of the AHEAD framework and presents its mathematical representation. We implement the approach in a first calculation, using freely available data at national resolution of global coverage. To underline the relevance of such an approach for climate impact research, we use results from the ISI-MIP project to outline the effects of changes in water availability on AHEAD. We assess in detail, how uncertainties associated with projections of potential future developments can be addressed within the framework. We analyse the results in Section 3 and critically discuss the method and results in Section 4. A brief conclusion completes our paper.

2 Methods and Materials

2.1 Identifying elements of AHEAD

The aim of the AHEAD approach is to quantify the Adequacy of Human livelihood conditions for wEll-being And Development, measured trough a set of elements. These elements include a range of tangible as well as intangible aspects, which represent an extended set of basic human needs (Littig and Griessler, 2005). Conceptually, elements of AHEAD are generally valid and globally applicable, allowing for a systematic and comparable assessment of livelihood conditions across space and time.

To derive a consistent set of elements to outline such conditions, AHEAD is based on a transdisciplinary set of approaches, identified trough a qualitative literature review (for a detailed outline of the conceptual basis of the AHEAD methodology see Lissner et al. (accepted)). On the basis of 11 theories, namely Maslow's Theory of Human Motivation (Maslow, 1943), the Basic Human Needs Approach, (McHale and McHale, 1979; Doyal and Gough, 1984; Weigel, 1986), Human Scale Development (Max-Neef, 1992; Cruz et al., 2009) the Capability Approach (Sen, 1985; Anand et al., 2008; Gasper, 2007; Nussbaum, 2000), Human Security (Gasper, 2005; UNDP, 1994; King and Murray, 2001), Sustainable Livelihoods (Scoones, 1998; Chambers and Conway, 1991), Quality of Life (QoL) (Cummins, 1996; Costanza et al., 2007), Subjective Well-Being (SWB) (Diener et al. (1999), cited in Alkire (2002)), the Millennium Ecosystem Assessment (MEA, 2005), Dimensions of

Poverty (Narayan et al., 2000) and the Measurement of Economic Performance and Social Progress (Stiglitz et al., 2009), we identify a set of 16 elements, which are relevant to measure AHEAD for climate impact research (see Figure 1). Detailed descriptions of AHEAD elements are available in the Supplementary Material, Table 1 (Lissner et al., 2014a, published on figshare).

In order to translate these identified elements into a quantified representation, we refer to the conceptual distinction between needs and satisfiers introduced by Max-Neef (1992) (see also Narayan et al., 2000; Sen, 1993). The *elements* of AHEAD (needs in Max-Neefs definition) constitute essential requirements to attain well-being and adequate livelihoods and are generally valid and globally applicable. However, the *satisfiers*, which can be used to access to these elements and meet needs may vary across space and time, for example according to cultural preferences or development status and various resources can contribute to meet needs. Further, following the underlying literature, no hierarchy can be assumed to exist between elements, with the exception of those elements directly relevant to physical survival (Max-Neef, 1992; Sen, 1993). For the purpose of measuring the fulfilment of AHEAD, we want to assess whether the availability of each element is *adequate* to meet human livelihood needs. Adequacy in this context refers to a situation, where elements are sufficiently available in quantity and quality to meet basic needs and permit a life in dignity (Wicks, 2012) as recognized for example in the Universal Declaration of Human Rights (UN, 1948). Adequate conditions therefore do not refer to a situation of luxury, but the sufficient availability of relevant resources. Similarly, inadequate conditions do not necessarily imply complete deprivation, but refer to a situation where livelihood needs are no longer met and development is compromised.

To facilitate the measurement of AHEAD, we group the 16 elements into three categories, (see Figure 1). Elements directly relevant to physical human survival are grouped into the domain of *Subsistence*, namely water, food and air. The remaining elements can be grouped according to their tangibility: aspects such as shelter and adequate sanitation provide essential *Infrastructure*. Further elements in this group include education, health care, as well as energy access, communication and mobility. Intangible aspects are relevant in their contribution to the *Societal Structure* and include social protection, security, participation, social cohesion as well as economic and political stability. In order to provide an estimate of comparable AHEAD at national resolution and global scale, we rely on data sets available at this level of detail and with as few missing values as possible.

The following paragraphs outline the method and discuss available data for a first implementation. We study in detail the relevance of changes in water availability for AHEAD over the course of the century, while the remaining elements are kept constant over time.

2.2 Integrating elements of AHEAD

Representing the concept of adequacy in mathematical terms can be difficult. The definition of exact thresholds of the sufficient availability of an element can be challenging, due to vagueness and uncertainties associated with such linguistic concepts. Fuzzy reasoning provides a means to express the degree of membership to linguistic concepts, thus translating qualitative elements into quantifiable units (for details see e.g. Kropp et al., 2006; Lissner et al., 2012; Zadeh, 1965) and allowing for the consideration of inherent vagueness. By calculating the degree of membership of each variable to a common linguistic category, namely the adequacy of conditions, the diverse range of elements become comparable with regard to their contribution to fulfilled AHEAD conditions.

The first step of the analysis is the fuzzification of the base variables with respect to a defined linguistic category. A function to calculate the degree of membership to the linguistic category is defined for each variable. In the case of our analysis, the degree of membership μ of each variable to the linguistic category "conditions are adequate" is determined. Fuzzified data sets take continuous values from 0 (adequacy is very low) and 1 (adequacy is very high). For the purpose of determining the fulfilment of AHEAD, fuzzy values near 0 reflect a basic level of resource availability, below which development would be compromised. Fuzzy values near 1 indicate a level of sufficiency, where basic needs are fully met and conditions are adequate.

Thresholds for membership (ι_1, ι_2) are defined to calculate continuous degrees of membership μ_{zi} of variable ι through Eq. 1 (linear increase), Eq. 2 (linear decrease), Eq. 3 (exponential increase) and Eq. 4 (exponential decrease). For Eq. 3 and 4, the value of ϵ determines the curvature of the function. For all Equations 1 through 4 $\iota_1 < \iota_2$ must be true. As the values for ι_1 and ι_2 critically determine the membership values for each element and thus the overall result, thresholds have to be context-specific and reflect the properties of the available data. Threshold values and membership functions for the analysis and are discussed in detail in the following Sec. 2.3 and are summarized in Table 1.

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{\iota - \iota_1}{\iota_2 - \iota_1}, & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \tag{1}$$

$$\mu_{zi}(\iota) = \begin{cases} 1, & \iota \leq \iota_1 \\ \frac{\iota_2 - \iota}{\iota_2 - \iota_1}, & \iota_1 < \iota < \iota_2 \\ 0, & \iota_2 \leq \iota \end{cases} \tag{2}$$

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{1}{1 - exp(-\epsilon)} \times (1 - exp[-\epsilon \frac{\iota - \iota_1}{\iota_2 - \iota_1}]), & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \tag{3}$$

$$\mu_{zi}(\iota) = \begin{cases} 1, & \iota \leq \iota_1 \\ \frac{1}{1-exp(-\epsilon)} \times (1 - exp[-\epsilon \frac{\iota_2 - \iota}{\iota_2 - \iota_1}]), & \iota_1 < \iota < \iota_2 \\ 0, & \iota_2 \leq \iota \end{cases} \tag{4}$$

Subsequent to their fuzzification, variables are aggregated using context-specific aggregation rules in a defined order (Fig. 1). The choice of aggregation rules should reflect the context of the analysis and be motivated by the properties of the indicators. Fuzzy decision rules thus allow incorporating the content-related properties of and relationships between variables. Operators for the aggregation are defined analogue to crisp set theory and additional fuzzy operators are available (Mayer et al., 1993). Unlike the strict application of boolean MIN or MAX operators, which result in a strict intersection or union of sets, fuzzy operators allow for compensation through a γ-value, which can take values between 0 and 1 (Equation 5 for fuzzy MIN; analogue quantification for fuzzy MAX) (Kropp et al., 2001). The introduction of γ results in the consideration of the arithmetic mean of all input values to some extent, thus diluting the strict application of the operator to the extent of γ, with values near to 1 resulting in a rather strict application of the operator and values near 0 introducing significant compensation. At γ=0 the arithmetic mean of the input values is calculated.

$$\mu(z_1 \wedge z_2 \wedge \ldots \wedge z_n) = \gamma * \min(\mu_{z1}, \mu_{z2}, \ldots, \mu_{zn}) + (1-\gamma) * \frac{1}{N} \sum_{i=1}^{N} \mu_{zi} \tag{5}$$

To assess the fulfilment of AHEAD, the characteristics of the contributing elements as well as their relationships determine the rules and order of aggregation, as outlined in Figure 1. Initially, the three dimensions of Subsistence, Infrastructure and Societal Structure are aggregated individually. An essential property of the elements of the Subsistence dimension is that they are non-substitutable: if one of the elements water, food or clean air is not available, it poses a direct threat to human health and well-being. Indicators within this dimension are therefore aggregated using a strict MIN operator with γ=1 (left column of Fig. 1). Elements relevant for the Societal Structure dimension, however, may to some extent be substitutable. Low availability of one resource may to some extent be compensated with the high availability of another, which is reflected in using the arithmetic mean (γ=0) (right column of Fig. 1). While those elements included in the Infrastructure dimension are not substitutable in a physical sense, high values in one of these domains imply high levels of technological advancement, which motivates the use of the arithmetic mean here (middle column of Figure 1). The final aggregation of the three dimensions to the full index of AHEAD reflects the fact that all three components are required to attain adequate conditions. We aggregate the dimensions Infrastructure and Societal Structure using a fuzzy MIN operator with γ = 0.6. This use of γ accounts for the fact that levels of adequacy in both dimensions are required for fulfilled livelihoods, but fully adequate conditions in one area may compensate other deficiencies to the extent of γ. While the order of magnitude and likely ranges of γ can be motivated by the context, the exact value is to some extent arbitrary within the in the global implementation of the approach. The subsequent aggregation of all dimensions to a measure of AHEAD is performed using a strict MIN operator (γ = 1), again reflecting the non-substitutability of the Subsistence domain.

2.3 Data and fuzzy membership functions to calculate the fulfilment of AHEAD

We implement the AHEAD index at global scale, relying on freely available data on national resolution (Table 1). As we rely on data sets that are available with global coverage, the consideration of possible satisfiers is limited in some cases, as only selected indicators are raised at this scale. Applied fuzzification methods for each variable are motivated by results from the literature as presented in Table 1. A more detailed summary of the translation of elements into a quantified representation in available in the Supplementary, Table 1 (Lissner et al., 2014a). Most elements can be represented with single datasets (Table 1). For the representation of some elements composite indicators have to be calculated, derived as follows:

- Water: sufficient water availability is essential both, directly, in terms of drinking water, as well as indirectly as an essential prerequisite for other elements, such as food and energy production. Drinking water availability is often not restricted by actual resource availability, but rather low quality or unimproved access are limiting factors (Rijsberman, 2006). Looking beyond physical water resources alone, 'water' is therefore represented using the two indicators 'access to improved water source', as well as 'available water resources', aggregated via a MIN operator. Adequate water resource availability refers to the cumulative water needs of all sectors.

- Air quality: both indoor and outdoor air quality determine health effects. The main determinant for indoor air quality is the use of solid fuels for heating and cooking, whereas negative health effects of outdoor air derive mainly from concentration of particulate matter (PM) (Klugman, 2011). The two indicators 'solid fuel use' and 'PM10 concentration' are aggregated using a MIN operator.

- Health care: the Human Development Index (HDI) includes the indicator 'life expectancy at birth' to represent the capability of leading a long and healthy life (Klugman et al., 2011). We combine the indicator with the average 'number of doctors per capita', using the arithmetic mean.

- Social protection: refers to a source of support available should one not be able to support oneself. In our analysis we identified three indicators, which can provide this support: 'institutional solidarity', 'traditional (community) solidarity' as well as 'access to micro credits' (de Crombrugghe et al., 2009). As either one of these can fulfill the need for support, we use a MAX operator for the aggregation.

– Economic stability: refers to conditions that enable the population to plan ahead and feel secure regarding the prospects for the future. We use the 'existence of labor legislation' and the degree of 'rigidity of employment contract' to represent 'economic stability' (de Crombrugghe et al., 2009). Indicators are aggregated with the arithmetic mean.

– Education: we use the HDI 2010 methodology (Klugman, 2011), which represents access to education with the two indicators 'mean years of schooling' as well as the 'expected mean years of schooling', aggregated with the arithmetic mean.

– Communication: we combine the indicators 'number of mobile phones' and 'number of internet users' as representatives of access to communication infrastructure, which have been recognised as essential tools of development (UN ICT Task Force, 2005), using a MAX operator.

Thresholds ι_1 ι_2, as well as the shape of the membership function (Eq.1-4) to fuzzify each input dataset, which are discussed in the following paragraphs, are motivated by literature (for an overview of all membership functions as well as the frequency distribution of the input data see Fig. A1a and A1b, Appendix). For the purpose of representing the adequacy of 'available water resources' for AHEAD, we use the Falkenmark Indicator, which defines a range of per capita water resource needs based on empirical estimates, including the domestic, agricultural and industrial sectors. We note that the application of such globally homogeneous thresholds represents a simplification which we deem appropriate for the purpose of the present, global study. Annual renewable water resources per capita (m^3 cap $^{-1}$yr^{-1}) below 500 m^3 cap $^{-1}$yr^{-1} indicate absolute water scarcity (ι_1), while an availability of more than 1400 m^3 cap $^{-1}$yr^{-1} indicates no water stress (water security) (ι_2) (Falkenmark, 1997; Brown and Matlock, 2011; Falkenmark and Rockström, 2004). Data sets for the variables 'access to improved water source' as an additional aspect of water availability, as well as 'access to improved sanitation' are grouped into three and four classes, representing the quality of access. For each country, the available data provides the percentage of households belonging to the respective class. To make use of this classification, we weigh each group according to the quality of access, as outlined in Howard and Bartram (2003). The classification and associated weights are as follows: access to water: (a) piped onto premises, weight 1, (b) other improved water source, weight 0.6 and (c) unimproved water source, weight 0.2; sanitation: (a) improved sanitation, weight 1, (b) shared facilities, weight 0.6, (c) unimproved sanitation, weight 0.2 and (d) open defecation, weight 0. The classes are then summed up, resulting in continuous values between 0 and 1, indicating the overall degree of adequacy of access.

It has been shown that a moderate increase in calorie intake has higher nutritional benefits at the lowest levels of calorie intake, approximated here by the use of a curved membership function (Equation 3) with $\epsilon = 3$ (Whitlock et al., 2009). Lower and upper thresholds refer to specifications by the FAO, who calculate minimum dietary requirement (MDER) for all countries, reflecting the demographic situation and propose a global average ideal nutrition level of 2800 calories $cap^{-1}day^{-1}$ (FAO, 2001). The effects of particulate matter on human health are especially strong at concentrations above 100ppm, while levels below 15ppm are acceptable (Desai et al., 2004); at lower concentrations health effects decrease (Pope III et al., 2002). The thresholds for the variables life expectancy at birth, as well as actual and expected mean years of schooling are set as used for the calculation of the HDI 2010 (Klugman et al., 2011). Adequate health coverage is likely to be achieved with a minimum health worker density of at least 0.0025 cap^{-1} and should be guaranteed at a density of 0.005 cap^{-1} (Chen et al., 2004).

Membership to the linguistic variable 'indoor air quality is adequate' is calculated using the indicator 'solid fuel use'. As some use of solid fuels can have lifestyle aspects, as for example in fireplaces (Lillemo and Halvorsen, 2013) we set the lower threshold to 5%, which represents fully adequate conditions. Membership decreases linearly up to a solid fuel use of 100%. We set the minimum electrification at 80% and calculate a linear increase of membership up to 100%, reflecting the fact that energy access is fundamental to many livelihood aspects, e.g. communication and most general household needs (Gaye, 2008) and restricted access also restricts many other livelihood needs. Both indicators for communication, the number of internet and mobile phone users, are fuzzified using continuous values between 0 and 1 cap^{-1}. For the fuzzification of mobility data we set ι_1 at 0.5 motor vehicles per cap^{-1}, as this reflects the lowest values of high HDI countries (World Bank, 2009). Similarly, ι_2 at 0.2 cap^{-1} reflects values in very low HDI countries.

Input data available to measure the Societal Structure are ranked continuously on a scale from 0 or 1 to 4. This ranking scale stems from the collection and preparation methodology of the data, where values of 0 mean that the respective element is not available at all, values near 1 represent low values and values of 4 indicate high availability or fulfilment of the respective element (de Crombrugghe et al., 2009). The linguistic representation of adequacy is thus already implemented in the initial classification and can directly be used in the fuzzy logic algorithm. Table 1 summarizes the relevant parameters for the fuzzification of elements and specifies the used datasets and sources (also see Supplementary, Table 1, for further details on the used indicators).

Data coverage differs slightly for the three dimensions of AHEAD and each dimension has missing values for some countries; the full measure was calculated for all cases with full data coverage across elements (111 countries). Shelter is the only aspect that cannot be represented adequately because of missing data and is therefore not included in the present analysis [1]. For the majority of indicators, no consistent scenarios are available. To address the question how potential climate change impacts may affect human livelihood conditions, we employ data from the Inter-Sectoral

[1] Data on housing availability and quality is scarce. The available slum indicator used for measuring the Millennium Development Goals, for example, is an aggregate of five indicators: access to improved water, access to improved sanitation, sufficient-living area, durability of housing, security of tenure, of which only access to water and sanitation have acceptable coverage (143 countries, compared to 53 to 68 countries for the other indicators). Both of these indicators are resolved individually in the analysis. Source: http://www.unhabitat.org/stats/

Impact Model Intercomparison Project ISI-MIP to address how changes in water availability affect AHEAD fulfilment.

2.4 Scenarios of water availability

For the analysis of water resource availability, we use global gridded runoff and discharge data, which has been calculated in the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; (Warszawski et al., 2014)). Simulations cover output by the impact models (IM) DBH (Tang et al., 2007), H08 (Hanasaki et al., 2008), Mac-PDM.09 (Gosling and Arnell, 2011), MATSIRO (Takata et al., 2003), MPI-HM (Stacke and Hagemann, 2012), PCR-GLOBWB (Wada et al., 2010), VIC (Liang et al., 1994), WaterGAP (Döll et al., 2003), and WBMplus (Wisser et al., 2010) hydrological models, the JULES (Best et al., 2011) land–surface model, and the LPJmL (Bondeau et al., 2007) dynamic global vegetation model. The models were driven by bias-corrected (Hempel et al., 2013) climate data from five global climate models (GCM) that participated in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. (2012)), based on four Representative Concentration Pathways (RCPs; (Moss et al., 2010)). As a first-order indicator of available renewable freshwater resources, we calculate annual mean runoff at each grid cell, and then redistribute it within each river basin according to the spatial distribution of discharge to account for cross–boundary flows between countries (Gerten et al., 2011). The result is summed up over every country and divided by the country's population to obtain water resources per capita per year. Country-level population data according to UNWPP estimates for the historical period, and according to the Shared Socio-economic Pathways SSP2 (ONeill et al., 2012) projection for the future, is obtained from the SSP Database at https://secure.iiasa.ac.at/web-apps/ene/SspDb and linearly interpolated to obtain annual values. For further details about the model simulations, see also Schewe et al. (2014). We calculate average per capita water availability for a baseline of 1981-2010 (2000) and calculate projected changes for the scenario period 2071-2099 (2090). Years in brackets will be used throughout the paper as a reference to the 30-year average. We calculate water availability for each RCP and each IM-GCM combination individually and also calculate the average across models (ensemble mean). Per capita water availability is then translated into fuzzy values as discussed in the previous section. We include scenario data for water availability only, while other elements of AHEAD are kept constant over time. Changes in conditions are thus a function of changes in water availability over the course of the century.

2.4.1 Assessment of the relevance of uncertainty

Finally, we analyse AHEAD results with regard to the relevance of the uncertainty associated with the RCPs as well as the IMs and GCMs. As a result of the different levels of warming associated with the RCPa as well as differences between models, projections of future water availability differ, leading to a spread of results (inter-model spread).

We categorize our results according to the relevance that this inter-model and scenario spread has for the results of our analysis. Following the decision tree outlined in Figure 2, we differentiate several combinations, which determine whether the modelling and scenario induced uncertainty affect AHEAD results. As the inter-model and scenario spread leads to a range of possible values of water resource availability, there is a consequent range of possible fuzzy values of water availability for AHEAD conditions. ”AHEAD spread” in the context of this analysis refers to the differences between the minimum and maximum possible values of aggregated AHEAD conditions as a result of the inter-model and scenario spread in projections of water availability in a given time period. In groups A, B and C.1/C.2 indicated in Fig. 2, the spread is not relevant with regard to the defined context-specific membership-functions and decision rules, and the country-specific result spread of aggregated AHEAD values is below 0.2. The result range is low, either because water is not limited (fuzzy water value of 1), regardless of the spread of the modelling output (A, C.1), because there is high agreement in the models and the result range is small (B) or because water is severely limited (fuzzy water value of 0) under all scenarios and models (C.2). For groups C.3 as well as all subgroups of D, the spread affects the results of fuzzy water values and overall AHEAD conditions and cannot be factored out. Here, we further differentiate results according to the magnitude of the spread. Group D.1 has a country-specific AHEAD result spread between 0.2 and below 0.5, whereas the result spread in classes D.2 are 0.5 or higher.

3 Results

3.1 Current and future fulfilment of AHEAD

The following paragraphs present the results of the analysis, based on the ensemble mean of the underlying scenarios of water availability. All country- and indicator-specific values using the ensemble mean, as well as results of the individual IM-GCM-RCP combinations are available in the Supplementary Material (Lissner et al., 2014a). The initial fuzzification of all input values leads to comparable values between 0 and 1, describing the adequacy of each AHEAD element. The directed aggregation procedure then allows to quantify the adequacy of conditions of the three subindices Subsistence, Infrastructure and Societal Structure as well as the overall fulfilment of AHEAD. The fuzzified and aggregated values can be represented according to the degree of membership to the linguistic category of adequacy, ranging from very high (1 - 0.8), high ($<$0.8-0.6), intermediate ($<$0.6-0.4), low ($<$0.4-0.2) to very low ($<$0.2-0).

Figure 3 shows overall global livelihood conditions for baseline conditions (2000), using per capita water availability from the ensemble mean. Based on these values, global mean AHEAD fulfilment is intermediate (0.48). Only few changes in overall AHEAD fulfilment occur for the future scenario based on ensemble mean values, therefore only baseline values are presented in Figure 3. Calculations using the full range of ISI-MIP modelling results for baseline as well as the scenario period as input for water availability lead to a result spread of intermediate to low AHEAD fulfilment on global average (between 0.34 and 0.53). The general spatial distribution of AHEAD is similar across all scenarios and models. A total of 9 (22) countries consistently show very high (very low) AHEAD fulfilment in all model and scenario combinations, while in 80 countries the results vary as a result of different values of water availability.

When comparing the adequacy values for the three sub-indices in terms of the main limitations on the basis of the ensemble mean, in 47 countries the Societal Structure is most limited, while Subsistence and Infrastructure pose strong limitations in 37 and 27 countries, respectively. While this differs slightly across models and scenarios, as water limitations are higher or lower, nonetheless the general distribution is consistent and societal aspects limit AHEAD fulfilment in many regions. With the regard to the highest adequacy of conditions, in 51 countries values in the Subsistence domain are highest, while is true for 33 and 27 countries for the Societal Structure and Infrastructure domain (see Table A1 for a summary of the degree of fulfilment of all AHEAD elements and subindices; individual country values in the Supplementary).

Further zooming into the single elements of AHEAD, within the Subsistence subindex it is most often the inadequate air quality which limits the adequacy of conditions (baseline: 61, 2090: 59). On the basis of the ensemble mean, for the baseline in 34 countries water availability is the strongest limitation (36 for 2090 values), while calorie availability and water access limit the Subsistence subindex in 1 and 15 countries, respectively. Nonetheless, water limitations are also present in many regions, where other elements present the highest limitations to AHEAD. Of the 111 countries, 67 countries have fuzzy water values below 1, however in 32 of these, water availability is only slightly below the threshold and adequacy in very high. In 44 countries, no limitations are present (fuzzy water is 1) while in 21 countries, fuzzy water availability is below 0.6. The calculations for 2090 show slight reductions in the adequacy of water availability. In 43 countries water availability remains above thresholds of water security and in 27 countries the adequacy of water availability is very high. Countries with values of below 0.6 increase to a number of 30 for 2090. Within the Infrastructure domain, the elements mobility, energy availability and communication show the highest limitations, with minimum values in 52, 29 and 22 countries, respectively. In the Societal Structure, the main limitations show in the elements participation (59) and economic stability (22).

3.2 The relevance of uncertainties in projections of water availability for AHEAD

Uncertainties in climate impact analyses derive from various sources. In the present results, uncertainties deriving from the inter-model spread of both GCMs and IMs as well as from green-house gas scenarios are visible in the results, as they produce a range of potential future developments of water availability. Further sources of uncertainty, such as an incomplete understanding of underlying processes (see e.g Schneider and Kuntz-Duriseti, 2002, for a detailed overview) exist, however these are not in the focus of the present analysis. The AHEAD methodology allows to view the uncertainty-induced result range within a context, which allows determining whether this specific type of uncertainty is relevant with regard to a specific question, in this case the adequacy of water resources and AHEAD fulfilment. Where the remainder of the paper refers to uncertainty, this specifically refers to modelling and scenario induced uncertainties, which produce a visible result range (inter-model spread).

The basic idea of the approach is simple: if the uncertainty causes AHEAD results to cross the thresholds of adequacy, uncertainties are relevant to the fulfilment of AHEAD. If this is not the case, uncertainty is not relevant with regard to the specific context, here the adequacy of conditions. Figure 4 exemplifies in more detail, how the fuzzification and aggregation procedures allow assessing the relevance of uncertainty for AHEAD results, by showing three subsequent analysis steps in several example countries: plots on the left show the overall per capita water availability (m^3 cap $^{-1}yr^{-1}$). The middle and right plots present fuzzified values for water availability and AHEAD, respectively. In each plot, the individual IMs as well as the two timeslices are plotted individually, showing the result spread across GCMs and RCPs. Comparing the modelling results regarding water availability per capita (plots a-c), it is visible that Sweden in this example has the highest spread stemming from both, IM and GCMs, with modelled ranges of water availability of up to 13240 m^3. When translating these values into a fuzzy representation of the adequacy of water availability (plots e-f), however, it becomes visible that this range is outside of values relevant to water security (fuzzy water availability is 1), as water supply in both countries is always adequate under all scenarios. The modelling and scenario related uncertainty present in the results is thus large, but is unlikely to affect human water security in the context of AHEAD. The two other examples Morocco and Ethiopia, have smaller results ranges of per capita water availability across models and scenarios. When translated into a fuzzified representation of water adequacy, however, it becomes clear that these ranges may be highly relevant to water security, as many of the potential future projections lie within a range of beginning or existing water scarcity. The third column (plots g-i) shows the resulting values of AHEAD for each country. In two of the examples, the result range of modelled water availability does not affect overall AHEAD conditions, either because the water availability is always above the relevant thresholds (Sweden), or because other factors determine the overall result (Ethiopia). In Morocco, water availability values are all within a critical range for water security and this remains visible within the overall results of AHEAD.

In this manner, the decision tree shown in Figure 2 allows to classify the results for each country according to the relevance of uncertainty for water security and overall AHEAD fulfilment. We use the value range across all models and scenarios for the classification, but differentiate between the time slices 2000 and 2090. The map in Figure 5 shows the resulting grouping of countries for baseline conditions, with grey colours representing groups with relevant uncertainty (C.3 and D). There are only few changes in this classification in the future scenario (see Supplementary Material for all country specific values).

Of the 111 countries for which AHEAD could be calculated, at present in 65 countries the model spread is outside the thresholds for AHEAD fulfilment. This number increases to 70 countries in 2090, as water scarcity increases and water security is below minimum requirements in all RCP-IM-GCM combinations. The reduction of uncertainty is due to the high model agreement with regard to reduction in water availability to levels, where water scarcity has to be expected. Those countries, which move towards classes where uncertainty is not relevant to water security move to classes which show very low values of fuzzy water availability. In 46 countries (41 for 2090 values), uncertainty is relevant to highly relevant. Both for baseline and 2090 values, in 54 of the countries outside the uncertainty range, there is agreement between models and scenarios that water resources are adequate and fuzzy water values are high to very high. In 11 countries (16 in 2090), models agree on severe limitations to water availability (fuzzy water availability is 0).

4 Discussion

While information on sectoral climate change impacts is increasing, a generally applicable framework to relate climate impacts to livelihood conditions and human well-being has so far been unavailable. We present an approach to quantify *Adequate Human livelihood conditions for wEll-being And Development* and link these conditions to assessments of climate impacts, exemplified with changes in water availability. Based on a set of 16 elements to represent requirements for human well-being and livelihood conditions, the AHEAD approach provides a means to view climate impacts in a wider context, focussing on their relevance for human development.

The approach measures elements within the three dimensions of Subsistence, Infrastructure and Societal Structure. Conceptually, the identified elements of AHEAD constitute generally valid requirements for adequate livelihoods. Their fulfilment can be measured through indicators, representing the access to satisfiers, which can differ according to prevailing possibilities and preferences. In the present implementation, the focus in on a comparable measurement of AHEAD conditions at global scale and national resolution. The selection of indicators (satisfiers) is therefore limited to data which is available at this scale, but focusses on using comprehensive satisfiers to provide a holistic perspective, where possible. In the case of measuring social protection, for example, the three indicators 'traditional solidarity', 'institutional solidarity' and 'micro-credits/micro-lending' can each contribute to a very high degree of fulfilment, reflecting different cultural preferences and development status (Cook and Kabeer , 2009).

With regard to the representation of water availability within the AHEAD framework, our approach to combine water resource availability with the access to an improved water source provides an important way forward to account for the fact that water resources alone to not guarantee access to water. Especially in developing countries, water access infrastructure poses a more important limitation to water availability, rather than the available resource (Rijsberman, 2006). At the same time, water shortages to some extent can be mitigated by good water infrastructure. In many countries of the EU, such as Germany for example, per capita water availability is very close to a scarcity threshold, yet good water management so far has limited problems with water security. Both, changes in water resources as well as changes in population have an effect on the per capita resource availability within a country. By selecting average per capita requirements for a life in dignity as the assessment unit, the various pressures exerted on resources can be represented by the approach. In the case of water availability, it is often the increase in population which reduces the adequacy of per capita water availability, rather than reduction in water resources.

Methodologically, the use of fuzzy logic allows translating inherently fuzzy concepts and data from different sources and in different units into a consistent framework. The translation of elements from a qualitative description into a quantified representation is associated with vagueness. The use of linguistic categories as well as the representation of gradual truth values of membership to these categories provides a means to address this vagueness in a comparable way. The aggregation of data from different sources with different units is challenging (Parsons et al., 2011), as data needs to be transformed into a compatible format to enable aggregation. The definition of context-specific linguistic categories allows translating the range of input values into a consistent and comparable format, in the case of the present analysis a representation of the adequacy of conditions, allowing for direct comparison between countries. Other indicator-based approaches have been criticized for their normalization and aggregation methods, which do not retain important cause-and-effect relationships between elements (e.g. the well-known HDI: (Kovacevic, 2011).) Opposed to this, the AHEAD approach is not a simple aggregation of elements, but it allows to maintain properties of single variables in the final result.

The approach also allows assessing the effects of climate change impacts on AHEAD. As exemplified with the example of water availability, an assessment of the relevance of changes for a specific context, here the adequacy of AHEAD conditions, becomes possible. The approach can be extended in this regard, as it allows assessing a range of sectoral climate impacts. Projections of climate change and impacts are subject to uncertainty, deriving from several sources. Especially in climate impact assessments, uncertainties multiply along the assessment chain (Schneider and Kuntz-Duriseti, 2002). The present approach allows addressing parts of such uncertainties, by assessing their relevance with regard to a specific context. Of the sources of uncertainties, those deriving from the modelling set-up as well as from potential future scenarios are directly visible in modelling intercomparison efforts, such as the ISI-MIP project, as these make visible the range of plausible future developments. The methodology presented in this paper can help in putting these result ranges into a perspective, by analysing their relevance with regard to specific questions. In many cases uncertainty in future projections is high. However, as we were able to show with the example of water availability, often these uncertainty ranges do not overlap with critical thresholds for livelihood aspects, in this case, water security. As results presented in Figures 4 and 5 show, countries can be classified according to the relevance of uncertainty regarding water availability. In countries such as Sweden, modelling and scenario induced uncertainties are substantial, but all values are well above basic human requirements and therefore the uncertainties do not affect water security, as the fuzzification step from column 1 to column 2 in Figure 4 illustrates. In the examples of Ethiopia and Morocco, however, uncertainty remains relevant in this context.

The AHEAD approach also allows viewing changes in single components within a wider framework of livelihood conditions. Our results show that the majority of countries with low values of AHEAD are not water limited, but are otherwise restricted (Figure 5, class B and C.1) and other development priorities are more pressing. In many countries a large inter-model spread is apparent in projections of future water availability, as visible in the example Sweden. The translation into a fuzzy representation allows determining, whether this uncertainty is relevant with regard to a specific question. In Sweden, all projections are above the thresholds for water security. In countries such as Ethiopia and Morocco the inter-model is spread is lower, however the result range is highly relevant to livelihood conditions and water security and uncertainty remains visible in the AHEAD result. The approach can thus reveal important insights into development priorities. Modelling uncertainties have been blamed for inaction regarding climate change policies (Lorenzoni et al., 2007). Such impasses can be resolved to some extent, if the visible uncertainty range is related to a specific context.

There are several limitations to the AHEAD approach and its present implementation. The use of global data at national resolution and the definition of globally applicable thresholds provides a comparable overview global AHEAD fulfilment, but is unable to include regional to local specificities. Country-specific management practices and preferences, for example, are thus not accounted for. An analysis at country-scale assumes, that national boundaries limit resource availability. However, especially in the food and water sectors, trade plays an important role for actual resource availability (Suweis et al., 2013; Chapagain et al., 2006). Additionally, the assessment of water requirements as an aggregate of all sectors does not take into account different sectoral requirements, with regard to quality and infrastructure for example. More detailed analyses at finer resolutions, as for example proposed by Lissner et al. (2014b), can provide important further information in this regard. Finally, the implementation at country-scale using annual mean water availability also assumes an even distribution of population and resources across space and time within country boundaries. Especially in large countries with uneven population distributions and diverse climatic conditions, such averages prove to be a limitation for the assessment of water availability.

The conceptual foundation of AHEAD is based on the ideas put forward in the literature of well-being and livelihoods. Following these ideas, the identified elements of AHEAD are non-culturally specific. However, the choice of indicators to represent their fulfilment (satisfiers) can vary, for example according development status or culturally-specific preferences. For the purpose of a global application, the availability of data sets of sufficient coverage is an important restriction. Some available data sets are limited in their ability to depict the potential range of satisfiers that could be used in order to meet the respective need. This is visible in the representation of mobility, for example. Mobility exists at different time-scales, different spatial scales and with different purposes. The focus of AHEAD is on short-term and local to regional mobility, which is relevant to social networks and inclusion, for example (Urry, 2003; Cass et al., 2005), but is also relevant to the accessibility of various services (Mokhtarian et al., 2001), such as health care for example (Molesworth, 2006). Existing indicators with sufficient coverage to present a global picture of mobility are scarce and the chosen indicator of motor vehicle density only represents a fraction of potential satisfiers for mobility needs. Similar restrictions apply to the other indicators used for the present calculation of AHEAD. Here, more targeted data-collection with a focus on regional specificities as well the different facets of satisfiers would be needed.

The current application of the index exemplifies how the relevance of uncertainty deriving from modelling approaches and scenarios can be assessed, using data on potential changes in water availability. For a holistic picture, consistent scenarios for all variables would have to be used, which is outside the scope of this assessment. It is also important to note that uncertainty ranges outside the thresholds relevant to AHEAD remain important for other water-related decisions, e.g. urban water flow management. While such changes may not directly affect water security, nonetheless other effects may negatively affect the adequacy of human livelihood conditions.

Knowledge on the biophysical impacts of climate change on global scale is becoming available at increasing levels of detail (Piontek et al., 2013), while assessments of impacts on societal systems and human livelihoods and well-being remain fragmented. The AHEAD approach proposes a framework which allows to systematically relate climate impacts to livelihoods at global to regional scales, providing a frame for the results of global modelling efforts. The adequate communication of research results is an essential requirement for the integration of scientific findings into policy decisions (Smith, 2011). Especially the role of uncertainty is often an impediment (Sigel et al., 2010). Embedding visible uncertainty of modelling output within a context allows showing where uncertainties are relevant with regard to specific questions and where they may be outside the range of relevance for the certain decisions. The results of course do not reduce the uncertainty of the modelling output, but they can help put existing uncertainties into a context. This may help in reducing the limiting and inhibiting effects that uncertainty currently has for climate change adaptation and mitigation policy decisions.

5 Conclusions

Uncertainty has been blamed for inaction in climate policy (Lorenzoni et al., 2007). This is also due to public misconceptions of the term uncertainty. The adequate and targeted communication of scientific results is essential in fields of high policy relevance, such as climate change research. To improve the communication and the transferability of results, adequate methodologies are urgently needed, which are rooted in scientific findings, but are able to bridge the gap between science and practice and are able to prepare results in an applicable and understandable way. The analysis and intercomparison of available impact models, as has been done in the ISI-MIP project, is an essential step towards the active consideration of uncertainties. By integrating these results into a wider context of human well-being and livelihood requirements, the AHEAD approach provides a novel way forward in the integrated and targeted communication of applicable scientific results.

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Table 1. Indicators and data used to quantify elements of livelihoods. Column two and three specify the indicators and sources used for calculation of elements. ι_1 and ι_2 are the lower and upper thresholds to define the degree of membership. The last column provides the source and motivation for each of the thresholds. Where no source is indicated, underlying assumptions are discussed in the text. Note that the element 'shelter' is not included in the present calculation of AHEAD due to missing data (see footnote 1).

Elements	Indicator	Data Source	ι_1	ι_2	membership function	Source ι_1 & ι_2
water	annual internal renewable water resources	ISI-MIP (see Section 2.4)	1000 m^3 $cap^{-1} yr^{-1}$	1400 m^3 $cap^{-1} yr^{-1}$	linear increase	Appelgren (1998); Falkenmark (1997)
	access to improved water source	WHO (2009)	-	-	-	analogue to Howard and Bartram (2003)
food	calories $day^{-1} cap^{-1}$	FAO (2009)	country specific MDER[2]	2800 kcal	exponential increase (3)	FAO (2001); Whitlock et al. (2009)
air	PM10 concentrations	WHO (2009)	15 ppm	100 ppm	exponential decrease (1)	Desai et al. (2004); Pope III et al. (2002)
	solid fuel use	WHO (2009)	5%	100%	linear decrease	Lillemo and Halvorsen (2013); Desai et al. (2004)
sanitation	access to improved sanitation	WHO (2009)	-	-	-	analogue to Howard and Bartram (2003)
health care	life expectancy at birth	WHO (2009)	30	70	linear increase	Klugman et al. (2011)
	health care worker density	WHO (2009)	0.0025 cap^{-1}	0.005 cap^{-1}	linear increase	Chen et al. (2004)
energy	electrification rate	OECD/IEA (2009)	80%	100%	linear increase	see Sec. 2.3
education	mean years of schooling	UNDP (2009)	4	10	linear increase	Bhuwanee et al. (2009)
	expected mean years of schooling	UNDP (2009)	4	10	linear increase	Bhuwanee et al. (2009)
mobility	motor vehicles	World Bank (2009)	0.2 cap^{-1}	0.5 cap^{-1}	linear increase	see Sec. 2.3
communication	mobile cellular subscriptions	World Bank (2009)	0 cap^{-1}	1 cap^{-1}	linear increase	see Sec. 2.3
	internet users	World Bank (2009)	0 cap^{-1}	1 cap^{-1}	linear increase	see Sec. 2.3
social protection	institutional solidarity	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	traditional solidarity	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	micro lending	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
political stability	political stability	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
economic stability	labour legislation	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	employment contract rigorosity	IDP (2009)	2	4	linear decrease	de Crombrugghe et al. (2009)
security of person	domestic security	IDP (2009)	3	4	linear increase	de Crombrugghe et al. (2009)
social cohesion	social inclusion	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
participation	population participation	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)

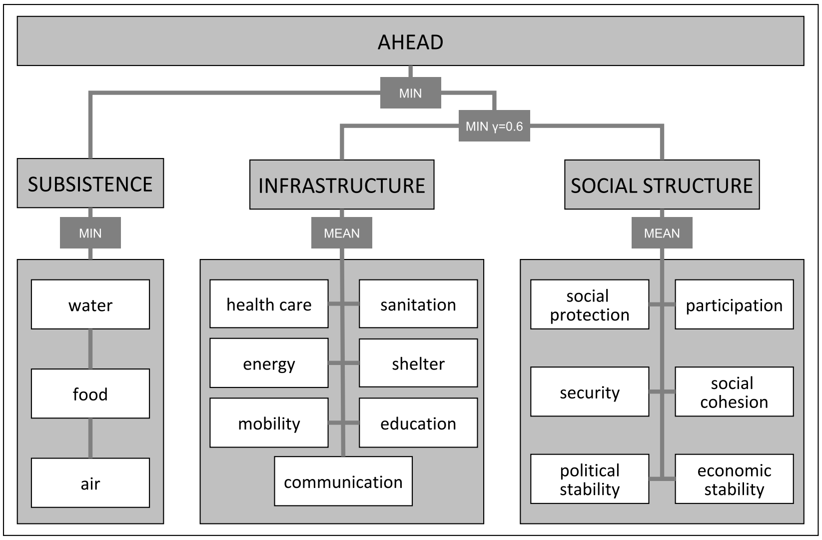

Fig. 1. Overview of the fuzzy aggregation tree to calculate AHEAD. Detailed explanations of each variable as well as the aggregation procedures are given in Sections 2.2 and 2.3.

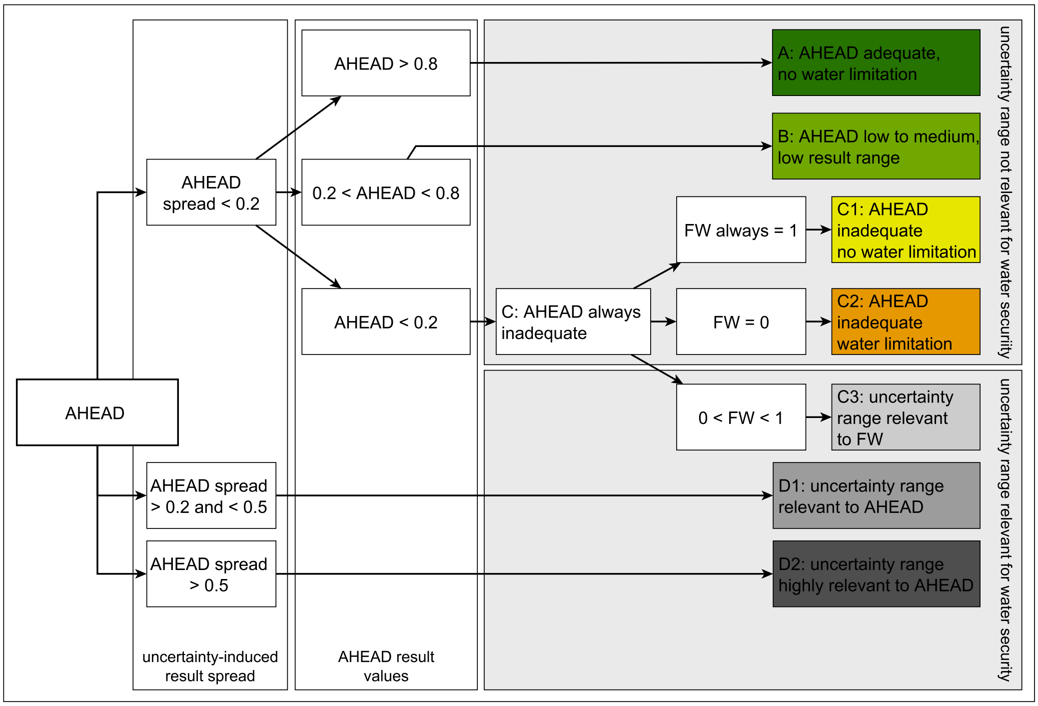

Fig. 2. Decision tree to classify AHEAD results according to the result range of water availability data. Note that where the term 'range' is mentioned in the Figure, this refers to the range of result values for a single country, deriving from the range of values of water resource of availability from the different IM-GCM-RCP combinations. FW refers to fuzzified values of water availability. Classes A, B and C.1, C.2 comprise results, which show a low range of values, indicating that the uncertainty-induced result range lies outside relevant boundaries for adequate AHEAD conditions and water security. In classes C.3 and all D classes, uncertainty ranges are relevant with regard to AHEAD conditions and/or water security.

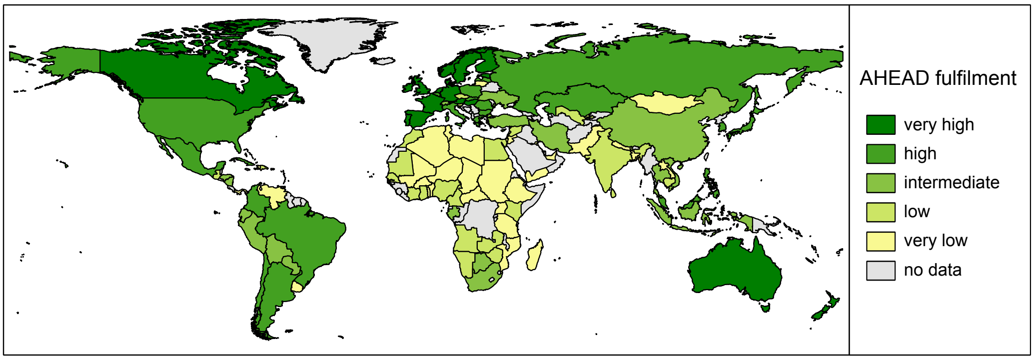

Fig. 3. AHEAD fulfilment at global scale for present conditions (water data: ensemble mean across all participating ISI-MIP climate and water models for the baseline 2000).

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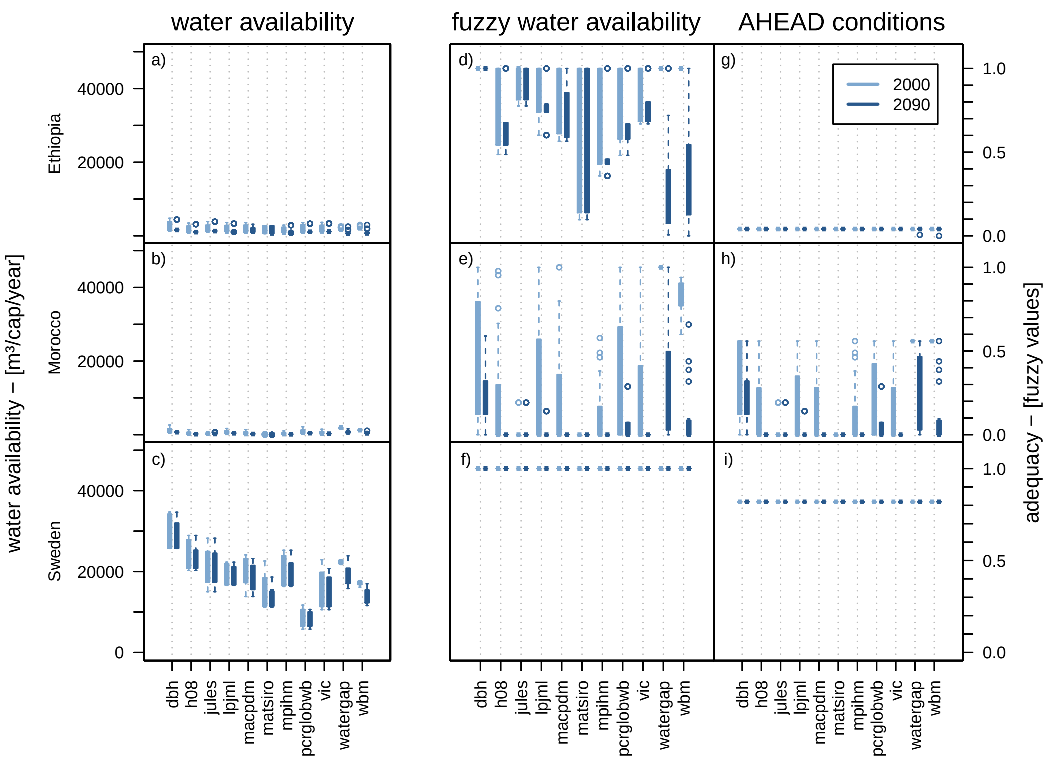

Fig. 4. Examples of input data and fuzzified values/results for left: per capita water availability, middle: fuzzified water data, right: AHEAD results, for the examples Ethiopia, Morocco and Sweden. Right axis labels and units (adequacy [fuzzy values]) apply to middle and right panels. Results of the individual impact models are plotted from left to right within panels, showing the result range for all GCMs and RCPs for each timeslice.

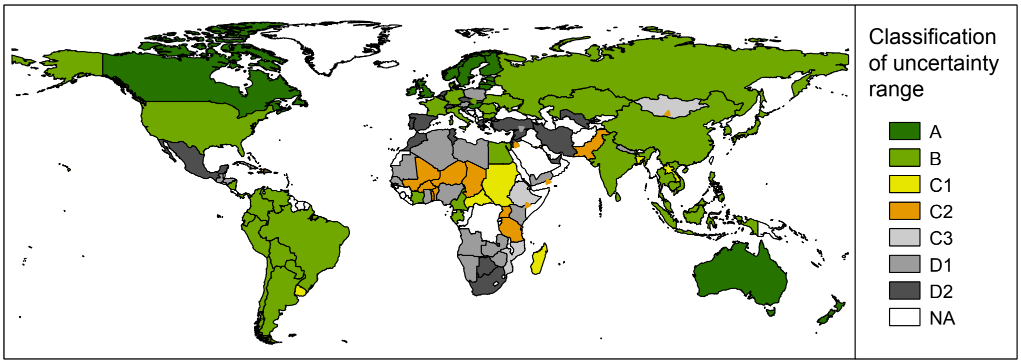

Fig. 5. Classification of countries for baseline conditions following the decision tree outlined in Figure 2. All result values for current and future calculations are published on figshare (Lissner et al., 2014a).

Appendix A

Table A1. Summary of results for each variable, showing the number of countries in each class. Classes correspond to 0.2 increments (0-<0.2 = very low, 0.2-<0.4 = low, 0.4-<0.6 = intermediate, 0.6-<0.8 = high, 0.8-1 = very high). The classification of the variable 'water' refers to results for baseline conditions using the ensemble mean.

	very low	low	intermediate	high	very high
water	20	7	2	5	161
food	2	2	2	20	150
water.access	16	8	35	30	107
air	36	12	21	23	83
health	0	35	37	19	100
sanitation	13	20	22	22	119
energy	51	7	9	7	102
education	6	14	27	38	90
mobility	116	9	6	2	41
communication	34	35	38	51	37
social_protection	0	3	24	65	29
economic_stability	8	15	48	34	16
political_stability	4	5	14	26	72
security	5	8	23	31	54
social_inclusion	9	15	41	28	30
participation	32	29	33	16	13

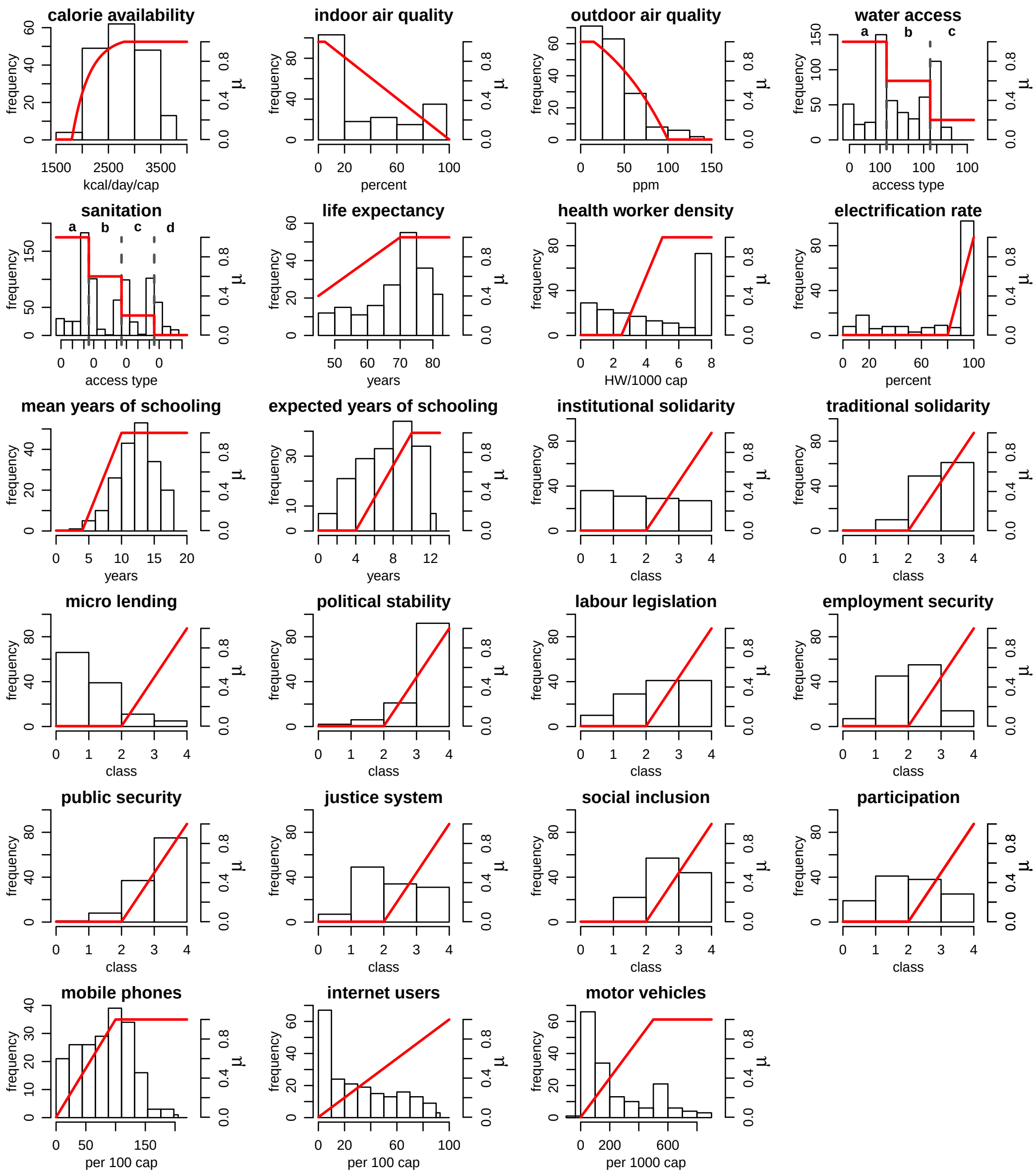

Fig. A1a. Frequency distributions of the original input data and the membership functions used for their fuzzification. For variable 'water access': a) piped on premises, b) other improved access, c) unimproved access. For variable 'sanitation': a) improved sanitation, b) shared facilities, c) other unimproved, d) open defecation.

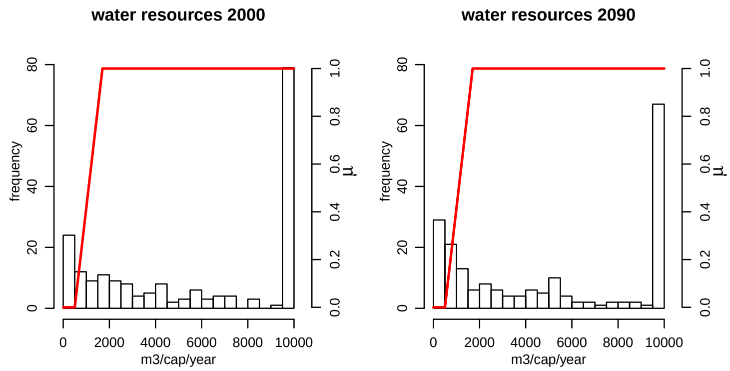

Fig. A1b. Frequency distributions of the input data and membership functions for water resource availability. Values show the ensemble mean across all ISI-MIP climate and impact models for the four 30-year periods.