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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 influential concepts addressing human well-being, 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 many countries today, livelihood conditions are compromised by water scarcity. However, more often, AHEAD fulfilment is limited through other elements. Moreover, the analysis shows that for 44 out of 111 countries, the water-specific uncertainty ranges are outside relevant thresholds for AHEAD, and therefore do not contribute to the overall uncertainty about climate change impacts on livelihoods. 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. Single aspects of climate change and impacts can be put into context by relating them to other development aspects and needs, allowing for a comparison of 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 such 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).

We present an integrated approach to quantify human well-being and livelihood requirements, allowing to assess the effects of climate impacts on human well-being and livelihoods. One important aspect of the method is its ability to assess the relevance of uncertainty within the overall result. 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 such a measure 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. 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

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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 Sect. 3 and critically discuss the method and results in Sect. 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, which include a range of tangible as well as intangible elements to represent an extended set of basic human needs (Littig and Griessler, 2005). To identify a consistent set of elements to outline such conditions, we base our analysis on a transdisciplinary set of influential approaches, 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 Fig. 1). Additional literature devoted to the topic, but not directly applicable for the purpose of defining single elements for the present analysis, further supports this set (see e.g. O'Riordan, 2013; Littig and Griessler, 2005; Wisner et al., 2004).

To measure the fulfilment AHEAD, the 16 elements can roughly be distinguished into three broad categories (see Fig. 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 extremely relevant in their contribution to the *Societal Structure* and include social protection, security, participation, social cohesion as well as economic and political stability.

The following paragraphs outline the method in detail and discuss available data for a first implementation. For the purpose of an initial presentation and implementation of the approach at global scale, we use freely available data at national resolution. 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

Assessments at the interface of human and environmental systems face several challenges, including the inclusion of data from different sources at various spatial and temporal scales (Ostrom, 2009), the integration of findings from a variety of disciplines, which have different research approaches and philosophies (Newell et al., 2005; Smith and Stern, 2011) as well as the general challenges of addressing issues of uncertainty (Sigel et al., 2010; Smith and Stern, 2011), requiring the development of adequate methods. Additionally, indicators may have specific properties, which need to be retained within the aggregated index, as for example the non-substitutability of water. 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 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). Representing the concept of adequacy in mathematical terms can be difficult, as the definition of exact thresholds of adequacy or sufficiency can be challenging. However, the idea of adequacy is easily presented in linguistic categories, for example "sufficient water is available".

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). By calculating the degree of membership of each variable to a common linguistic concept, the diverse range of elements become comparable. The first step of any fuzzy analysis is the fuzzification of the base variables with respect to a defined logical clause (linguistic categories).

A function to define the degree of membership to a linguistic category, in the case of our analysis the adequacy of conditions, is defined for each variable. Threshold values and membership functions depend on the data available for the analysis and are discussed in detail in the following Sect. 2.3. Fuzzified data sets take continuous values between 0 (conditions are inadequate) and 1 (conditions are adequate). Upper and lower thresholds for membership (ι_1, ι_2) are defined to calculate continuous degrees of membership μ_{zi} of variable ι through Eq. (1) for a linear increase or Eq. (2) for a linear decrease.

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

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

Equations (3) and (4) calculate exponential/curved membership functions, where the value of ϵ determines the curvature of the function.

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

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

For all Eqs. (1) through (4) $\iota_1 < \iota_2$ must be true. The choice of membership thresholds ι_1, ι_2 as well as the shape of the membership function are determined depending on context and data (see following Sect. 2.3) (Kropp et al., 2001; Lissner et al., 2012).

Subsequent to their fuzzification, variables are aggregated using context-specific aggregation rules in a defined order (Fig. 1). Operators for the aggregation are defined analogue to crisp set theory and additional fuzzy operators are available (Mayer et al., 1993). 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 to incorporate the content-related properties of and relationships between variables. 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 (Eq. 5 for fuzzy MIN; analogue quantification for fuzzy MAX) (Kropp et al., 2001).

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

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 $\gamma = 0$ the arithmetic mean of the input values is calculated. Further operators available for the aggregation of variables include average operators, such as harmonic, geometric and arithmetic mean (Mayer et al., 1993).

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 Fig. 1. Initially, the three dimensions of Subsistence, Infrastructure and Social 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 $\gamma = 1$ (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 ($\gamma = 0$) (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 Fig. 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 Social Structure using a fuzzy MIN operator with $\gamma = 0.6$. 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 direction and function of γ can be motivated by the context, the exact value is to some extent arbitrary 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 ($\gamma = 1$), again reflecting the non-substitutability of the Subsistence domain.

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

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. For the purpose of determining the fulfilment of AHEAD, the lower threshold ι_1 should reflect a basic level of resource availability, below which survival would be compromised. The upper threshold ι_2 delineates a level of sufficiency, where basic needs are fully met and conditions are adequate. We implement the AHEAD index at global scale, relying on freely available data on national resolution (Table 1). We therefore have to rely on data sets that are available with global coverage, which presents a limitations to depict the full range of possible satisfiers in some cases. Applied fuzzification methods for each variable are motivated by scientific findings. Some elements can be represented with single datasets and sources given in Table 1 (column "Source ι_1 & ι_2") also support the use of the respective dataset to represent the element. 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 limited 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.

- 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 “$PM_{2.5}$/10 concentration” are aggregated using a MIN operator.
- Health care: the 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 (Eqs. 1–4) to fuzzify each input dataset are motivated by relevant findings (for an overview of all membership functions as well as the frequency distribution of the input data see Fig. A1). 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 ($\mathrm{m^3\,cap^{-1}}$) below $500\,\mathrm{m^3\,cap^{-1}}$ indicate absolute water scarcity (ι_1), while an availability of more than $1400\,\mathrm{m^3\,cap^{-1}}$ indicates no water stress (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 percentage of households belonging to the respective class is given. To make use of this classification, we weigh each group according to the quality of access, as outlined in WHO (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 (Eq. 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 $2800\,\mathrm{calories\,cap^{-1}\,day^{-1}}$ (FAO, 2001).

The effects of particulate matter on human health are especially strong at concentrations above 100 ppm, while levels below 15 ppm 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 2.5/(1000 cap)$^{-1}$ population and should be guaranteed at a density of 5/(1000 cap)$^{-1}$ (Chen et al., 2004).

Membership to the linguistic variable "indoor air quality is adequate" using 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 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 (100 cap)$^{-1}$. For the fuzzification of mobility data we set ι_1 at 500 motor vehicles per 1000 inhabitants (motor (1000 cap)$^{-1}$), as this reflects the lowest values of high HDI countries (World Bank, 2009). Similarly, ι_2 at 200 motor (1000 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.

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 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 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 that participated in

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[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/.

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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 (O'Neill 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 30 year periods, using the baseline 1981–2010 (2000) and calculating projected changes for the scenario periods 2011–2040 (2030), 2041–2070 (2060) and 2071–2099 (2090). Years in brackets will be used throughout the paper as a reference to the 30 year average. 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.

Assessment of the relevance of uncertainty

Finally, we analyse AHEAD results with regard to the relevance of the uncertainty associated with the inter-model spread and categorize our results according to the relevance that the spread of the modelling output has for the results of our analysis. Following the decision tree outlined in Fig. 2, we differentiate several combinations, which determine whether the modelling and scenario induced uncertainty can be factored out of the results.

In groups A, B and C.1/C.2, the uncertainty range is not relevant with regard to the defined context-specific membership-functions and decision rules, and the country-specific result range of fuzzified AHEAD conditions is 0.2 or lower. The result range is low, either because water is not limited, 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 under all scenarios and models (C.2). For groups C.3 as well as all subgroups of D, the uncertainty spread affects the results and cannot be factored out. Here, we further differentiate results according to the result spread. Group D.1 has a country-specific AHEAD result spread between 0.2 and 0.5, whereas the result spread in classes D.2 are 0.5 or higher.

3 Results

The initial fuzzification of all input values leads to comparable values between 0 and 1, describing the adequacy of each AHEAD element. The fuzzified 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 present values, using per capita water availability from the ensemble mean.

Using the values of the ensemble mean, global mean AHEAD fulfilment is intermediate (0.48). When comparing the adequacy values for the three sub-indices, in the majority of countries (47) 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. Conversely, in 51 countries conditions in the Subsistence domain are most adequate, while is true for 33 and 27 countries for the Societal Structure and Infrastructure domain (see Table A1 for a complete summary of AHEAD fulfilment).

Calculations using the full range of ISI-MIP modelling results as input for water availability lead to a range 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. Generally, the distribution of countries between classes is rather even.

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 directly visible in the results.

Uncertainties and the associated spread in the results can not be completely eliminated, but need to be addressed explicitly. 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.

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 ($m^3\,cap^{-1}\,year^{-1}$). The middle and right plots present fuzzified values for water availability and livelihood conditions, respectively. Comparing the modelling results regarding water availability per capita (plots a–d), it is visible that Sweden and Venezuela in this example have the highest spread stemming from both, IM and GCMs, with modelled ranges of water availability of up to 13 240 and 48 649 m^3, respectively. When translating these values into a fuzzy representation of the adequacy of water availability (plots e–h), however, it becomes visible that this range is outside of values relevant to water security, 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. The two other examples Morocco and Ethiopia, have a seemingly 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 i–l) show the resulting values of AHEAD conditions for each country. In three of the examples, the result range in modelled water availability does not affect overall AHEAD conditions, either because the water availability is always above the relevant thresholds (Sweden, Venezuela), 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 conditions.

In this manner, the decision tree shown in Fig. 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 four time slices 2000, 2030, 2060 and 2090.

The map in Fig. 5 shows the resulting grouping of countries, with grey colours representing groups with relevant uncertainty (C.3 and D). Where changes occur between baseline and 2090 calculations, these are hatched in the respective colour. Of the 111 countries, for which AHEAD could be calculated, at present in 67 countries the model spread is outside the thresholds for AHEAD fulfilment. This number increases to 72 for the end of the century, as water scarcity increases water security is below minimum requirements in all RCPs-IM-GCM combinations. In 44 countries (39 for 2090 values), uncertainty is relevant to highly relevant.

4 Discussion

While information on sectoral climate change impacts is increasingly abundant, a generally applicable framework to relate climate impacts to livelihood conditions and human well-being is needed. We present an approach to quantify *Adequate Human livelihood conditions for wEll-being And Development* and link these condition to assessments of climate impacts. 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. The approach builds upon influential concepts and includes relevant elements for human well-being and livelihoods from three dimensions. The selection of indicators and data for the purpose of quantification focusses on a holistic representation of important aspects. Regarding the representation of water availability within the AHEAD framework, for example, 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 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. Especially in developing countries, water access infrastructure poses a more important limitation to water availability, rather than the available resource (Rijsberman, 2006).

Methodologically, the use of fuzzy logic allows translating inherently fuzzy concepts and data from different sources and in different units into a consistent framework. 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 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. The approach 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 the adequacy of 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 specific contexts. 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 they 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 Figs. 4 and 5 illustrate, countries can be classified according to the relevance of uncertainty regarding water availability. In countries such as Sweden and Venezuela, 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 Fig. 4 illustrate. 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. In Venezuela, for example, other AHEAD elements are far below adequacy levels and may require more urgent attention to increase human well-being and livelihoods (class C.1). In fact, our results show that the majority of countries with low values of AHEAD are not water limited, but are otherwise restricted (Fig. 5, class B and C.1) and other development priorities are more pressing. In countries such as Ethiopia and Morocco, however, the range of uncertainty is highly relevant to livelihood conditions and water security. Though other AHEAD elements also need to be improved urgently, strategies to deal with potential water scarcity here may prove important (class C.3). 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.

The use of global data and globally applicable thresholds in a fuzzy logic algorithm adds other types of uncertainties and short-comings. Country-specific management practices or interactions between elements, for example, cannot be accounted for. An analysis at country-scale assumes, that national boundaries limit resource availability, for example. However, especially in the food and water sectors, trade plays an important role in actual resource availability (Suweis et al., 2014; Chapagain et al., 2006). 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. Uncertainty ranges may also remain important for other water related decisions, e.g. urban water flow management.

The adequate communication of research results in an essential requirement for the integration of scientific findings into policy decisions (Smith, 2011). In the light of limited time and resources to understand and access potentially complicated results, synthesized, filtered and targeted information needs to be provided (Hanger et al., 2012). 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 often been blamed for inaction in terms of climate mitigation and adaptation. This also due to public misconceptions of the term uncertainty. The adequate and targeted communication of scientific results is essential in field 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.

Elements	Indicator	Data source	ι_1	ι_2	Membership function	Source ι_1 and ι_2
water	annual internal renewable water resources	ISI-MIP (see Sect. 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 WHO (2003)
food	calories/day/cap	FAO (2001)	country specific MDER	2800 kcal	exponential increase (3)	FAO (2001), Whitlock et al. (2009)
air	$PM_{10}/PM_{2.5}$ concentrations	WHO (2009)	15 ppm	100 ppm	linear decrease	Desai et al. (2004), Pope III et al. (2002)
	solid fuel use	WHO (2009)	5 %	100 %	exponential decrease (1)	Desai et al. (2004), Pope III et al. (2002)
sanitation	access to improved sanitation	WHO (2009)	–	–	–	analogue to WHO (2003)
health care	life expectancy at birth	WHO (2009)	30	70	linear increase	Klugman et al. (2011)
	health care worker density	WHO (2009)	$2.5/(1000\,cap)^{-1}$	$5/(1000\,cap)^{-1}$	linear increase	Chen et al. (2004)
energy	electrification rate	OECD/IEA (2009)	80 %	100 %	linear increase	see Sect. 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)	$200/(1000\,cap)^{-1}$	$500/(1000\,cap)^{-1}$	linear increase	see Sect. 2.3
communication	mobile cellular subscriptions	World Bank (2009)	0/100 cap	$100/(100\,cap)^{-1}$	linear increase	see Sect. 2.3
	internet users	World Bank (2009)	0/100 cap	$100/(100\,cap)^{-1}$	linear increase	see Sect. 2.3
social protection	institutional solidarity	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	traditional solidarity	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	micro lending	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
political stability	political stability	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
economic stability	labour legislation	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	employment contract rigorosity	de Crombrugghe et al. (2009)	2	4	linear decrease	de Crombrugghe et al. (2009)
security of person	domestic security	de Crombrugghe et al. (2009)	3	4	linear increase	de Crombrugghe et al. (2009)
social cohesion	social inclusion	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
participation	population participation	de Crombrugghe et al. (2009)	2	4	linear increase	de Crombrugghe et al. (2009)

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).

	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

Table A2. Summary of the number of countries with lowest and highest adequacy values in the respective subindices.

	lowest adequacy	highest adequacy
subsistence	37	51
infrastructure	27	27
social structure	47	33

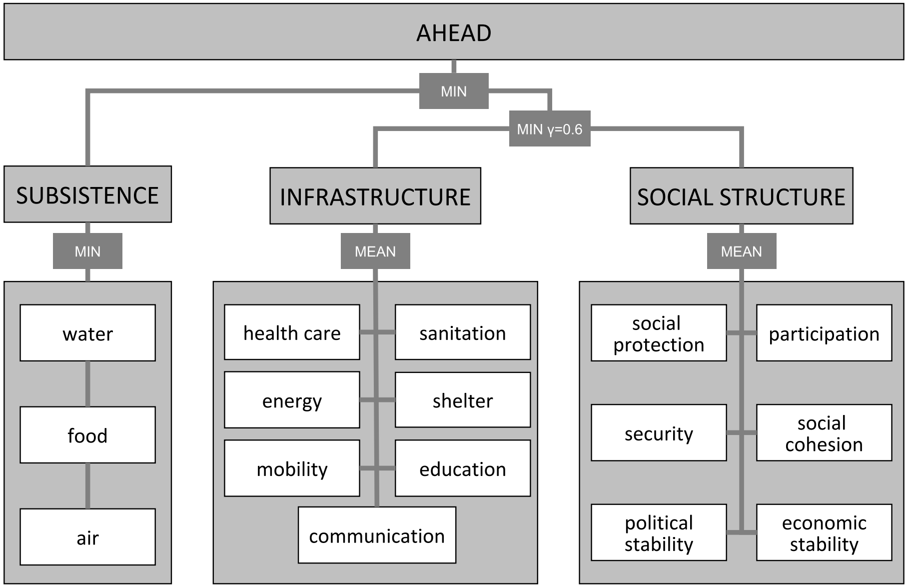

Fig. 1. Overview of the fuzzy aggregation tree to calculate AHEAD. Detailed explanations of each variable as well as the aggregation procedures are given in Sects. 2.2 and 2.3.

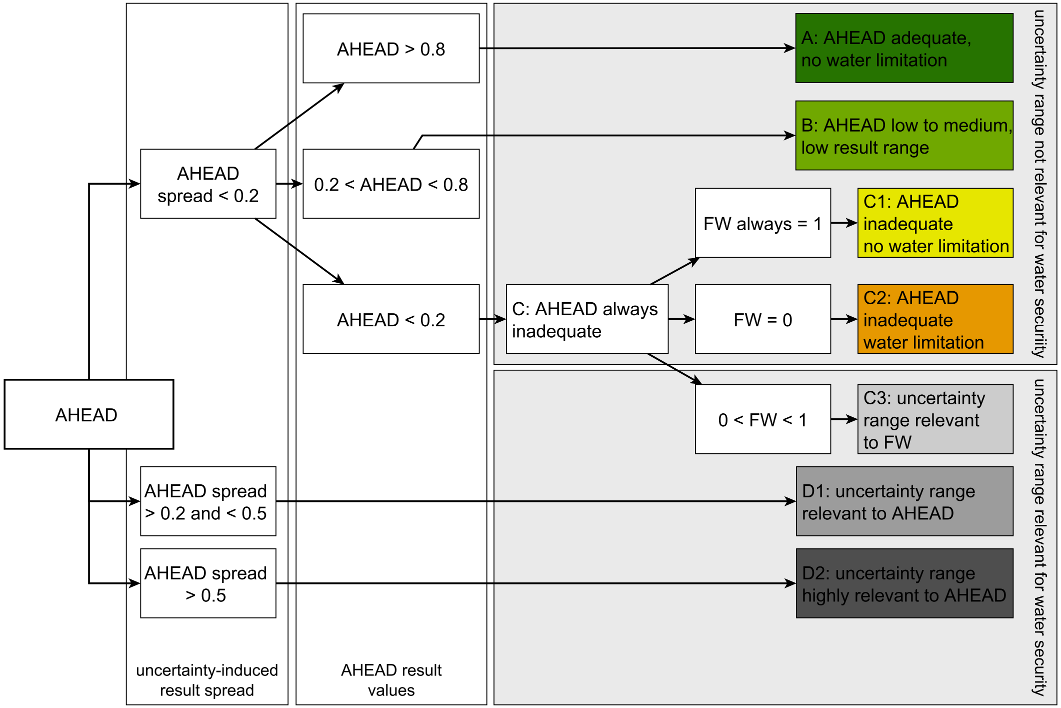

Fig. 2. Decision tree to classify AHEAD results according to the result range of water availability data. Note that where the term "range" is mentioned in the figure, this refers to the range of result values for a single country, deriving from the range of water data. FW refers to fuzzified values of 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.

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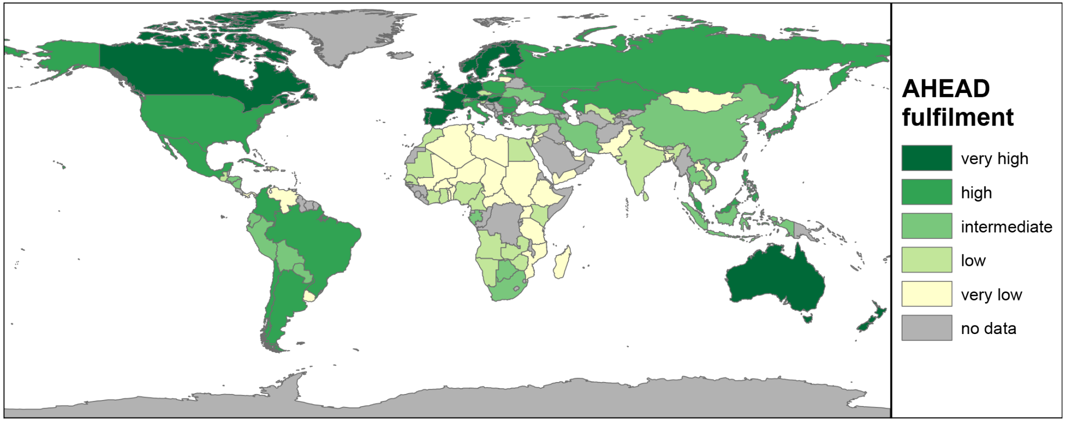

Fig. 3. Degree of AHEAD fulfilment at global scale for present conditions (water data: ensemble mean across all participating ISI-MIP climate and water models).

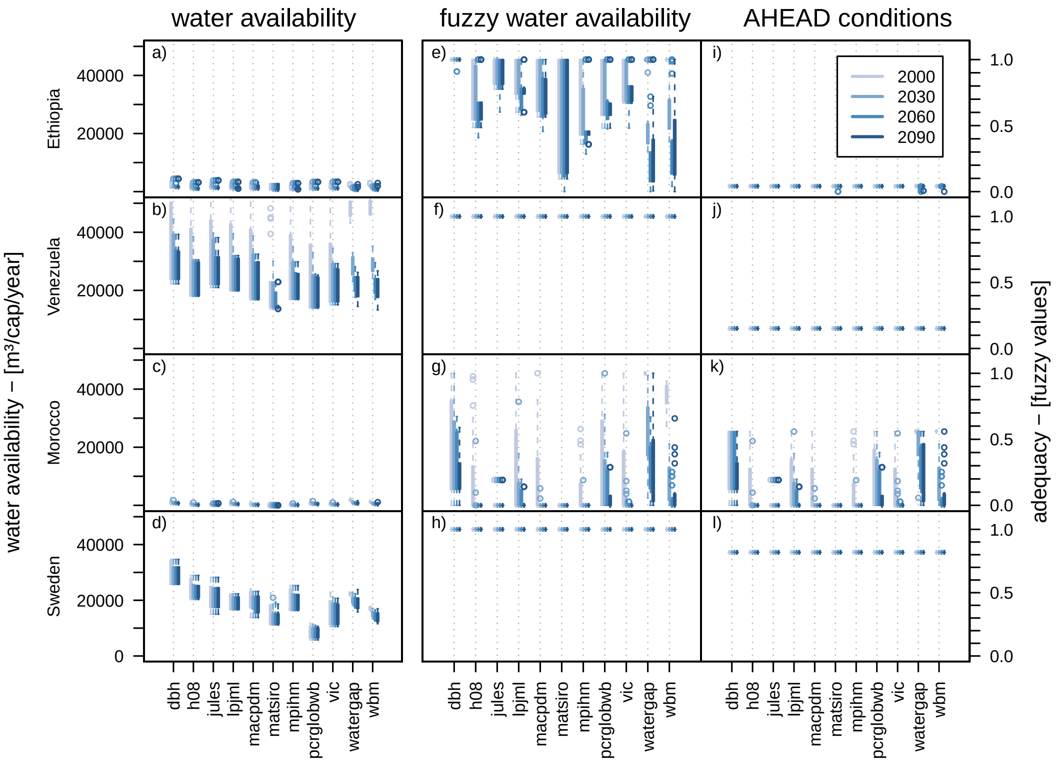

Fig. 4. Examples of input data and fuzzified values/results for left panel: per capita water availability, middle panel: fuzzified water data, right panel: livelihood results, for the examples Ethiopia, Venezuela, Morocco and Sweden. Results of the individual impact models are plotted from left to right panels, showing results for all GCMs and RCPs for each timeslice.

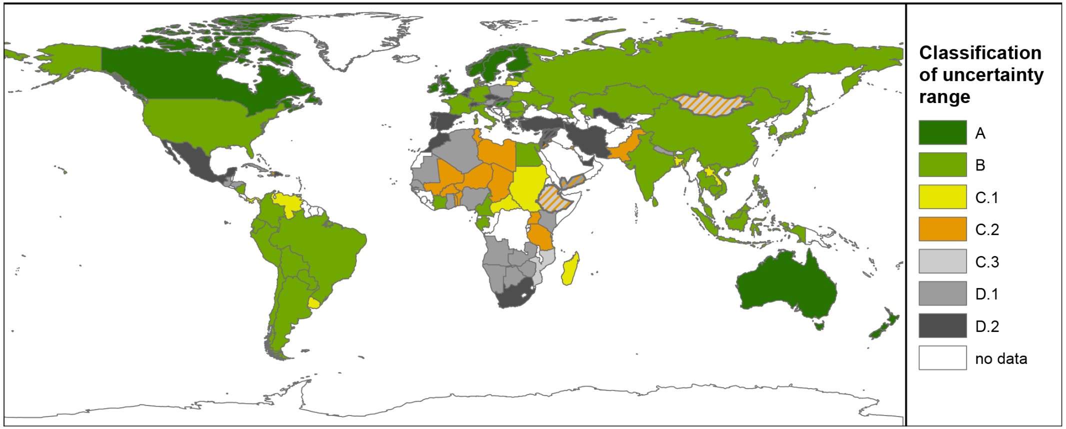

Fig. 5. Classification of countries following the decision tree outlined in Fig. 2. Full colors depict results for current values, changes towards the 2090 are shown in hatching in the colour-scheme of the legend (4 countries).

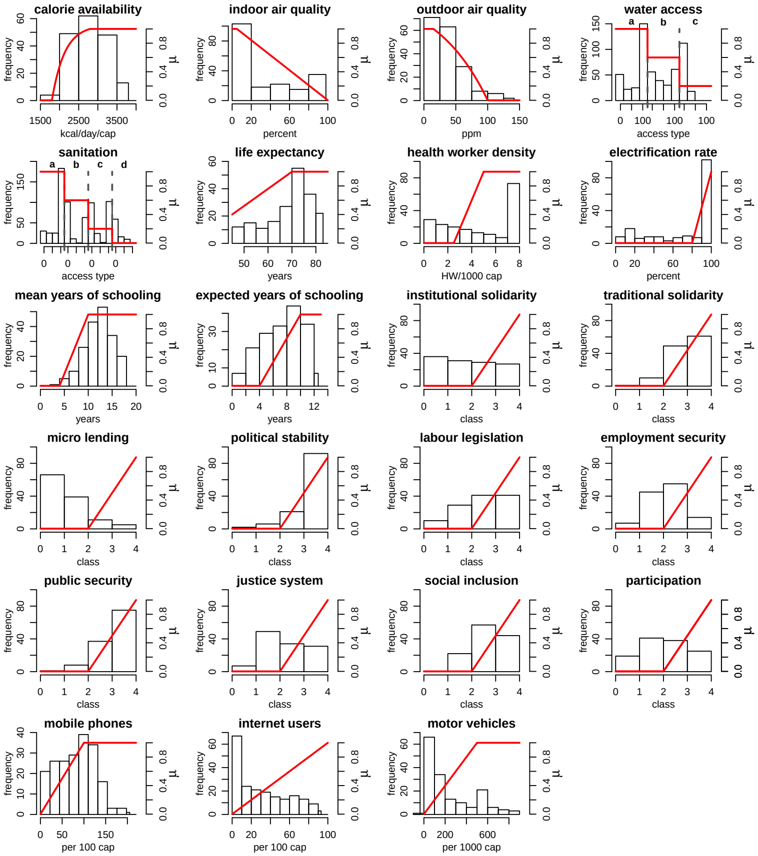

Fig. A1. Frequency distributions of the original input data and the membership function used for their fuzzification. For variable "water access": **(a)** piped on premises, **(b)** other improved access, **(c)** unimproved access. For variable "sanitation": **(a)** improved sanitation, **(b)** shared facilities, **(c)** other unimproved, **(d)** open defecation.

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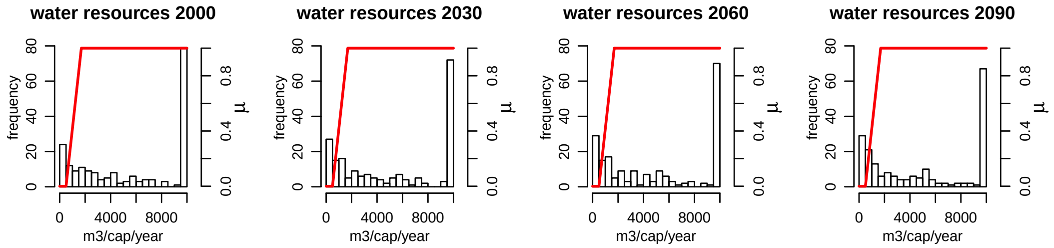

Fig. A2. Frequency distributions of the input data and membership functions for water resource availability. Values show the ensemble mean across all ISI-MIP climate and impact models for the four 30 year periods.