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Categorisation of typical vulnerability patterns in global drylands

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ABSTRACT

Drylands display specific vulnerability-creating mechanisms which threaten ecosystems and human well-being. The upscaling of successful interventions to reduce vulnerability arises as an important, but challenging aim, since drylands are not homogenous. To support this aim, we present the first attempt to categorise dryland vulnerability at a global scale and sub-national resolution. The categorisation yields typical patterns of dryland vulnerability and their policy implications according to similarities among the socio-ecological systems. Based on a compilation of prevalent vulnerability-creating mechanisms, we quantitatively indicate the most important dimensions including poverty, water stress, soil degradation, natural agro-constraints and isolation. A cluster analysis reveals a set of seven typical vulnerability patterns showing distinct indicator combinations. These results are validated by case studies reflecting the cluster-specific mechanisms and their spatial distribution. Based on these patterns, we deduce thematic and spatial entry points for reducing dryland vulnerability. Our findings could contribute new insights into allocating the limited funds available for dryland development and support related monitoring efforts based on the manageable number of key indicators.

1. Introduction

For their specific vulnerability-creating mechanisms which substantially endanger ecosystems and human well-being, drylands receive particular attention at global scale (Jäger et al., 2007). Among international institutions, the UN Convention on Combating Desertification (UNCCD) specifically aims at sustaining functioning ecosystems and improving human development across global drylands. However, as the scientific basis supporting this aim is still growing (e.g., Reynolds et al., 2007; Safriel and Adeel, 2008), the 10-year Strategy of the UNCCD (2008–2018) calls for an improved understanding of dryland development and related decision-making. One outstanding goal is the upscaling of successful interventions to reduce vulnerability. This is challenging, since drylands display very diverse characteristics including their ability to assimilate external shocks. In describing this diversity, local case studies generate valuable knowledge on vulnerability contexts and interventions. However, these case studies are specific to one or a few locations. Hence, the need emerges for drawing relevant generalisations from the assemblage of observations. Geist and Lambin (2004) took a major step toward this aim by identifying typical patterns of dryland degradation in a meta-analysis of case studies.

To illustrate the aim of this paper, we introduce the example of agricultural land in the drylands of Burkina Faso where heavy soil degradation endangered livelihoods and caused food insecurity (Reij et al., 2005). Upon application of the zaï technique – a traditional land rehabilitation approach – the degraded soils and consequently local food production improved with positive effects on rural poverty and out-migration. Should this approach be upscaled, the question must be asked as to whether such insights are applicable to dryland locations elsewhere. This is a fundamental question, since important policy decisions have to be taken at a higher than local level, for example to provide advisory and financing services as in the case described above. In response to this question, our paper presents an approach to categorise dryland vulnerability at a global scale. We identify typical patterns of dryland vulnerability and their policy implications based on similarities among the socio-ecological systems.

Our approach follows the hypothesis that the multitude of vulnerability-creating mechanisms show similarities based on which they can be reduced to a limited number of typical vulnerability patterns. Recognising these similarities, we hypothesise that intervention options are transferable among similar socio-ecological systems. Given the limited amount of resources available to reduce vulnerability in drylands, the identification of similarities provides additional information necessary for ensuring targeted and effective interventions. By integrating multiple environmental and developmental components across the world's drylands, our approach seeks to address the challenges of considering multiple drivers of and pathways to vulnerability. It

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further aims to contribute toward a more dynamic approach by considering the impacts of endogenous social and biophysical processes which modify sensitivity and adaptive capacity without external exposure. With this, our approach builds on recent advances in vulnerability research (e.g., Turner et al., 2003a, b; Lüdeke et al., 2004; O'Brien et al., 2004).

Following recent conceptualisation (McCarthy et al., 2001), we understand vulnerability as a function of the sensitivity and adaptive capacity of socio-ecological systems in drylands when they are exposed to environmental or socio-economic changes. This definition allows the identification of regions, people and ecosystems that are potentially affected by external changes. Furthermore, it also reveals causes of vulnerability to these changes. It emphasises the capacity of affected people and societies to react to changes by adapting and/or building resilience. The concept of resilience describes a system's capacity to absorb the impacts of external stimuli while maintaining its basic structure and functions (Folke, 2006). Essentially, this refers to a system's ability to revert to its original state following an alteration caused by an external stimulus. In our approach, the contrasting concepts of vulnerability and resilience are used to define a spectrum wherein drylands may be categorised.

The paper is organised in five sections: based on the compilation of specific vulnerability-creating mechanisms in drylands (Section 2), quantitative indicators are chosen to capture the most important vulnerability dimensions (Section 3.1). We employ a cluster analysis (Section 3.2) to identify typical vulnerability patterns and their spatial distribution at a global scale (Section 4.1). These patterns are used to deduce specific entry points for vulnerability reduction (Section 4.2). The paper concludes with a summary and outlook (Section 5).

2. Background: vulnerability-creating mechanisms in drylands

Drylands display a close human–nature interdependence based on marginal natural resources and are often home to marginalised populations (Safriel et al., 2005; World Bank, 2007). When disequilibrated, marginal natural resources degrade, ecosystem functions get lost, food supply becomes insecure and human lives are put at risk – all demonstrating important facets of the vulnerability of socio-ecological systems. Ongoing population growth, mainly accounted for by developing countries (UN, 2007), will further challenge the fragile socio-ecological systems. To systematically analyse dryland vulnerability, we specify typical mechanisms that reflect the complex interplay between the marginal ecosystems and human society dependent upon them. This interplay determines the sensitivity and ability to cope with or adapt to changes. Under the impact of external stimuli, higher damage is expected in more sensitive systems with lower coping and adaptive capacity. Particular external stimuli such as droughts, inequitable terms of trade and migration movements (Bardhan, 2006; Leighton, 2006) are considered important components of dryland vulnerability.

The development of dryland vulnerability depends on how well human livelihoods are adjusted to the natural agro-constraints typical in drylands. Given that the marginal natural resources barely provide sufficient opportunities to sustain a high human well-being for the growing population, the people's capacity to adjust their livelihoods is in turn influenced by their integration into wider infrastructural and decision-making networks. Overall, we suggest distinguishing between unadjusted and adjusted livelihoods. The resulting implications for dryland vulnerability are described along two contrasting trajectories illustrating how the dryland mechanisms unfold. The described mechanisms combine the most important facets of recent advances in dryland research presented by the Dryland Development Paradigm (Reynolds et al., 2007) and the Dryland Livelihood Paradigm (Safriel and Adeel, 2008). These paradigms lay out the characteristics and development pathways of drylands which we aggregate with specific focus on aspects that explain vulnerability.

Unadjusted livelihoods enforce vulnerable conditions resulting from the degradation of marginal natural resources and induce poverty, conflicts and migration. In the past, dryland degradation has reached serious levels in developing, transitional and industrialised regions alike (Dregne, 2002). The different levels of human development in these regions suggest that the degradation of natural resources results from multifaceted interactions between the environmental, socio-economic and policy contexts (Safriel et al., 2005). For example, poverty-induced intensification of agricultural production provokes water stress and soil degradation. Natural resources can degrade to such an extent that potential yield increases are far outweighed by the severe consequences of degradation (Reardon and Vosti, 1997; Petschel-Held et al., 1999; Barbier, 2000). Thus, the expected improvement of livelihoods is not achieved. Especially in view of degraded natural resources, the degree of isolation becomes an important vulnerability dimension. Isolated people experience particular disadvantages when working to diversify their livelihoods and improve their well-being, since they face difficulties in accessing service facilities and markets (e.g., Fay et al., 2005; Macours and Swinnen, 2008). In addition, policies and institutions may even exacerbate regional disparities and poverty if they are framed without considering the specific local livelihood contexts (Barbier, 2000; Bardhan, 2006). With this, the isolation dimension merges the two aspects of "remoteness" and "distant voice" – key features of dryland development as suggested by Reynolds et al. (2007). Following this trajectory, the degradation of natural resources combined with the isolation of the people reinforces the downward spiral of decreasing human well-being leading to impoverishment (Fig. 1, left-hand side). The resulting deficient livelihood conditions can drive dryland people into even deeper poverty forcing conflicts and migration (Homer-Dixon, 1999; Dobie, 2001).

In contrast, adjusted livelihoods generate resilient conditions by conserving natural resources while at the same time fostering developmental progress. In this trajectory, resources are used within the narrow natural boundaries based on conservative water consumption and integrated land management. These practices help in preventing water stress and conserving productive soils. Along with the adjusted use of resources, the integration of people and regions in infrastructural and decision-making networks encourages developmental progress. For example, the proximity to urban areas can stimulate the rural non-agricultural sector as an important source for income (Ferreira and Lanjouw, 2001). This is particularly important in developing regions with limited income opportunities. In addition, people in better integrated regions can benefit from specific dryland characteristics such as their potential for eco-tourism or solar energy production. These opportunities favour non-agricultural activities which help in both conserving natural resources and reducing dependence upon marginal natural resources (Adeel and Safriel, 2008). To successfully implement adjusted practices, adaptive institutions are required which interlink their initiatives with other relevant sectors and employ a variety of decision-rules (Dietz et al., 2003). Thus, functional institutions are crucial in drylands. The resulting improved human well-being generates suitable conditions for developmental progress and a positive feedback to sustainable resource use (Fig. 1, right-hand side).

Together, the two trajectories span a vulnerability gradient ranging from vulnerable to resilient conditions (Fig. 1). Dryland vulnerability develops between the extreme end points of this gradient with severity varying from place to place. While a given

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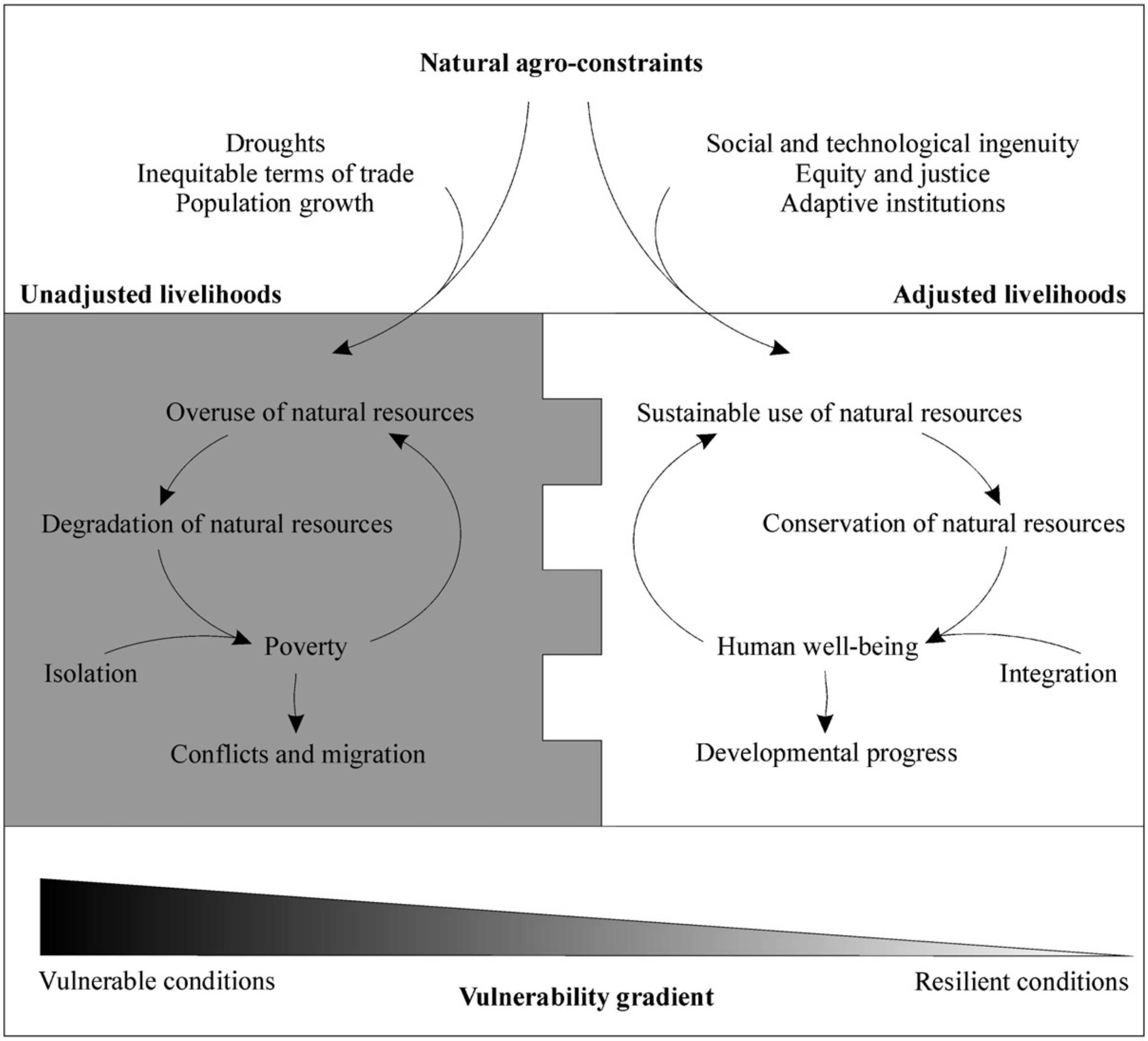

Fig. 1. Impact trajectories of unadjusted and adjusted livelihoods on dryland vulnerability. A selection of important external and endogenous stimuli driving unadjusted or adjusted livelihoods is given.
Source: Developed on the basis of Reynolds et al. (2007) and Safriel and Adeel (2008).

livelihood strategy may foster resilience in one region given the area's natural conditions, it may exceed the boundaries in another region generating vulnerability. However, local constraints do not necessarily translate into overuse of natural resources. Instead, they may promote innovative practices which can foster adaptation to local constraints particularly when being accompanied by supportive policies (e.g. Tiffen et al., 1994; Mortimore and Harris, 2005). This social and technological ingenuity was proposed by Safriel and Adeel (2008) as an important stimulus for sustainable dryland development.

3. Data and methods

3.1. Quantitative indication of vulnerability

The mechanisms presented in Section 2 form the basis to choose quantitative indicators for dryland vulnerability. Indicators are chosen to capture the most important vulnerability dimensions including poverty, degradation of natural resources, natural agro-constraints and isolation as mentioned in Fig. 1. Among these dimensions, poverty as outcome and driver of vulnerability is considered the primary vulnerability dimension. It is an essential segment in the poverty-degradation spiral which enforces vulnerability (see Fig. 1, left-hand side). Another fundamental dimension in this spiral, the degradation of natural resources, indicates the maladjustment of human livelihoods to the marginal natural resources. The marginal resources which are characterised by natural agro-constraints build the biophysical basis for configuring dryland livelihoods. Besides these direct human–nature interactions, the degree of isolation describes the socio-economic and political contexts which shape opportunities to adjust livelihoods.

Quantitative information to indicate the vulnerability-creating mechanisms would ideally be provided by spatially and temporally well-resolved global data sets. Thereby, the spatial resolution needs to be fine enough to allow for sufficient differentiation of relevant mechanisms within drylands. A minimum requirement for this is a sub-national resolution. Working at a high spatial resolution may even facilitate group-specific analyses, as highly resolved spatial units sometimes represent the living space of a particular social group, for example smallholders in the Sahel or Northeast Brazil. Furthermore, the temporal resolution determines the potential to incorporate changes in the vulnerability dimensions. Some dimensions may change rather rapidly, for example water scarcity as a result of population growth and lifestyle changes. Others may be more persistent, such as the natural agro-constraints. To ensure comparability, the data would ideally be collected at the same spatial resolution, at the same temporal

Table 1
Vulnerability dimensions and indicators used for the cluster analysis.

Vulnerability dimension	Indicator	Spatial resolution	Indicator range in global drylands	Reference period and data source
Poverty	Infant mortality	$2.5' \times 2.5'$	40–2,031 deaths per 10,000 live births	2000; CIESIN (2005)
Degradation of natural resources				
Water stress	Water scarcity	$0.5^\circ \times 0.5^\circ$ based on major river basins	1–4	1995[a]; Alcamo et al. (2003)
Soil degradation	Severity of human-induced soil degradation	$0.5^\circ \times 0.5^\circ$ based on polygons of FAO world soil map	0–4	1988–1989; Oldeman et al. (1991) 1996; Van Lynden and Oldeman (1997) 2007–2009; FAO (2009)
Natural agro-constraints	Agropotential	$5' \times 5'$	1–9	1996[a]; GAEZ (2000)
Isolation	Road density	$0.5^\circ \times 0.5^\circ$	0–0.25 km/km^2	2000; ESRI (2002)

[a] Including 1961–1990 climatology.

intervals and based on similar methodologies. If vulnerability dimensions cannot be indicated by observations, modelling provides suitable approaches to fill the gaps.

Available data, however, entail compromises for the quantitative indication of vulnerability. For poverty, commonly used indices such as poverty headcount, cannot be used, as they are not available at a sub-national resolution for all dryland regions. National indices available for countries whose territories include drylands and non-drylands would not properly express the specific values and distribution of dryland poverty. For this reason, we follow CIESIN's suggestion of considering infant mortality as an integrating indicator for poverty (Table 1). It measures the results of multidimensional efforts across nutrition, health and environmental dimensions to improve human well-being (CIESIN, 2005).

Further, we differentiate the degradation of natural resources into the most important outcomes as a result of unadjusted livelihoods: water stress and soil degradation (Table 1). Thus, as a second dimension, water stress is indicated by the water scarcity – the ratio of water withdrawal/availability in relation to the availability/cap. We assume that as long as the water withdrawal is well below the available renewable water resources, the water situation is acceptable. Here, we have used the water scarcity measure given by WaterGAP (Alcamo et al., 2003). To transform these results into an appropriate water stress indicator, this ratio is related to the actual water availability/cap based on the classification proposed by Kulshreshtha (1993). This classification takes into account that a high withdrawal fraction becomes more critical if the actual water availability/cap is rather low and varies greatly across space and time. We, hence, classify the water scarcity measure into four classes ranging from freshwater surplus to scarcity. Regarding the soil degradation, a number of studies describe soil degradation from a local to a regional scale. The findings are, however, often incompatible due to methodological and temporal differences. Recognising this constraint, we used the GLASOD and its follow-up assessments, since they are the best global judgment of the severity of human-induced soil degradation at a sub-national resolution (Oldeman et al., 1991; Van Lynden and Oldeman, 1997; FAO, 2009).

Though the natural agro-constraints, the fourth vulnerability dimension (Table 1), significantly limit productivity in drylands as compared to non-drylands, the production potential differs within the drylands. We assume that they are mainly determined by the properties of soils, rainfall and topography at production sites. These characteristics are composited in the globally available agropotential index (GAEZ, 2000). Finally, taking into account the fifth dimension of isolation, we screened indices on infrastructure, service supply as well as access to health care, markets and institutions, for example Road Distance, Good Governance and Corruption Perceptions Indices. Given the scarcity of well-resolved global data, we consider that service supply, income generation and participation in decision-making are potentially facilitated by and hence correlated with denser road networks. Thus, we use the road density (ESRI, 2002) as an indicator. Table 1 summarises the five vulnerability dimensions and respective indicators.

Some of the indicators needed adjustment. First, the infant mortality and agropotential were resampled to the $0.5^\circ \times 0.5^\circ$ resolution to integrate them with the other indicators (see Table 1). Then the agropotential and road density were adjusted by using the 2° running mean values. This procedure smoothes the values and, therefore, allows integration at a more equal spatial scale with the soil degradation originally defined on the less-resolved polygons of the FAO world soil map. Finally, we distinguish the two main components of infant mortality: (a) the natural mortality which is independent of livelihood conditions and (b) the poverty-driven component determined by for example conditions of and access to health care systems (Rutstein, 2000). To incorporate this adequately, we assume that the typical values for industrialised countries well reflect the natural component. Hence, the respective indicator values $\leq$100 deaths/10,000 live births were clearly distinguished to emphasise the poverty-driven component.

All indicators were normalised to the 0–1 interval according to their minimum and maximum values. Thereby, the original values for isolation were inversed, so that now all maximum values represent conditions that contribute to vulnerability. Overall, we focus our analysis on areas where an absolute lack of water significantly constrains the socio-ecological systems. Following the World Atlas of Desertification (Middleton and Thomas, 1997), we concentrate, therefore, on all types of drylands defined by an aridity index of up to 0.5 including hyper-arid, arid and semi-arid areas.

3.2. Cluster analysis

The selected set of vulnerability indicators (see Table 1) can be integrated in various ways to combine the relevant dimensions of dryland vulnerability. In this paper, we direct our attention to typical combinations of environmental and human development conditions upon which dryland vulnerability develops. In particular, a cluster analysis of the five vulnerability indicators is employed to investigate the structure of the data space. Here, specific vulnerability dimensions remain transparent, as they are not merged into one final value which is a usual procedure in conventional vulnerability studies (e.g., Petschel-Held et al., 1999; Luers et al., 2003; O'Brien et al., 2004). One major problem of these approaches is the substitutability among the vulnerability dimensions. In contrast, the cluster analysis keeps the individual dimensions discernable. The cluster method, however, does not automatically generate a vulnerability ranking. This needs an additional qualitative interpretation of the different clusters. The qualitative interpretation is feasible because it has to be performed only for the limited number of resulting representative indicator combinations.

Using a mask for the dryland types described earlier, we focus our analysis on about one-third of the global land mass (for further details see Safriel et al., 2005, Table 22.1). A total of 19,933 grid elements at $0.5^\circ \times 0.5^\circ$ resolution for which all necessary data are available (95% of the dryland mask) are used for the cluster analysis. The cluster analysis is performed in the five-dimensional data space spanned by the indicators detailed in the previous section. Prior to the cluster analysis, we identify correlations and variances within the data space. The absolute values of the correlation coefficients between the indicators reach a mean of 0.17. Thereby, the highest correlation coefficients are found between the isolation and soil degradation (−0.33) as well as the natural agro-constraints (0.55). This well reflects the discussion of vulnerability causes and consequences provided in Section 2. Further, indicators with a large variance tend to have a higher discriminatory power in a cluster analysis than small variance indicators (e.g., Yeung and Ruzzo, 2001; Chang, 1983). For this reason, we perform a principal component analysis (PCA) to provide insights into the variance of the indicators. For the PCA, we apply standard Pearson correlations using the statistics package R (RDCT, 2009). The PCA shows higher loadings for water stress, soil degradation and infant mortality (0.97, 0.92 and 0.49, respectively), while the natural agro-constraints and the isolation yield lower loadings (0.27 and 0.26, respectively) in the first three components explaining 89% of the total variance. These findings are considered in discussing the results of the cluster analysis (Section 4.1).

Among the vulnerability indicators, infant mortality has clearly an exceptional position. It is the only purely socio-economic indicator. It reflects aggregated aspects of for example food security and income distribution. Within the poverty-degradation spiral, the socio-economic segment is an important factor resulting from and feeding back into the segment of combined biophysical and infrastructural conditions. To reflect the similar importance of both these segments, we treat infant mortality on a par with the four remaining indicators by weighing it four times. Based on such equal weights, we identify distinct vulnerability patterns in developing/transitional and industrialised regions. This distinction is plausible because the mechanisms which for example shape resource degradation or adaptive capacity in developing/transitional regions differ significantly from those active in industrialised regions (Petschel-Held et al., 1999; Geist and Lambin, 2004). The cluster analysis (for mathematical detail see Appendix A) generates seven clearly separable clusters which depict typical combinations of the vulnerability indicators.

4. Results and discussion

4.1. Characteristics and spatial distribution of vulnerability patterns

The seven combinations of vulnerability indicators represent typical patterns of dryland vulnerability. For their interpretation, we choose two different representations (Fig. 2). First, the indicator values of each cluster are piled, so that each cluster is characterised by a column as depicted in Fig. 2a. The total height of the columns builds a bridge to conventional vulnerability metrics, since high indicator values in our analysis contribute to vulnerability. Therefore, the size of the columns can be carefully used as a measure in a vulnerability ranking. This ranking links to the vulnerability gradient in Fig. 1. Fig. 2b shows the cluster-specific values for each of the five indicators. This allows easy discernment of how the seven clusters differ in each single dimension. Thereafter, the spatial distribution of the vulnerability patterns is shown in Fig. 3. As a first rough structure, it displays a divide between developing/transitional countries (clusters 1–5) and industrialised countries (clusters 6 and 7). In the following discussion, case study evidence is given that validates the

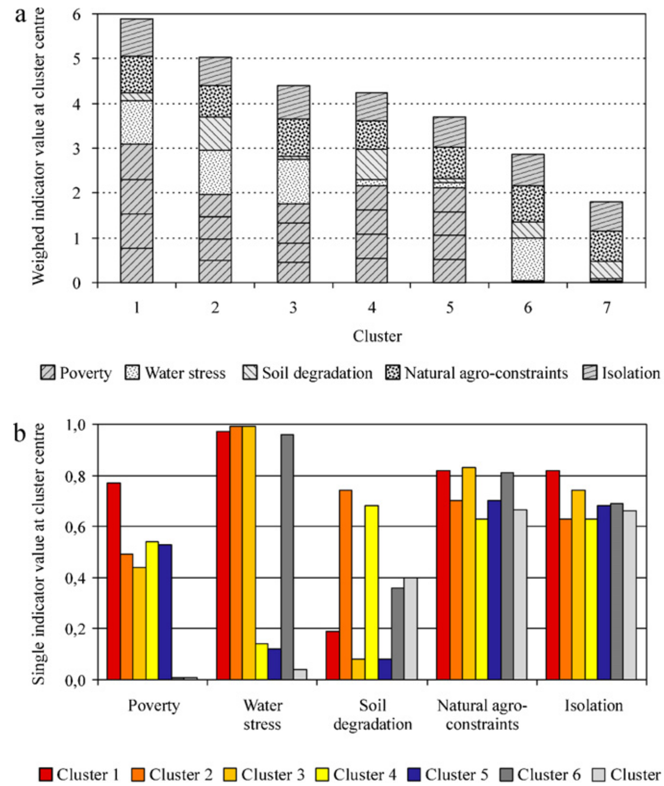

Fig. 2. Typical patterns of dryland vulnerability as result of the cluster analysis depicting the combinations of the five indicators at the seven cluster centres. Poverty is weighed four times (see Section 3.2), so that the indicator is given accordingly in a. To facilitate cross-cluster comparison, single indicator values at the cluster centres are given for each vulnerability dimension in b.

cluster-specific mechanisms and their spatial distribution (their location is indicated in Fig. 3).

Cluster 1 represents the most vulnerable regions according to the highest indicator sum (Fig. 2a). It identifies the poorest people in the most isolated regions where highly overused water resources and pronounced agro-constraints limit human well-being (red colour in Figs. 2b and 3). Here, the harsh desert conditions are likely to explain the still comparably moderate level of soil degradation, as agricultural and grazing activities are not favoured. Taking up the underlying vulnerability-creating mechanisms, cluster 1 represents the downward spiral of most threatened human well-being among all clusters in combination with severe water stress. The crisis region of Somalia serves as an example where, despite improvements in access to natural resources and security, the ability of people to recover and stabilise their livelihoods is very limited (Le Sage and Majid, 2002). The poorest people there are not able to benefit from occasionally better rainfall due to the depleted asset base and war-related constraints to access productive resources. Even though better situated people may produce more crops, debt repayment and recurrent droughts continue to exhaust their livelihood assets. According to our analysis, this specific vulnerability pattern occurs mainly in Africa and Afghanistan including parts of major deserts like the Sahara, Kalahari, Nubian and Afghan deserts.

Clusters 2–5 all show lower poverty, but differ significantly in the degree of livelihood adjustment (orange-blue colours in Figs. 2b and 3). In particular, clusters 2 and 3 display the highest water stress. Clusters 2 and 3 occur in immediate vicinity to each other in almost all continents, in Africa mainly in deserts and their adjacent areas, in the Middle East, India and across Latin America.

In cluster 2, poverty and water stress are accompanied by the severest soil degradation among all clusters. This specific

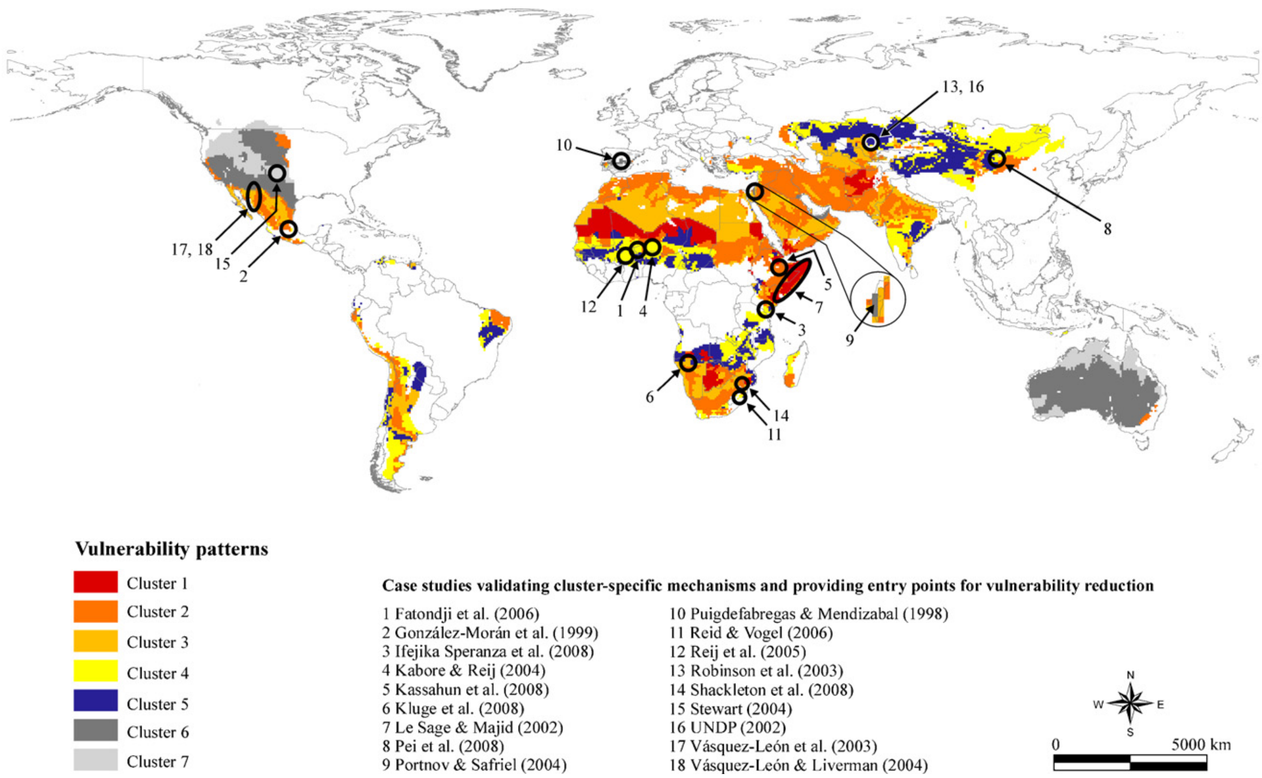

Fig. 3. Spatial distribution of the typical vulnerability patterns resulting from the cluster analysis of drylands across the globe. Exemplary case studies are mapped that validate cluster-specific mechanisms and provide entry points to reduce vulnerability.

combination is reported for various regions including Northeast Ethiopia and Central Mexico. Rangeland degradation has increased in rural areas of Northeast Ethiopia since the 1970s resulting in widespread erosion, compaction and salinisation of soils (Kassahun et al., 2008). Additionally, declining water discharge and the diversion of rivers are reported there to have decreased the availability of water resources. The ongoing overuse of natural resources has induced decreasing agricultural yields, food insecurity and conflicts over available resources. As a further example, the basin of Mexico is characterised by an excessive water uptake to supply the densely populated metropolitan area of Mexico City with potable water (González-Morán et al., 1999). The resulting over-abstraction has caused water stress to such an extent that water needs to be supplied from external, distant sources. Additionally, the over-abstraction has caused land subsidence, a specific type of soil degradation. Negative consequences for well-being in both regions are in line with the medium poverty indices in our analysis (Fig. 2b).

Likewise, cluster 3 still shows vulnerable conditions, though livelihoods are somewhat better adjusted to the severest natural agro-constraints. Here, the least degraded soils may be the result of lesser or somewhat better adapted agricultural activity. With respect to the severe water situation, Kluge et al. (2008) report few available water resources which are overused by the dense population in northern Namibia, an area covered by cluster 3. The limited and highly variable rainfall recorded there exemplifies the natural agro-constraints (Fig. 2b). In addition, they highlight that existing water institutions are inappropriate, as they rarely integrate relevant sectors in decision-making processes. This results in stress on human well-being and generates conflicts over the scarce water resources.

In contrast to the aforementioned clusters, livelihoods are relatively well adjusted to the scarce water resources in clusters 4 and 5. They are found in adjacent areas above all in the Sahel region, Southeast Africa, Central Asia, India and South America. However, the more favourable conditions are challenged by the severe soil degradation in cluster 4. The depicted situation prevails for example in some eastern areas of South Africa. The Mooi River in the KwaZulu-Natal province provides permanently water for agricultural production, so that water stress is limited to drought periods (Reid and Vogel, 2006). However, degraded soils especially in grazing areas counterbalance the relatively favourable water situation. Moreover, while the irrigation systems have improved water and food supply, the use of poor quality river water for domestic purposes has caused serious health problems owing to the absence of appropriate hygienic services. Another example where heavily degraded croplands also limit human well-being is the Makueni district in South Kenya (Ifejika Speranza et al., 2008). The constrained food production there also translates into poverty.

Comparing clusters 4 and 5, it is observed that the well preserved soils in cluster 5 do not generate significant improvements in human well-being. Central Kazakhstan may serve as an example here. Though winter fodder provision during the Soviet Union period allowed increasing the average livestock size, Robinson et al. (2003) concluded that seasonal rotation of livestock during the 1980s–1990s was an important factor contributing toward the prevention of soil degradation in some central parts of Kazakhstan. Although soils had been relatively conserved, their overall marginality limited human well-being. Other factors limiting human well-being included socio-economic disparities, legal barriers and social sector cutbacks since the collapse of the Soviet Union (UNDP, 2002). These factors forced a considerable decrease in agricultural production and livelihood assets eventually driving rural out-migration. The shortage of both agricultural assets and working-age people in this region has further impeded the advancement of human well-being.

Clusters 6 and 7 in industrialised regions are the least vulnerable areas (Fig. 2a) depicting the lowest poverty indices (dark and light grey colours in Figs. 2b and 3). However, the intensive agricultural production provokes the depletion of natural resources. In particular, cluster 6 shows a high water stress in combination with a medium level of soil degradation. The Negev region in Israel is an example where the advanced human well-being does not guarantee the sustainable use of natural resources: synergetic forces of climate and socio-economic drivers generate water stress and soil degradation which are not compensated for by the available knowledge and technologies (Portnov and Safriel, 2004). A similar failure is reported in Central Spain. Puigdefabregas and Mendizabal (1998) document the exhaustion of water aquifers in the Castile-La Mancha region driven by population reallocation leading to increased local tension over scarce water resources. In comparison, cluster 7 shows the lowest water stress, but soil degradation still reaches medium levels. For example, a favourable water situation allowed widespread irrigation in the Southern Great Plains, but the fragile soils severely degraded under the highly mechanised monocultural cropping (Stewart, 2004). Later, conservation agriculture triggered by the increasing oil prices of the 1970s somewhat improved the soil's quality. However, as not all farmers applied conservation measures, soils have not fully recovered.

The results of the cluster analysis are also validated for three clusters in relative vicinity to each other in the neighbouring states of Sonora and Arizona along the Mexico–USA border (clusters 2 and 3 as well as 6, respectively). The different livelihood strategies and levels of human well-being differentiate the severity of vulnerability to droughts in these highly water-stressed regions (Vásquez-León et al., 2003; Vásquez-León and Liverman, 2004). In the municipality of Alamos (Sonora), water is particularly scarce due to the diversion of rivers for agricultural purposes outside of the municipality. Adding to the water scarcity, widespread overgrazing and deforestation have led to severe soil degradation especially in the eastern parts (cluster 2). The western parts of this municipality are predominantly used by large-scale cattle ranchers. They have increasingly engaged in capital-intensive soil conservation practices which have resulted in generally better preserved agricultural land (cluster 3). Overall, the high competition for the scarce water resources poses significant disadvantages for poor smallholders on communal land (ejidatarios) who account for 80% of all producers. Under these conditions, the great majority of the population could not cope well with droughts especially when coinciding with uncertain landownership following privatisation and structural adjustment programmes. The severe consequences including production failure and loss of livelihood assets link to a limited human well-being as identified by our analysis. On the other hand, technology-centred approaches to improve water supply have stabilised agricultural production in the Sulphur Springs Valley (Arizona). However, water withdrawal from groundwater aquifers exceeded natural recharge there, so that water table depths have dropped and induced a critical water situation (cluster 6). As a consequence, new irrigation schemes were temporarily prohibited in this region. Overall, the region has not fully aligned agricultural practices with available options for sustainable production.

Our analysis shows that the natural agro-constraints and isolation as incorporated in this study do not distinguish clearly between the different vulnerability-creating mechanisms (Fig. 2b). This is in line with the smaller variance in these indicators (see Section 3.2). Thus, a further differentiation would be useful: on the one hand, the importance of natural agro-constraints for human well-being depends largely on how far livelihoods rely on agriculture and forest use. Thus, refining the initial mechanism could involve an additional dimension that takes into account people's dependence on natural resources. On the other hand, the isolation dimension could be evaluated in greater depth by extending the indication to include for example an indicator of the distance to service or decision-making centres as used in the accessibility/remoteness index of Australia (ARIA) (DH and AC, 2001).

The identified vulnerability patterns describe typical indicator combinations. Each of them shows specific causes of vulnerability and opportunities to increase a system's ability to assimilate shocks.

4.2. Entry points to reduce dryland vulnerability

The variance between the typical vulnerability patterns suggests that there is no one single option to reduce vulnerability in all dryland regions. We rather propose that each combination demands for a typical mix of options. We illustrate them in the following section with special emphasis on the most important constraints in developing regions. Since agricultural production is important to secure human well-being, this aspect receives particular attention. Thereby, the severity of vulnerability may guide the prioritisation of interventions at a global scale. Selected case studies demonstrate how cluster-specific approaches can be successfully translated into practice (for their location see Fig. 3).

We deduce the entry points for vulnerability reduction (Table 2) from the indicator values at the cluster centres. Thereby, dimensions with high indicator values (0.67–1) would require particular attention (↑↑↑), while medium values (0.33–0.67) still indicate areas which need improvement (↑). In contrast, dimensions with low indicator values (0–0.33) would need to be stabilised to secure benefits from these relatively favourable conditions (●). Table 2 shows that the natural agro-constraints need particular attention in nearly all clusters. Thereby, the mainly water-related constraints are assumed as the natural dryland context which may benefit across all clusters through trade-offs from well-managed water resources. In addition, approaches to ameliorate the effects of widespread isolation would generate improvements throughout the clusters.

Starting with the most vulnerable regions, cluster 1 would require particular attention in almost all vulnerability dimensions (Table 2). As basic interventions, two options to better adjust livelihoods to marginal water resources are: decreasing water withdrawal and increasing water availability. Given the severe natural water constraints in the prevalent desert areas and the limited enabling environment in the water sector in many African countries (ECA et al., 2000), it is difficult to increase the water availability. Until these constraints are overcome, it becomes essential to assess how the water situation can be improved more pragmatically by lowering water withdrawal. Estimates of water-use efficiency in dryland agriculture indicate that farmers tend to over-irrigate their crops based on their perception of crop-specific

Table 2
Entry points for vulnerability reduction according to the indicator values at the cluster centres.

Cluster	Poverty	Water stress	Soil degradation	Natural agro-constraints	Isolation
1	↑↑↑	↑↑↑	●	↑↑↑	↑↑↑
2	↑	↑↑↑	↑↑↑	↑↑↑	↑
3	↑	↑↑↑	●	↑↑↑	↑↑↑
4	↑	●	↑↑↑	↑	↑
5	↑	●	●	↑↑↑	↑↑↑
6	●	↑↑↑	↑	↑↑↑	↑↑↑
7	●	●	↑	↑	↑

Symbols mean: ↑↑↑ = particular attention needed, ↑ = improvement needed, ● = stabilisation needed.

water requirements, rainfall and market conditions (Deng et al., 2006; Shideed et al., 2005). Hence, investigating necessary water requirements would help to adjust perceptions and reduce water withdrawal.

Even though an improved water situation would create positive effects on agricultural production and human well-being, some regions require immediate interventions to improve basic livelihood conditions in view of the high poverty indices. In cluster 1, a better integration of these isolated regions would facilitate the delivery of food, water and services especially in times of crop failure and other emergencies. Improved integration also encourages the employment of water-independent, non-agricultural livelihood options.

To release pressure from the overused water and soil resources in cluster 2, it would be worth considering a decrease in the intensity of land use. This may involve commercialisation of local products. For example, poor people in the Northeast of South Africa improved their income by selling locally produced brooms, furniture and traditional marula beer (Shackleton et al., 2008). Elaborate safety nets, diversified livelihoods and increased food security improved the people's well-being. A shift of water-intensive agricultural production to more water rich areas may provide another strategy. Both options should, however, be carefully evaluated in the given socio-economic context of each region to avoid triggering a more pressing dependency on the markets.

Improved human well-being allows efforts to create livelihoods that are better adjusted through applying more labour-intensive and time-consuming measures. We give two examples for cluster 4 where soil degradation is the most important vulnerability dimension. One option to address the frequent problem of overgrazing is the shift from continuous grazing to the more demanding livestock rotation. Livestock farmers in North China successfully reduced soil degradation utilising this approach (Pei et al., 2008). The aforementioned zaï technique applied in Burkina Faso (Reij et al., 2005) also requires more labour input. As yields rapidly increased, higher labour input was accepted and the technique was widely adopted on degraded lands. In this vulnerability pattern, it is essential to explore how a well-balanced water situation can be maintained even in more productive systems.

The example of Burkina Faso (cluster 4) highlights the relevance of similarities among various locations. The cluster analysis reveals the same vulnerability-creating mechanisms for other parts of the Sahel zone. Given the similarities in vulnerability causes, the same types of intervention are expected to reduce vulnerability in these regions. Two examples are given that confirm this hypothesis. First, the land rehabilitation approach applied in Burkina Faso was transferred to villages in Southwest Niger (Kabore and Reij, 2004, p. 23) which also belong to cluster 4. Improving the technique ensured that the soil's quality began to recover, food supply increased and livelihoods improved. Later, the same approach also yielded improved soils and agricultural production in other cluster 4 locations in Southwest Niger (Fatondji et al., 2006). Thus, the cited approach helped in overcoming the most important soil constraints in these regions which showed similarity in our cluster analysis.

The case of Niger underlines the importance of the sub-national resolution of our analysis. Throughout the country, we find a number of vulnerability patterns each suggesting particular interventions. Such a spatial differentiation provides important insights for prioritising necessary action within a country.

Besides its general applicability, the implementation of cluster-specific entry points has to be further adjusted to particular local conditions. For example, different social groups such as the illiterate, women or the elderly and areas with conflicting development interests may require special attention. As these aspects are necessarily beyond the functional resolution of an analysis with global coverage, they have to be considered in the sense of refining the deduced entry points.

5. Conclusions

The pattern approach presented in this paper outlined one way of dealing with the complex vulnerability-creating mechanisms in drylands. It is the first attempt to quantitatively analyse dryland vulnerability sub-nationally and with global coverage. The proposed cluster approach enabled us to deduce similarities among the diverse socio-ecological systems. It identified typical vulnerability patterns that gave distinct combinations of vulnerability-creating mechanisms and respective policy implications. The results were validated by selected case studies reflecting the cluster-specific mechanisms and their spatial distribution. By ranking the vulnerability patterns according to the severity of vulnerability, we suggested spatial and thematic priorities for vulnerability reduction. Thereby, the sub-national resolution of analysis allowed recognising heterogeneity within countries to help focus relevant interventions. Altogether, our results could stimulate new insights on reducing dryland vulnerability and respond to the need of rationally allocating the limited funds available to strengthen dryland development. To further support more tailored vulnerability reduction efforts and monitor changes in the vulnerability causes, data sources need to be developed accounting for the spatial and temporal variability of the relevant processes.

Current ecosystem and human development in most dryland regions suggest that an increase of agricultural production related to the ongoing population growth would aggravate existing vulnerability due to the incrementing risks of further resource degradation. This is especially true in the most vulnerable clusters. However, some of the less vulnerable clusters show a certain potential to assimilate an agricultural production increase without necessarily aggravating vulnerability. This is the case in cluster 5 with comparatively conserved natural resources and in cluster 7 with the potential to overcome some extent of natural production limitations and human-induced degradation by using available knowledge and technologies.

To further advance the presented research on dryland vulnerability, the quantitative indication should be updated based on the vulnerability-creating mechanisms when relevant sub-national data become globally available. The general methodology for identifying vulnerability patterns should be further elaborated. In addition, the analysis would benefit from an even more rigorous validation. Finally, exploring the value of typical vulnerability patterns for dryland decision-makers will promote the refinement of specific mechanisms and the required support for decision-making.

Appendix A. Cluster analysis

The cluster analysis was performed using a sequence of a common hierarchical and partitioning cluster algorithm, i.e., hclust and kmeans, based on sub-routines from the open source statistics package R (MacQueen, 1967; RDCT, 2009). There are a number of comparable approaches for estimating the optimal number of clusters (e.g., Mufti et al., 2005; Tibshirani and Walther, 2005). We developed an approach which enables us to identify the optimal number of clusters based on reproduction and well-defined cluster characteristics. For this, we use both (a) a consistency measure which describes the reproduction of the cluster partitions and (b) the ratio of the between-cluster variance and the inner-cluster variance (Calinski and Harabasz, 1974).

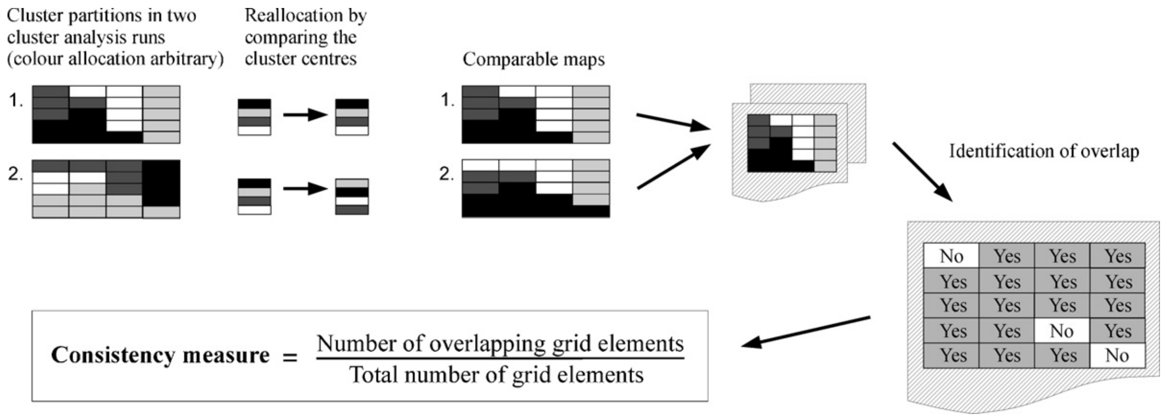

Fig. 4. Approach developed to calculate the consistency of cluster reproductions. An example is given for two cluster partitions showing four clusters.

Table 3
Consistency measure and ratio of the between-cluster variance and the inner-cluster variance for cluster partitions with 2–10 clusters. The given values are averages of 50 repetitions of 400 cluster partitions, that is 200 pairwise comparisons for the consistency measure. Standard deviations of the 50 repetitions are given accordingly in brackets.

	Cluster number								
	2	3	4	5	6	7	8	9	10
Consistency measure	0.819 (0.014)	0.987 (0.002)	0.893 (0.009)	0.908 (0.008)	0.861 (0.007)	0.874 (0.007)	0.848 (0.006)	0.847 (0.007)	0.848 (0.005)
Between/inner-cluster variance	1.40 (0.05)	2.02 (0.06)	2.45 (0.06)	2.89 (0.06)	3.31 (0.06)	3.74 (0.06)	4.13 (0.05)	4.50 (0.07)	4.88 (0.06)

In our approach, we assume that the stochastically initialised cluster algorithm will tend to generate similar results in repeated runs if the cluster number fits the data structure. Therefore, we first generate two cluster partitions on all dryland grid elements for a defined cluster number. For each partition, the hierarchical cluster algorithm is stochastically initialised with a randomly chosen sub-set of the data. Second, the number of grid elements with an identical cluster allocation in both cluster partitions is counted. This amount of overlap divided by the total number of grid elements is the consistency measure (Fig. 4). The pairwise comparison was repeated 200 times for each cluster number to identify the cluster number which maximises the consistency measure. The 2×200 cluster partitions generated with this procedure for each cluster number serve to determine the ratio of the between-cluster variance and the inner-cluster variance.

Table 3 gives the consistency measure for cluster numbers 2–10. The values represent averages for 50 repetitions of the 200 pairwise comparisons specific for each cluster number. To show the reliability of our method, we present the standard deviation describing the variability in the consistency measure among the 50 repetitions. The very small standard deviation shows the very good convergence of the stochastic approach. Overall, cluster numbers three, five and seven show relative maxima for the consistency measure.

On the other hand, the variance ratio increases strongly up to cluster number seven, while for larger cluster numbers the gain in the variance ratio becomes smaller (Table 3). Combining these two observations, we use seven clusters for the vulnerability analysis. This choice is also supported by the development of cluster partitions with increasing cluster numbers. For cluster numbers greater than five, the algorithm yields an explicit distinction of clusters with high, medium and low poverty. This is an important differentiation of a relevant driver and outcome of dryland vulnerability. Moving from six to seven clusters, this differentiation is maintained and the newly emerging cluster is characterised by medium poverty and conserved natural resources which provides interesting insights for the discussion of vulnerability patterns.

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