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A systematic approach to assess human well-being demonstrated for impacts of climate change

Abstract: Climate change impacts will affect many important societal sectors, with potential negative consequences for human well-being and livelihoods, however an integrated and systematic measure to assess the state of livelihood conditions in this context is not available. At the same time, human livelihoods and well-being are an important part of (social) sustainability. Yet, aspects of human needs and well-being within assessments of sustainability are criticised for being arbitrary and incomplete. This paper presents a systematic approach to assess Adequate Human livelihood conditions for wEll-being And Development (AHEAD) on a regional to global scale. Based on an interdisciplinary literature review, we first select a consistent set of elements that allow to describe and quantify well-being and livelihoods. In a second step, we analyze documented associations between the elements to outline climate impact pathways and indirect effects of changes in single system components, using an influence matrix. The novel approach provides an important first step to point towards climate change adaptation measures, which most effectively increase human well-being, while identifying potential unintended side-effects. Even though there are some limitations to assessing well-being and livelihoods on a global scale, a consistent measure of AHEAD is of utmost importance for future sustainability and climate impact analyses.

Keywords: livelihood conditions, social sustainability, climate impacts, systems thinking

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1 Introduction

Human influences on the natural system are altering biophysical processes and humanity is facing substantial challenges, including climate change, pollution and degradation of critical ecosystem services [1]. A transition towards sustainability is urgently needed, including pathways towards reduced resource use, while enabling and increasing human well-being [2]. While efforts to improve our understanding of sustainability to provide guidance on such transition pathways have been substantial, operable and integrative approaches to link human and environmental systems remain scarce.

The relevance of jointly addressing processes of the environmental and societal domains has often been noted [3-6], however the integration of domains remains challenging. Sustainability is commonly analysed using a three-pillar approach, differentiating economic, environmental and social sustainability. While the integrative nature of sustainability studies is stressed, the focus of assessments is often on the environmental components and representations of the social aspects are much less elaborated [7-9]. Social sustainability has been described as the satisfaction of an extended set of human needs [10,11] and "has to do with improving or maintaining the quality of life of people'' [12]. However, indicators to represent social aspects are often inconsistent [13] or seem arbitrary and motivated by political reasons, rather than scientific ones [10,14].

Impacts of climate change on livelihood conditions and human well-being are determined by processes in both, the environmental and societal domains [15], yet linkages remain insufficiently explored. On the one hand, development pathways, which are followed in order to improve livelihood conditions and increase human well-being, are often associated with emissions of greenhouse gases and are an underlying cause of climate change [16]. Reductions in human welfare and prosperity are feared, if strong mitigation measures to tackle climate change are implemented [17]. On the other hand, manifestations of climate change through impacts on natural and societal sectors have direct and indirect effects on human well-being. Climate impact studies show that climate change may threaten important aspects of peoples' livelihoods and may have severe repercussions for our current lifestyles [18,19]. In order to reduce negative consequences, strategies to adapt to existing and anticipated impacts can be developed. However, if such adaptation strategies are devised in an unsustainable manner, these can further exacerbate climate change and degradation, leading to maladaptation [20]. Integrative assessment methods, which allow to assess the indirect effect of adaptation are thus important, in order to increase human well-being, while promoting sustainable development.

While the important position of well-being and human livelihoods within human- environmental systems is recognized, so far an integrative and systematic measure of livelihoods and well-being is unavailable. Many approaches exist which outline important constituents of fulfilled human livelihoods and provide information on the relevance of each aspect for attaining human well-being (see for example [21]). However, existing approaches originate from different disciplines, leading to differing foci in the selection of components. Various definitions of the terms livelihoods, well-being and human needs exist, which often overlap or are used synonymously (see Section 2). In the remainder of the paper we use the term well-being as a representative of the concepts. Further, approaches remain conceptual and qualitative, making a systematic quantification difficult. Generally, interdisciplinary topics require the *integration* of knowledge from different disciplines, but should also result in the *formation* of new knowledge or approaches, applicable in several disciplines [22]. On the one hand, interdisciplinary topics need to be formalized in a way that is applicable and quantifiable. On the other hand, such a formalization needs to be sufficiently flexible to be adjusted to the various fields of application.

In the case of human well-being and livelihoods, an additional challenge are the various inter-linkages that exist between determinants that constitute human well-being, as well as linkages to external processes, such as climate change. We propose to address the topic using a systems thinking approach, which promotes the idea of seeing the parts of a system as a whole and focussing on processes and relationships between system parts [23]. Work on the food-energy-water nexus, for example, underlines the importance of such an approach, especially in coupled human-environmental systems [24,25]. System thinking methods have been applied in various contexts of sustainability assessments, including settlement planning [26], urban regions [27] and sustainable transport [28], but are novel in the context of addressing human well-being, where conceptual and qualitative approaches prevail and linkages to processes in the environmental domain are usually not included.

Existing approaches linking indicators of human well-being to processes of global change and sustainability often fall short in (I) substantially defining components of human well-being and (II) translating existing causalities into an integrated mathematical representation. The aim of the present paper is thus to develop an approach to assess the conditions for Adequate Human livelihood conditions for Well-being And Development (AHEAD) by a consistent set of elements, which allow to relate processes of the environmental domain to human well-being. We focus on the systematic identification of elements and explore the associations and inter-linkages between them, thus contributing both to the integration as well as the formation of inter-disciplinary research. We exemplify how the AHEAD approach can contribute to understanding the impacts of climate change on well-being. The AHEAD approach can address a range of scales from global to local, however it does not take into account individual aspects of human well-being.

As a first step, we identify those (measurable) elements, which constitute essential requirements for AHEAD conditions (Section 2). We base the analysis on a comprehensive literature review, to derive scientifically valid determinants of AHEAD. We then look in detail on inter-linkages and relationships between the identified elements, again based on scientific findings, using a systems thinking approach (Section 3). The paper outlines how such an approach can be developed on a global scale and outlines generally valid elements, inter-linkages and potential dynamics. Elements and inter-linkages are presented in generic way, providing the basis for a first consistent formalization and quantification of the concept. To underline the importance of viewing AHEAD as an interconnected system and to look at the linkages between elements, we discuss selected examples of climate change impacts (Section 3.2). We critically discuss the results in Section 4 and summarize the main findings in a brief conclusion (Section 5).

2 Identifying elements of AHEAD

On the basis of a range of available approaches to measure human well-being, needs and livelihoods, we identify essential requirements for AHEAD. For the purpose of a generally applicable framework, the elements should be globally valid, regardless of cultural differences and rooted in scientific findings. Following the definition of Wisner et al. (2004) [29], AHEAD describes access to "an income and/or bundles of resources that can be used or exchanged to satisfy needs. This may involve information, cultural knowledge, social networks and legal rights as well as tools, land or other physical resources'', thus representing an extended set of needs required for human well-being and social sustainability [10].

To identify those approaches relevant to defining elements of AHEAD, we perform a qualitative literature review [30]. As we aim to identify a set of operable dimensions, we look for approaches that specifically list elements which contribute to AHEAD. Using combinations of the initial search terms 'human', 'well-being, 'needs', 'livelihoods' and searching title and abstract, we screen the results according to the following criteria: (1) human-centred (explicit focus on human well-being) (2) global applicability (3) transferability (4) explicit multi-dimensionality and (5) plausible foundation and accessible documentation. Our initial keyword search returned over 900 results in the database of www.scirus.com. The results originate from a variety of disciplines. Hence, significant differences in terms of framing, tangibility and applicability exist. A very important aspect becoming apparent when screening the results is the fact that terminology is not straightforward: on the one hand, the same term is used to describe different things (homonyms) (see e.g. for the term well-being [31,32]). On the other hand, many terms exist to describe similar and overlapping concepts (synonyms), e.g. quality of life [33], well-being [34], livelihoods [29] or human security [35], which are often used interchangeably [36] (see also [21,35,37]. The initial keyword search was thus extended to a forward and backward search, screening the references of the identified important approaches in order to detect additional approaches, which may not be covered through the applied keywords.

After screening the initial results, as well as the additional approaches from the forward/backward search according to criteria 1 through 5, a total of 11 approaches could be identified, on which a measure of AHEAD can be based (detailed descriptions in Table S1, Supplementary), namely Maslow's Theory of Human Motivation [38], the Basic Human Needs Approach [39-41], Human Scale Development [42,43], the Capability Approach [44-47], Human Security [35,48,49], Sustainable Livelihoods [50,51], Quality of Life (QoL) [33,52], Subjective Well-Being (SWB) ([53], cited in [21]), the Millennium Ecosystem Assessment [54], Dimensions of Poverty [55] and the Measurement of Economic Performance and Social Progress [56].

Many articles are concerned with describing and defining human well-being and livelihoods, however only few specifically outline and list relevant elements and determinants, which was the main restriction on the number of approaches directly suitable for the analysis (criterion 4: explicit multi-dimensionality). Therefore not all important contributions have been directly included to define dimensions of AHEAD, but after the comprehensive review it appears that all important aspects are covered through the sample. Several studies which are relevant to the topic, but are not applicable for the analysis, as they do not fit the five criteria introduced above, support the identified elements relevant to measure AHEAD (e.g. [10,57,58]).

The 11 identified approaches to define elements of human well-being and livelihood requirements differ in terms of scope as well as terminology. However, each approach provides a specific list of elements relevant to human well-being, along with descriptions of the meaning and purpose of each element. This provides the basis on which to compare approaches and identify synonyms which are used to describe the elements in each approach. Some elements are included consistently in the majority of approaches, e.g. there is agreement on the need for subsistence, including elements such as water, food and air or the need to be healthy and have access to health care. Societal aspects, such as participation or social protection are also referred to in the majority of approaches, however here the framing and the definitions diverge more.

We grouped equivalent and similar elements of well-being identified in the samples according to the descriptions in the corresponding literature. From this grouping, nine key elements emerge (Figure 1, see also Table S1 and S2 (Supplementary Material) for detailed descriptions).

Of the nine groups of elements, social cohesion is most consistently included in the 11 selected approaches (10 out of 11). Further, the aspects of subsistence, health/health care, economic stability, security (all 8 out of 11) and political stability/freedom/participation (7 out of 11) are clearly important. The elements of social protection, education (5) and shelter (4) are less consistently named in the approaches, however, they are often mentioned implicitly, e.g. through 'material living standards' [56]. Those aspects which clearly refer to individual aspects of human well-being (e.g. family, romantic relationships) are not included, as this would require a different scale of analysis. For individual well-being, these aspects play a critical role. To depict the general conditions and resources, both tangible and intangible, which provide a basis on which well-being can be attained, individual factors cannot be accounted for (for a list of all aspects from all approaches see Table S1, Supplementary Material).

To achieve measurability, some of the key elements shown in Figure 1 have to be further differentiated. Especially the aspects of subsistence have to be assessed separately. We therefore distinguish water availability, water quality, calorie availability and air quality. Further, we distinguish political stability from participation. We also include three additional elements, which are not directly mentioned in any approach, but are of increasing importance in a globalized world, namely energy availability [59,60], communication [61] as well as mobility [62]. In total, 16 measurable elements of AHEAD emerge from the analysis. Table S2 (Supplementary Material) gives further detailed support for identified elements for AHEAD, underlining their relevance as well as the respective literature sources.

While income is sometimes included as a separate requirement, for our approach we draw on findings from research on the relationship of subjective well-being and income, which indicate that wealth contributes to well-being and happiness up to where basic needs are met, but no strong direct correlation is apparent [53,63,64]. That is also reflected in the approach to the Human Development Index (HDI), for example, where GDP is included at log-scale [65]. The importance of access to basic material goods within AHEAD is covered through the element of economic stability as well as the availability of essential resources (e.g. food, water) and infrastructure (e.g. shelter). Several elements may however have a dimension of affordability, as monetary resources may be used/ needed to access them [66,67].

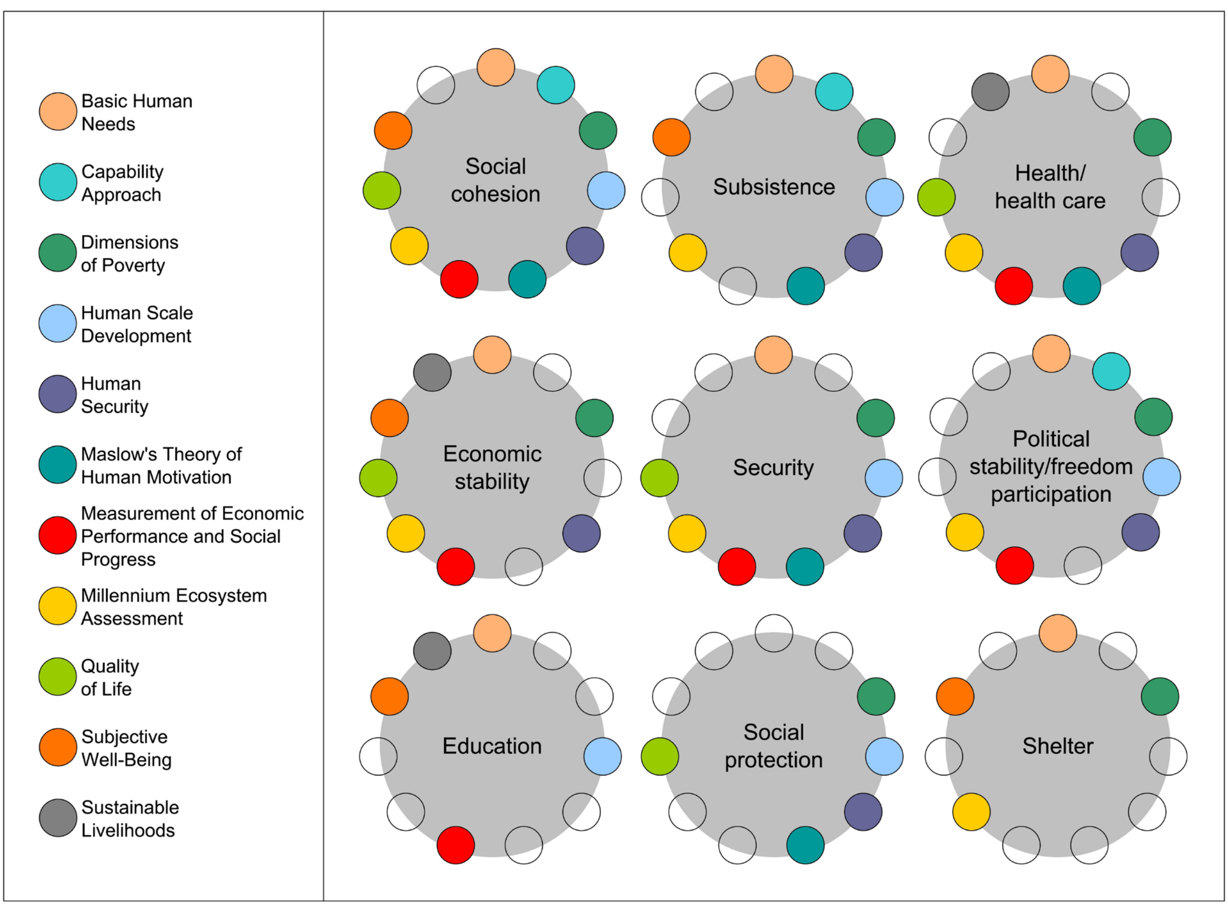

Figure 1: Key elements of requirements for human well-being as identified from relevant literature, sorted by coverage from the approaches. Colored bubbles depict, which approach identifies the respective element. The alphabetical order of the approaches (left) is identical to the order of the bubbles in clockwise direction, starting at 12 o'clock.

3 Relationships between the elements of AHEAD

While the identification of AHEAD elements in itself is important and each aspect is an essential factor for adequate living conditions, the elements are also highly interconnected and a holistic view gives important insights into the overall system of AHEAD conditions. We therefore investigate the relationships between the identified elements, using a system thinking approach [23,68,69]. Such an approach can increase the understanding of processes within a system and show how external effects propagate through the system, as isolated assessments of single processes can ignore important feedbacks or secondary impacts.

The use of an influence matrix, as proposed by Vester (2007) [23], requires detailed knowledge of the relevant system components and general relationships between variables (elements). We perform an additional literature search to find sufficient scientific evidence for the directed relationships between elements. The scale and scope of the present exemplification of the approach only allow for connections, which are generally valid on a global scale and for which scientific evidence could be found. Other associations may exist at different spatial scales or may not have been documented in the literature.

In the AHEAD approach, the system is characterized by a definite set of elements that are interconnected within a defined boundary. As we show in Section 3.2, external effects may impact the system state, but are not considered in the initial assessment of system associations and interconnections.

3.1 Identification of associations and linkages

The system boundaries of AHEAD are defined, so that all variables are part of the system, while outside effects are initially not considered. The question we are addressing is whether conditions are adequate for human well-being and livelihoods.

Clearly, AHEAD is nested within other systems, and important processes come from the ecological and the political environment. According to the definition of the system boundary, activity and connectivity of outside factors are initially not considered and only direct relationships are included. The system is first formalized within the defined boundaries, then outside effects on the system are assessed.

Using the influence matrix, the existence of a relationship between each element is denoted. For the purpose of an exemplification with generally valid relationships, we use two classes with 0 = no documented relationship and 1 = documented relationship, drawing on scientifically rooted, general findings on existing relationships. In regional to local applications of the approach, context-specific intensities and graduations of the relationships could further be differentiated, using expert knowledge or regionally specific assessments. The influence matrix is a square matrix M_{ij}, containing the system variables 1 to n in identical order in rows (i) and columns (j), in which identified relationships are denoted. Using this matrix, it becomes possible to rank the system components according to their activity and connectivity within the system.

$$AS = \sum_{i=1}^{n} M_{ij} \quad (1) \qquad PS = \sum_{j=1}^{n} M_{ij} \quad (2)$$

From the row sums AS (active sums) (Equation 1) and column sums PS (passive sums) (Equation 2), the degree of connectivity P (Equation 3) as well as the degree of activity Q (Equation 4) of all components can be calculated.

$$P = AS \; x \; PS \quad (3) \qquad P = AS \; x \; PS \quad (4)$$

The connectivity P provides a measure of interconnectedness of the system components: higher values stand for a high degree of interconnection of the respective variable into the system, while variables with low connectivity P are least relevant for the overall system. The degree of activity Q gives important insights into the properties and position of each variable within the system. Active components (Q > 1) influence many other system components, but are influenced only by few elements. Opposed to this, passive components (Q < 1) have a weaker influence on other system components, but may be heavily influenced [68,69]. Identified linkages are shown in the influence matrix in Figure 2 (for detailed explanations and literature sources for the documented linkages see Table S3, Supplementary Material).

From the determined inter-linkages, the activity measures P (Equation 3) and connectivity measures Q (Equation 4) are calculated. Indirect connections, where changes are effected through an intermediate element, are not accounted for with additional linkages within the matrix. Results denoted in the influence matrix can be visualized in an influence diagram (Figure 3), with the degree of activity Q denoted on the x-axis and the degree of connectivity P denoted on the y-axis. Four main zones can be differentiated within the plot, according to the

Influence of ↓on →	WA	WQ	CA	AQ	EA	SH	HCI	SP	PS	ES	SoP	SC	EDU	PAR	COM	MOB	AS	P
water availability WA		1	1	0	1	0	0	0	1	1	0	0	1	0	0	0	6	12
water quality WQ	1		0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	4
calorie availability CA	0	0		0	0	0	0	0	1	0	0	0	1	0	0	0	2	12
air quality AQ	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
energy availability EA	1	1	1	1		0	1	0	0	0	1	0	1	0	1	1	9	18
shelter SH	0	0	0	0	0		0	0	0	0	1	0	0	0	0	0	1	0
health care infrastructure HCI	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
social protection SP	0	0	0	0	0	0	0		0	0	1	1	1	0	0	0	3	3
political stability PS	0	0	1	0	0	0	0	0		0	1	0	0	0	0	0	2	10
economic stability ES	0	0	1	0	0	0	0	0	0		0	0	0	0	0	0	1	3
security of person SoP	0	0	0	0	0	0	0	0	1	0		0	0	0	0	1	2	10
social cohesion SC	0	0	0	0	0	0	0	1	1	1	1		0	0	0	0	4	8
education EDU	0	0	0	0	0	0	0	0	0	1	0	0		1	0	0	2	12
participation PAR	0	0	0	0	0	0	0	0	1	0	0	0	0		0	0	1	2
communication COM	0	0	0	0	0	0	0	0	0	0	0	1	0	1		0	2	2
mobility MOB	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0		2	4
PS	2	2	4	1	2	0	2	1	5	3	5	3	4	2	1	2		
Q	3.00	1.00	0.80	0.00	4.50	0.00	0.00	3.00	0.40	0.33	0.40	2.00	0.75	0.50	0.50	1.00		

Figure 2: Influence Matrix of the AHEAD system. Based on available scientific evidence (Table S2, Supplementary), valid relationships between elements are denoted with the number 1. PS and AS represent the passive and active scores of elements, Q represents their degree of activity and P represent their degree of connectivity.

activity and connectivity of elements (Z1 to Z4). These groups provide a first indication of the each element's position within the system, relative to all other system components. With regard to the degree of activity, the zones differentiate active and passive elements (Q >/< 1). The identification of highly connected elements is based on the average connectivity of all elements. In the case of the present system of AHEAD the value of 6.25.

Elements in the lower left corner (Z1) of the plot are the least active and least connected. Elements in the upper left corner (Z2) describe those elements, which are strongly influenced by other elements of the system, however they have little influence themselves. These variables present good indicators of the state of the system. Compared to that, elements in the lower right corner of the plot (Z3) strongly influence the overall state of the system, but are less affected by influences of other parts. Elements within this zone can thus point to good intervention points, as investments in the improvement of those elements can most actively have positive influences on other parts. The top right corner (Z4) is most active as well as connected within the system. Elements within this zone are both influenced by other variables, and in turn also effect stronger influences on other elements. They can lead to strong feedback effects, but also may have most leverage for effective interventions.

Of the 16 elements of AHEAD, five elements actively influence other components within the AHEAD system (Z3/Z4), while 9 elements are passive within the system (three of those are omitted from the plot, as both Q and P have a value of 0). The elements water quality and mobility have a Q-value of 1 and are thus neither passive, nor active. In terms of connectivity, seven elements are highly connected, while 9 have low to zero connectivity. Of the passive elements, five also have a low connectivity are thus less relevant from a systems perspective. The other five passive elements are found in Z2 and therefore may provide good indicator variables to describe and monitor the state of the system. Such elements are dependent on other parts of the system and subject to feedbacks from changes in other elements. Security of person, for example results from stable and secure situations in other system parts. The two active elements social protection and communication in Z3 are not highly connected, thus providing potential efficient and controllable intervention points. Changes in these elements may have strong effects on the rest of the system, but are less influenced by the system components themselves. Such elements are

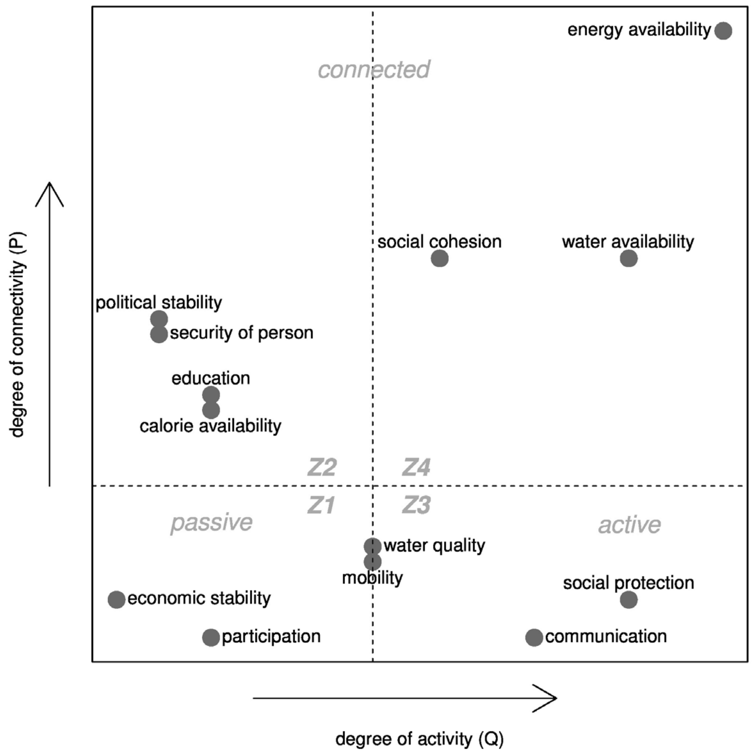

Figure 3: Influence diagram of activity and connectivity of the elements of AHEAD. Elements with Q=0 and P=0 are omitted (air quality, health care, shelter). For visibility, the elements 'political stability' – 'security of person', 'education' – 'calorie availability, as well as 'water quality' – 'mobility' have been moved apart slightly, but actually have identical positions. Since the plot provides an overview of the positions of element relative to all other system components, there are no units given for the axis. Values correspond to those given in Table 1.

highly relevant for the system in terms of their potential to significantly change the overall system state and low connectivity does not refer to the importance of an element within the system. The results of our analysis places the elements energy availability, water availability and social cohesion into Z4, which are also amongst those elements recognized as most essential for human well-being in the literature.

3.2 Impact pathways of change

The influence diagram (Figure 3) gives important insights into the degree of integration of each element. Further insight can be gained by looking in more detail into the properties of the relationships. Causal loop diagrams visualize the direction and types of the connections and can help in identifying impact pathways or possible feedback effects. To further illustrate the relevance of a systems thinking approach for AHEAD, we show how changes in single elements can propagate through the system and have indirect effects on other system components.

Several elements are directly sensitive to climate change impacts. These elements are also amongst those, which are most closely related to environmental and economic sustainability and provide obvious linkage points between the pillars of sustainability. Water availability, for example, is especially at risk of adverse effects of climate change and is projected to change in the future [70], as precipitation patterns and temperatures change. At the same time, water pollution is one of the most pressing environmental problems, which reduces resource availability for human use [71]. Energy as the most active and connected element within the system, is core challenge of sustainable development: energy availability is critical for general development and as an input for a range of human activities and needs, but also contributes actively to environmental degradation and pollution, as well as resource use [72]. It is also an essential income generating factor and contributes to economic prosperity. At the same time, energy availability is both directly and indirectly affected by climate change, in terms of production as well as consumption [73].

An integrated view of the system properties can illustrate how impacts on single components may propagate through the system and have secondary effects. Using the example of climate change and its effects on water availability, we outline potential impact pathways and their relevance for AHEAD, visualized in Figure 4.

Water availability directly influences energy production, as the latter relies on water for cooling, growing biomass for energy and water for hydro-power [74]. Reduced water availability can thus reduce energy availability through multiple pathways. Reliable access to energy can increase time for learning after dark [75] as it reduces time for the collection of fuel wood, for example, [76,77] and can thus increase education. Sufficient water availability can also directly influence education, as time is freed to attend school instead of collecting water resources [78]. The link between water availability and education is further enhanced through the availability of sufficient calories: agriculture and food production critically depend on water availability and availability of food can affect learning capacity and school attendance [79,80]. In turn, basic education is a prerequisite to access important services and to contribute to societal stability [81]. For example, higher levels of education seem to increase likelihood for voting and other ways of civic participation and understanding seems to be key to be able to access existing channels of communication [82]. Education enhances job skills, or the ability to acquire them, and thus secures better economic positions to ensure (personal) economic stability. On a higher level, better educated personnel will ensure economic reliability and availability of skilled workers to keep productivity up [83].

There are indications that water scarcity directly influences the potential for conflicts and political stability [84]. However, this relationship is a topic of scientific discussion and cooperative water management is more frequent than (violent) conflict [85]. Adequate access to sufficient water reduces time spent to acquire water and generally raise health status, so more time can be spent on generating household income and ensure economic stability [78,86]. A lack of economic and political stability can increase the likelihood of conflicts and thus reduces personal security [87,88]. Impacts on personal security can further derive from reduced energy availability, as the availability of electric street lights after dark can significantly improve security, especially of women [77]. In this chain of processes, changes in water availability can thus have far reaching and potentially unexpected indirect impacts on single AHEAD elements and the overall system.

4 Discussion

A systematic approach to integrate human well-being into assessments is of high importance, however, existing concepts and approaches are currently not in an appropriate form for application in sustainability and climate change research. Disciplinary assessments of human well-being requirements are often based on limited theories of human well-being and topical foci or political

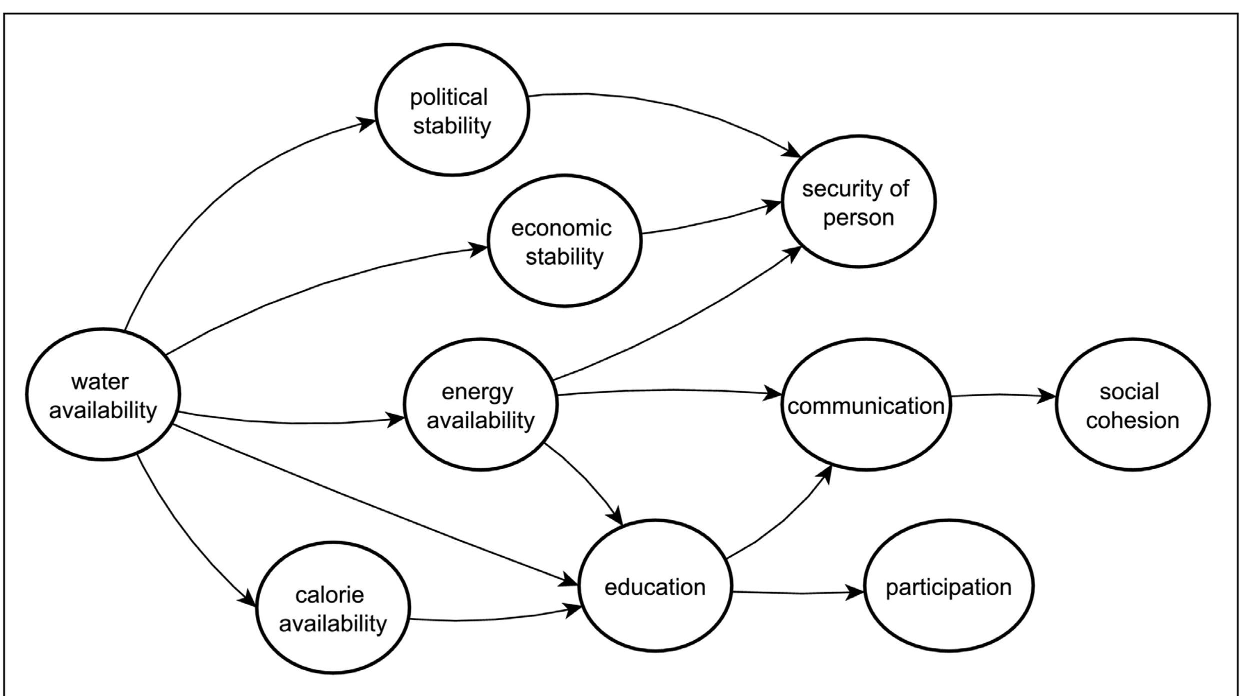

Figure 4: Exemplary pathway of impacts of changes in water availability on selected elements of AHEAD.

reasons guide the definition elements [10,89]. Integrating knowledge from a range of disciplines, we show that commonalities between approaches can be identified and that the consolidation and aggregation of approaches from different disciplines is possible. We identify the core elements and translate them into measurable components to represent human well-being and needs for sustainability in an operable and consistent way. While the single components of the proposed framework all provide essential resources for human welfare separately, processes and associations between system components prove to be important for the assessment of AHEAD conditions. Based on scientific evidence, we are able to show how the system components are interrelated. The system view allows identifying impact pathways and can thus provide important insights for climate change and sustainability science, by formalizing the process pathways and making visible indirect effects and interactions.

The analysis of a system by means of an influence matrix allows to point towards properties of the system components, which are relevant for the policy process. Policy options in general are often constrained by limited resources, thus efficient and high impact measures and actions which maximize human well-being and development should be favored. At the same time, knowledge of possible side-effects or feedbacks is important to avoid unintended outcomes. The degree of connectedness and activity of the system components can give such insights [68,69]. Social cohesion, for example, has been shown to have an important contribution to reducing the fragility of nation states [90] and is also associated to a significantly higher health status of the community [91]. In our results, social cohesion is identified as a highly active element of AHEAD. It is also most consistently included as an important element of human well-being and needs.

The four zones in Figure 3 can be differentiated and especially elements in Z2 through Z4 can become relevant in a decision-making context. Elements in Z2 are not very active within the system, however, they are highly connected and are affected by changes in other elements. These elements can be helpful as indicators of the system state, as changes in the overall system are usually reflected here. Our results place the elements security of person and political stability in Z3, for example. Both have been found to diminish as a consequence of inadequate societal, economic and political realities [92]. They thus reflect the fact, that living conditions are declining. Directly investing in either of these elements, however, has little consequence for the system, as feedbacks from other elements will quickly dampen investments made. Elements in Z3, on the other hand, are little affected by system components, but can have a strong leverage effect, as they are actively influencing other elements and investments are dampened less through influence from other system elements. The two most active and connected elements within the framework, water availability and energy availability (both in Z4), are central to the challenge of a transition towards sustainability and also directly sensitive to climate change. Elements in Z4 are intensively interacting with system parts, and active interventions at these points often have strong effects, but feedbacks have to be expected. This is important information for policy-makers, for example, as potential side-effects can be taken into account if such properties are known.

In the case of water availability and use, for example, this is well reflected in the extensive body of research devoted to integrated water resources management (IWRM), which has the purpose of modelling many of these interactions. When reacting to the impacts of climate change on these sectors, for example, an integrated system view can make visible some of the potential pathways within AHEAD and reduce unintended consequences of adaptation interventions. The fact that energy, water and also calorie availability are not only essential human subsistence needs, but are also strongly interconnected is well documented [24,93].

The approach is an important contribution in several ways. The consistent set of AHEAD indicators contributes to reducing current shortcomings in the measurement of social sustainability, regarding the arbitrariness of currently used indicators [10]. Further, linkages between the three pillars of sustainability can be assessed. As we were able to show with the example of water availability, changes in external factors, like climate change, can affect human well-being both directly and indirectly. Focussing on inter-linkages and associations between elements, the presented approach allows to assess how changes in one element propagate through the system and lead to indirect effects and potential feedbacks.

While the approach gives some important insight, it also has several limitations. We are aware that the present framework is stylized and therefore provides a simplified model of real world processes. The results are valid at a generalized and global scale, but cannot reflect local or regional characteristics, which of course play an important role for individual and subjective human well-being. In order for the approach to provide applicable results to inform the potential policy-decision, localised case-study applications, taking into account local specificities and drawing on expert knowledge would be required. In its present form it provides the first step of a formalization and provides a starting point for a subsequent detailed and rigorous analysis. Several limitations apply to the present identification of associations between elements. For the present implementation, these are solely based on scientific literature. On the one hand, this means that additional association may exist, which have not been documented. On the other hand, the underlying analyses which document existing association also use different methods in order to establish potential causalities. Such differences may lead to uncertainties and differences in the quality of the underlying assumptions. Such aspects would need additional consideration in a further elaboration of the approach. Additionally, association may vary according to regional specificities or cultural influences.

For the purpose of outlining and developing the approach, we denoted all relationships with the number 1, regardless of the intensity of the relationship. The present results therefore do not provide information on the strength or direction of the interaction. If more specific information on the relative intensity of connections is available, for example in regional or local applications of the approach, graduations or increments between 0 and 1 can be used within the influence matrix, thus further refining the specific positions of the elements within the system. Similarly, in a regional or local context additional (or fewer) elements may be needed to describe AHEAD, which are not documented in generally valid scientific assessments. A participatory assessment of local interconnections, drawing on expert knowledge, would be a useful realization of the approach for example. It is important to note that the degree of activity/interconnectedness does not measure the absolute importance of the respective element of AHEAD. It only depicts the degree to which the element influences the other parts of the system, assuming that the system is bounded, and can thus give indications for where interventions may be most effective or where the possibility of unintended feedback may be high. The defined system boundaries affect the position of the elements within the influence matrix: the positions within the system may change if outside factors, additional elements or a different intensity of relationships are taken into account. Although we base our approach on a variety of approaches, it is possible that contrarian or alternative world views are not covered in the published literature and are consequently not covered by our approach.

The outline of elements of AHEAD as well as the qualitative assessment of associations and linkages give first important insights to interactions between determinants of human well-being, sustainable development and climate impacts. However, further research is needed in order to make the approach applicable, focussing on a case study setting. It is planned to implement and quantify the approach with available data to calculate detailed impact pathways and show in more detail how external impacts affect human well-being and livelihood conditions.

5 Conclusions

We have presented a flexible formalization of human well-being and livelihoods, conceptualizing the aspects identified in an influence matrix, based on generally valid, scientific findings. A fundamental novel aspect of the approach is its foundation in a range of established theories of human well-being and livelihoods, ensuring a comprehensive representation of requirements for human well-being with linkages to climatic impacts. The approach highlights the fact that integrated methodologies have to be developed to improve understanding of processes and interlinkages at the human-nature interface. With an approach as the one presented here, leverage points to maximize human welfare while working towards the much needed transition towards sustainability can be identified. As we were able to show, the system of AHEAD elements is highly interlinked and well-documented direct impacts on important sectors, such as food, water and energy will directly and indirectly affect important aspects of societal stability. With increasing levels of global warming, hot spots of climate impacts have to be expected. To prioritize adaptation along with efforts towards sustainable development, systematic knowledge on the constituents of human well-being in essential. The AHEAD framework contributes to the optimization of human well-being as a core part of sustainable development and to reconcile goals of sustainability with climate adaptation and mitigation.

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