MANUSCRIPT

Categorisation of typical vulnerability patterns in global drylands

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Abstract

Drylands display specific vulnerability-creating mechanisms which threaten ecosystem and human wellbeing. Up-scaling 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 global scale and in 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 results in a set of seven typical vulnerability patterns showing distinct indicator combinations. These results are verified by selected case studies reflecting the cluster-specific mechanisms and their spatial distribution. Based on the patterns we deduce thematic and spatial entry-points for reducing dryland vulnerability. Our results could contribute new insights to allocating the limited funds available for dryland development and support related monitoring efforts based on the manageable number of key indicators.

Keywords: Vulnerability pattern, socio-ecological system, quantitative indication, sub-national resolution, global drylands

1 Introduction

For the presence of specific vulnerability-creating mechanisms which substantially endanger ecosystem and human wellbeing drylands receive particular attention at global scale (Jäger et al., 2007). Among the international institutions the UN Convention on Combating Desertification (UNCCD) specifically aims at sustaining ecosystem functioning and improving human development across global drylands. However as the scientific basis is still growing (e.g., Reynolds et al., 2007; Safriel & 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 up-scaling of successful interventions to reduce vulnerability. Since drylands show very diverse characteristics including their ability to assimilate external shocks, this is however challenging. Describing this diversity local case studies generate valuable knowledge on vulnerability contexts and interventions, though specific to one or a few locations. Hence the need emerges for generalising the assemblage of observations. For example 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 heavily degraded agricultural land in the drylands of Burkina Faso causing food insecurity and risky livelihoods (Reij et al., 2005). Applying the zai technique, a traditional land rehabilitation approach, the degraded soils and consequently local food production improved with positive effects on rural poverty and out-migration. Following the aim of up-scaling the question arises of how relevant are such insights for dryland locations elsewhere? This is a fundamental question since important policy decisions have to be taken at higher than local level, e.g., 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 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 limited resources to reduce vulnerability in drylands, the indication of similarities hence provides additional information for targeted interventions. By integrating multiple environmental and development components across the global drylands, our approach seeks to address the challenges of considering multiple drivers and pathways of vulnerability. It further aims at contributing to 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 and b; Lüdeke et al., 2004; O´Brien et al., 2004).

Following recent conceptualisations, we understand vulnerability as a function of sensitivity and adaptive capacity of the socio-ecological systems in drylands when being exposed to environmental or socio-economic changes. While this definition allows identifying regions, people and ecosystems that may be affected by external changes it also reveals causes of vulnerability to these changes. It further emphasises the capacity of affected people and societies to react by adapting to changes or building resilience. Thereby 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). This means that even though a system is forced to leave its current state while being exposed to an external stimulus, it bounces back to this former state. In our approach, resilience complements the concept of vulnerability.

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

2 Background: Vulnerability-creating mechanisms in drylands

Drylands display a close human-nature dependence based on marginal natural resources and are often home to marginalised populations (Safriel et al., 2005; World Bank, 2007). When being desequilibrated, marginal natural resources degrade, ecosystem functions get lost, food supply is not secured and human lives are at risk - all demonstrating important facets of vulnerability of the 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 services supplied by the marginal ecosystems and human society depending on these ecosystems. This interplay determines the endogenous 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 as 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 wellbeing for the growing populations the people´s capacity to adjust their livelihoods is in turn influenced by the integration into wider infrastructure and decision-making networks. Overall, we suggest to distinguish between exploiting and adjusted livelihoods. The resulting implications for dryland vulnerability are described along two trajectories to illustrate 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 & Adeel, 2008). These paradigms lay out the characteristics and development pathways of drylands which we aggregate with specific focus on aspects that explain vulnerability.

Exploiting livelihoods enforce vulnerable conditions resulting from the degradation of marginal natural resources inducing 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 extend that potential yield increases are far outweighed (Reardon & Vosti, 1997; Petschel-Held et al., 1999; Barbier, 2000). Thus the expected improvement of livelihoods is not achieved. Furthermore in view of degraded natural resources, the degree of isolation becomes an important vulnerability dimension. Isolated people experience particular disadvantages when striving for diversification of their livelihoods and improvement of their wellbeing, since they face difficulties to access service facilities and markets (e.g., Fay et al., 2005; Macours & Swinnen, 2008). In addition policies and institutions may even exacerbate regional disparities and poverty when being 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” being key features of dryland development suggested by Reynolds et al. (2007). Following this trajectory, the degradation of natural resources and isolation of people reinforce a downward spiral of decreasing human wellbeing leading into poverty (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 preserving natural resources while at the same time fostering development 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 preserving productive soils. Alongside the adjusted use of resources, the integration of people and regions in infrastructure and decision-making networks encourages development progress. For example the proximity to urban areas can stimulate the rural non-agricultural sector as an important source for income (Ferreira & Lanjouw, 2001). This is particularly important in developing regions with limited income opportunities. In addition people in better integrated regions can easier benefit from specific dryland characteristics such as the potential for eco-tourism or solar energy production. These opportunities favour non-agricultural activities which help in preserving natural resources and reduce the dependence on the marginal natural resources

(Adeel & Safriel, 2008). To successfully implement adjusted practices adaptive institutions are required which interlink their arrangements with other relevant sectors and employ a variety of decision-rules (Dietz et al., 2003). Though functioning institutions are important in many contexts, they are crucial in drylands for the marginal natural resources and particular dependence of human livelihoods. The resulting improved human wellbeing implies suitable conditions for development progress and a positive feedback to sustainable resource use, given potential investments in resource management (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 varying severity from place to place. Thereby livelihood strategies that are within the natural boundaries in one region and foster resilience there may exceed the boundaries in another region generating vulnerability. However narrow local boundaries do not necessarily favour the over-use 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 & Harris, 2005). This social and technological ingenuity was proposed by Safriel and Adeel (2008) as an important stimulus for sustainable dryland development.

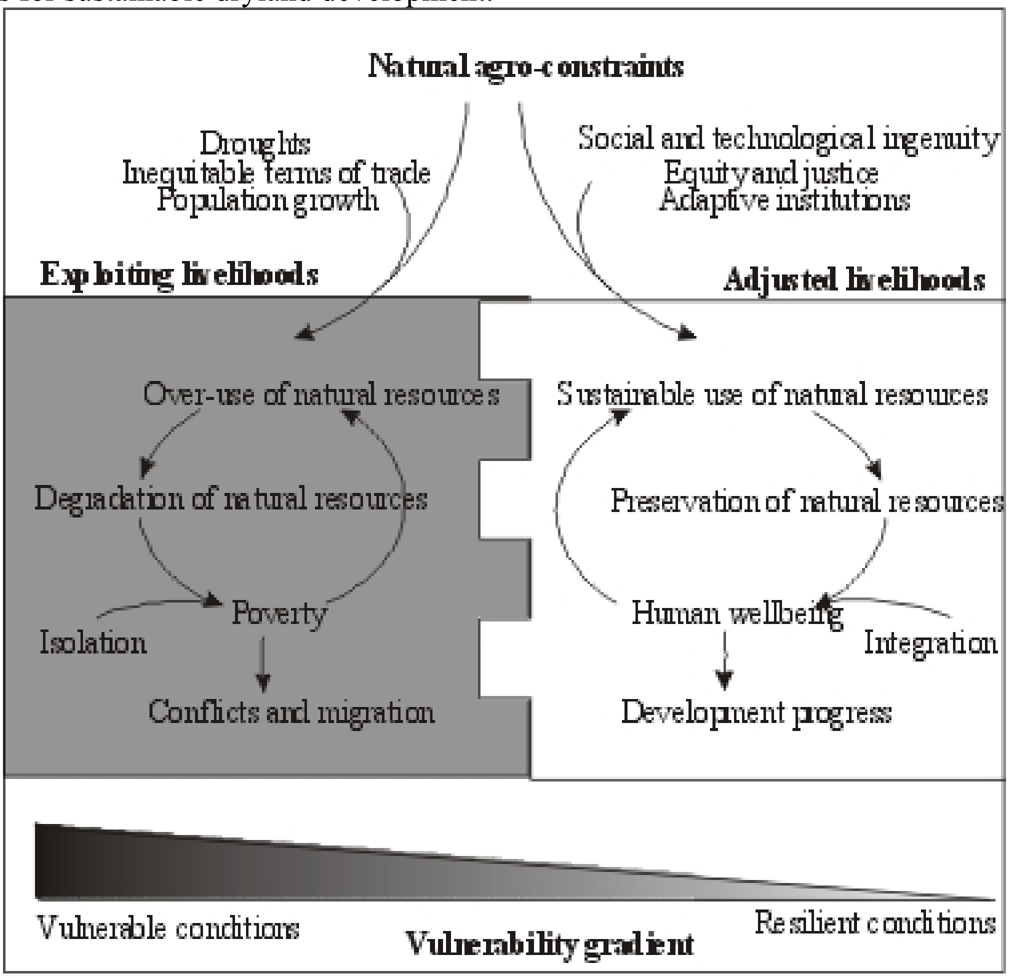

Figure 1. Impact trajectories of exploiting and adjusted livelihoods on dryland vulnerability. Typical dryland interactions between marginal natural resources and human livelihoods can generate two trajectories depending on the level of adjustment of livelihoods to the natural agro-constraints. A selection of important external and endogenous stimuli driving exploiting or adjusted livelihoods is given. The resulting trajectories shape vulnerable or resilient conditions. (Source: Developed on the basis of Reynolds et al. (2007) and Safriel & Adeel (2008)).

3 Data and method

3.1 Quantitative indication of vulnerability

The mechanisms presented in section 2 are the basis to choose quantitative indicators for dryland vulnerability. Indicators were chosen to capture the most important vulnerability dimensions including poverty, degradation of natural resources, natural agro-constraints and isolation as given in Figure 1. Among these dimensions, poverty as outcome and driver of vulnerability is considered the primary vulnerability dimension. It is an essential element in the poverty-degradation spiral which enforces vulnerability (see Fig. 1, left-hand side). The other fundamental dimension in this spiral, the degradation of natural resources, indicates the adjustment of human livelihoods to the marginal natural resources. The marginal resources which are characterised by the 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 context 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 high spatial resolution may even facilitate group-specific analyses as highly resolved spatial units sometimes represent the living space of a particular social group, e.g., 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, e.g., water scarcity as a result of population growth and lifestyle changes while others may be more persistent such as the natural agro-constraints. To ensure comparability the data would be collected ideally in the same spatial resolution and temporal intervals based on similar methodologies. If vulnerability dimensions cannot be measured directly modelling provides suitable approaches to fill the gaps.

Available data however require compromises. For poverty commonly used indices, e.g., poverty headcount, could not be used as they are not available at sub-national resolution for all dryland regions. National indices available for countries whose territories assemble 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 infant mortality as an integrating indicator for poverty (Tab. 1). It measures the results of multidimensional efforts across nutrition, health and environmental dimensions to improve human wellbeing (CIESIN, 2005).

Further we differentiate the degradation of natural resources into the most important outcomes as a result of livelihood adjustment in drylands: water stress and soil degradation (Tab. 1). Thus as a second dimension, water stress is indicated by the water criticality, i.e., 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 balanced. Here we used the water scarcity measure given by WaterGAP 2 (Alcamo et al., 2003). To transform these results into an appropriate water stress indicator, this ratio is related to the actual water availability/caput after Kulshreshtha (1993). This takes into account that a high withdrawal fraction becomes more critical if additionally the actual water availability/cap is rather low and varies greatly across space and time. Kulshreshta (1993) characterised the resulting criticality in four classes ranging from freshwater surplus to scarcity which we use in our analysis. Regarding the soil degradation, a number of studies describe soil degradation at local to regional scale. Their findings are however hardly comparable among each other due to methodological and temporal differences. Recognising this constraint, we used the GLASOD and its follow-up assessments since they best represent the severity of human-induced soil degradation sub-nationally resolved (Oldeman et al., 1991; van Lynden & Oldeman, 1997; FAO, 2008).

Though the natural agro-constraints, the fourth vulnerability dimension (Tab. 1), significantly limit productivity in drylands compared with non-drylands, the production potential differs within the drylands. We assume that they are mainly determined by the properties of soils, rainfall and topography of production sites. These characteristics are composited in the globally available agropotential index (GAEZ, 2000). Finally indicating the fifth dimension of isolation we screened indices on infrastructure, service supply as well as access to health care, markets and institutions, e.g., 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 from ArcWorld ESRI (2002) coverages as an indicator. Table 1 summarises the five vulnerability dimensions and respective indicators.

Vulnerability dimension	**Indicator**	**Spatial resolution**	**Indicator range in global drylands**	**Reference period and data source**
Poverty	Infant mortality	2.5x2.5`	40-2031 deaths per 10,000 live births	2000; CIESIN (2005)
Degradation of natural resources				
Water stress	Water scarcity	0.5x0.5° based on major river basins	1-4	1995*; Alcamo et al. (2003)
Soil degradation	Severity of human-induced soil degradation	0.5x0.5° based on polygons of FAO world soil map	0-4	1988-1990; Oldeman et al. (1991) 1996; Van Lynden & Oldeman (1997) 2007-2009; FAO (2009)
Natural agro-constraints	Agropotential	5x5`	3.0-8.3	1996*; GAEZ (2000)
Isolation	Road density	0.5x0.5°	0-0.15 km/km^2	2000; ArcWorld ESRI (2002)

* including 1961-1990 climatology

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

Some of the indicators needed adjustment. First, the infant mortality and agropotential were resampled to the 0.5x0.5° resolution to integrate them with the other indicators (see Tab. 1). Then the agropotential and road density were adjusted by using the 2° running mean values. This procedure smoothes the values and hence allows integrating them 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, e.g., conditions of and access to health care systems (Rutstein, 2000). To reflect this adequately, we assume that the typical values for industrialised countries well reflect the natural component. Hence the respective indicator values ≤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 is a major constraint for the development of the socio-ecological systems. Following the World Atlas of Desertification (Middleton & 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 Tab. 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 amongst the vulnerability dimensions. In contrast the cluster analysis keeps the individual dimensions discernable. The cluster method however does not imply automatically a vulnerability ranking. This needs an additional qualitative interpretation of the different clusters. This 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 above we focus our analysis on about one third of the global land mass (for further details see Safriel et al., 2005, Tab. 22.1). 19933 grid cells with 0.5x0,5° resolution for which all necessary data are available are used for the cluster analysis (95% of the dryland mask). The cluster analysis is performed in the five-dimensional data space spanned by the indicators detailed in the previous section. Preparing the cluster analysis we identify correlations and variance in 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 reflects well the discussion of vulnerability causes and consequences given in section 2. Further, variables with a large variance tend to have a higher discriminatory power in a cluster analysis than small variance variables (e.g., Yeung and Ruzzo 2001; Chang 1983). Thus we performed a principal component analysis (pca) to provide insights in the variance of the variables. For the pca we apply standard Pearson correlations using the statistics package R (RDCT, 2009). The pca shows higher loadings for the water stress, soil degradation and infant mortality (0.97, 0.92 and 0.49 resp.), while the natural agro-constraints and the isolation yield lower loadings (0.27 and 0.26 resp.) in the first three components explaining 89% of the total variance. The implications of these findings are outlined along with the results of the cluster analysis (sect. 4.1).

Among the vulnerability indicators the infant mortality has clearly an exceptional position. It is the only purely socio-economic indicator. It reflects aggregated aspects of, e.g., food security and income distribution. Within the poverty-degradation spiral the socio-economic segment is an important building block resulting from and feeding back to the segment of combined biophysical and infrastructure 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 which per definition differ in their socio-economic conditions. This distinction is also plausible because the mechanisms which, e.g., shape resource degradation or adaptive capacity in developing/transitional regions significantly differ from the ones being active in industrialised regions (Petschel-Held et al. 1999, Geist & Lambin 2004). The cluster analysis (for mathematical detail see the Appendix) generates seven clearly separable clusters that depict typical combinations of the vulnerability indicators.

4 Results and discussion

4.1 Characteristics and spatial distribution of vulnerability patterns

The seven combinations of the vulnerability indicators represent typical patterns of dryland vulnerability. For their interpretation we choose two different representations. First, the indicator values of each cluster are piled, so that each cluster is characterised by a column given in Figure 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 for a vulnerability ranking. Then, the cluster-specific values for each of the five indicators are depicted in Figure 2b. This allows seeing easily how the seven clusters differ in each single dimension. Thereafter, the spatial distribution of the vulnerability patterns is shown in Figure 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 verifies the cluster-specific mechanisms and their spatial distribution (their location is given in Fig. 3).

Cluster 1 represents the most vulnerable regions according to the highest indicator sum (Fig. 2a). It identifies poorest people in isolated regions, where highly over-used water resources and relatively pronounced agro-constraints limit their human wellbeing (red colour in Figs. 2b and 3). Here, the harsh desert conditions are likely to explain the still comparably moderate level of soil degradation, since agricultural and grazing activities are not favoured. Taking up the underlying vulnerability-creating mechanisms, cluster 1 represents the downward spiral of most threatened human wellbeing among all clusters and water resource degradation. The crisis region of Somalia gives an example where people are hardly able to recover and stabilise their livelihoods despite coinciding improvements in access to natural resources and security (Le Sage & 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 again 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.

The following clusters 2-5 all show lower poverty, but largely differ in the degree of livelihood adjustment (orange - blue colours in Figs. 2b and 3). In particular, clusters 2 and 3 display a very high water stress. Clusters 2 and 3 occur in immediate vicinity in almost all continents, in Africa mainly in deserts and their neighbourhood, in the Middle East India and across Latin America.

In cluster 2 poverty and water stress is accompanied by the severest soil degradation amongst all clusters. This specific combination is reported for various regions, e.g., 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, the diversion of rivers there decreased the accessibility of water resources. The ongoing over-use of natural resources has induced declining agricultural yields, food insecurity and conflicts over available resources. As a further example the basin of Mexico is also characterised by an excessive water uptake to supply the metropolitan areas with potable water (González-Morán et al., 1999). The resulting over-abstraction causes land subsidence as a specific type of soil degradation. Negative consequences for wellbeing in both regions are represented by the still 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 comparably least degraded soils may be the result of less or somewhat better adapted agricultural activity. With respect to the severe water situation, Kluge et al. (2008) report few available water resources which are over-used by the dense population in northern Namibia, an area covered by cluster 3. The limited and highly variable rainfall recorded there specifies the natural agro-constraints (Fig. 2b). In addition they continue that existing water institutions are inappropriate as they rarely integrate relevant sectors in decision-making processes. This results in stress on human wellbeing and generates conflicts over the scarce water resources.

In contrast to the above 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. Irrigation systems in the KwaZulu-Natal province permanently provide water for agricultural production, so that water stress is limited to drought periods (Reid & Vogel, 2006). However degraded soils especially in grazing areas counterbalance the relatively favourable water situation. In addition while improving water and food supply, using the poor quality river water for domestic purposes causes serious health problems, since appropriate hygienic services are absent. Another example where heavily degraded croplands also limit human wellbeing, is the Makueni district in South Kenya (Ifejika Speranza et al., 2008). The constrained food production there also translates into poverty.

Comparing now clusters 4 and 5, the well preserved soils in cluster 5 do not generate significant improvements in human wellbeing. Central Kazakhstan may serve here as an example. Though winter fodder provision during the Soviet Union allowed to increase the average livestock size, Robinson et al. (2003) concluded that seasonal rotation of livestock was an important factor that prevented soil degradation in the predominant pastoral grazing systems during the 1980-90s in some central parts of Kazakhstan. Even though having been relatively preserved the overall marginality of the natural resources limited human wellbeing. This is an essential pathway included in the DLP (Safriel & Adeel 2008). Adding to the natural marginality the limited human wellbeing in this region also resulted from socio-economic disparities, legal barriers and social sector cutbacks since the collapse of the Soviet

Union (UNDP, 2002). These developments forced a considerable decrease in agricultural production and livelihood assets, e.g., as people sold parts of their livestock to raise cash income and with this drove rural out-migration. The shortage of both agricultural assets and working age people has impeded in turn the advancement of human wellbeing.

The remaining clusters 6 and 7 in industrialised regions are the least vulnerable areas (Fig. 2a) depicting lowest poverty indices (dark - light grey colours in Figs. 2b and 3). However the intensive agricultural production provokes the depletion of natural resources. Especially cluster 6 shows a high water stress in combination with medium degraded soils. The Negev region in Israel is an example where the advanced human wellbeing does not guarantee the sustainable use of natural resources: synergetic forces of climate and socio-economic drivers generate water stress and soil degradation which is not compensated for by the principally available knowledge and technologies (Portnov & 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, so that local tension over the scarce water resources increased. In comparison, cluster 7 shows the lowest water stress, but soil degradation reaches still medium levels. To illustrate this, widespread irrigation improved the water situation in Colorado and Kansas, but the fragile soils severely degraded under the highly mechanised monocultural cropping (Stewart, 2004). Later the soils somewhat recovered through conservation agriculture triggered by increasing oil prices in the 1970s. But not all farmers apply conservation measures, so that soils have not yet fully recovered.

The results of the cluster analysis are also verified for the relative vicinity of three vulnerability patterns in the neighbouring states of Sonora and Arizona along the Mexico-USA border (clusters 2 and 3 as well as 6, resp.). The different livelihood strategies and levels of human wellbeing differentiate the severity of vulnerability to droughts in these highly water-stressed regions (Vásquez-León et al., 2003; Vásquez-León & Liverman, 2004). In the municipality of Alamos (Sonora) widespread overgrazing and deforestation have led to severe soil degradation above all in the eastern parts (cluster 2). In contrast 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 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 well cope with droughts especially when coinciding with an uncertain landownership following privatisation and structural adjustment programs. The severe consequences including production failure and loss of livelihood assets link to the limited human wellbeing as identified by our analysis. On the other hand technology-centred approaches to improve water availability have stabilised agricultural production in the Sulphur Springs Valley (Arizona). However water withdrawal from groundwater aquifers exceeds natural recharge there so that water stress is widespread (cluster 6). Overall, the region has not fully aligned agricultural practices with available options for sustainable production.

Our analysis shows that natural agro-constraints and isolation as incorporated in this study do not distinguish straightforward between the vulnerability-creating mechanisms (Fig. 2b). This can be explained by the smaller variance in these variables compared to the remaining variables (see sect. 3.2). Thus a further differentiation would be useful: on the one hand the importance of natural agro-constraints for human wellbeing depends much on how far livelihoods rely on, e.g., agriculture and forest use. Thus refining the initial mechanism could involve an additional dimension for the dependence on natural resources. On the other hand the isolation dimension could be evaluated more in-depth by extending the indication to include for example an indicator for the distance to service or decision-making centers as used in the ARIA index in Australia (DH & 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 capability to assimilate shocks.

Figure 2a

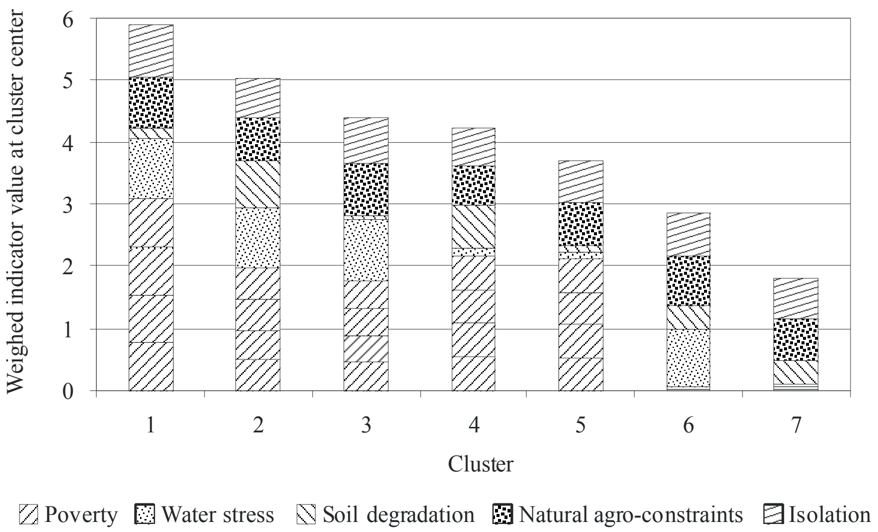

Figure 2b

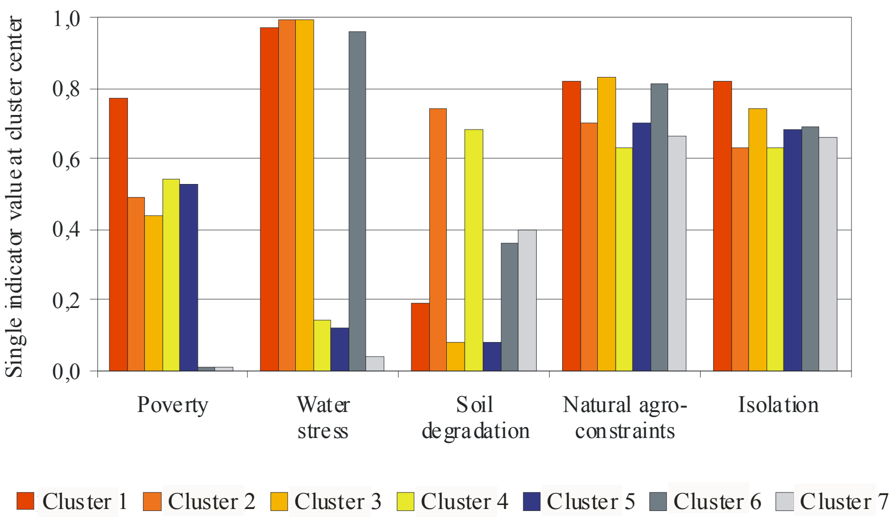

Figure 2. Typical patterns of dryland vulnerability given by the combinations of the five vulnerability indicators at the seven cluster centers. The indicator values range from 0-1, with 0=minimum and 1=maximum values. Maximum values represent dimensions which increase vulnerability. Thus the decreasing sum of cluster-specific indicator values determines the cluster order (Fig. 2a). Poverty is weighed four times (see sect. 3.2), so that the indicator is given accordingly. The cluster order links to the vulnerability gradient in Fig. 1 referring to specific vulnerability-creating mechanisms. To facilitate cross-cluster comparison, single indicator values at the cluster centers are given for each vulnerability dimension (Fig. 2b).

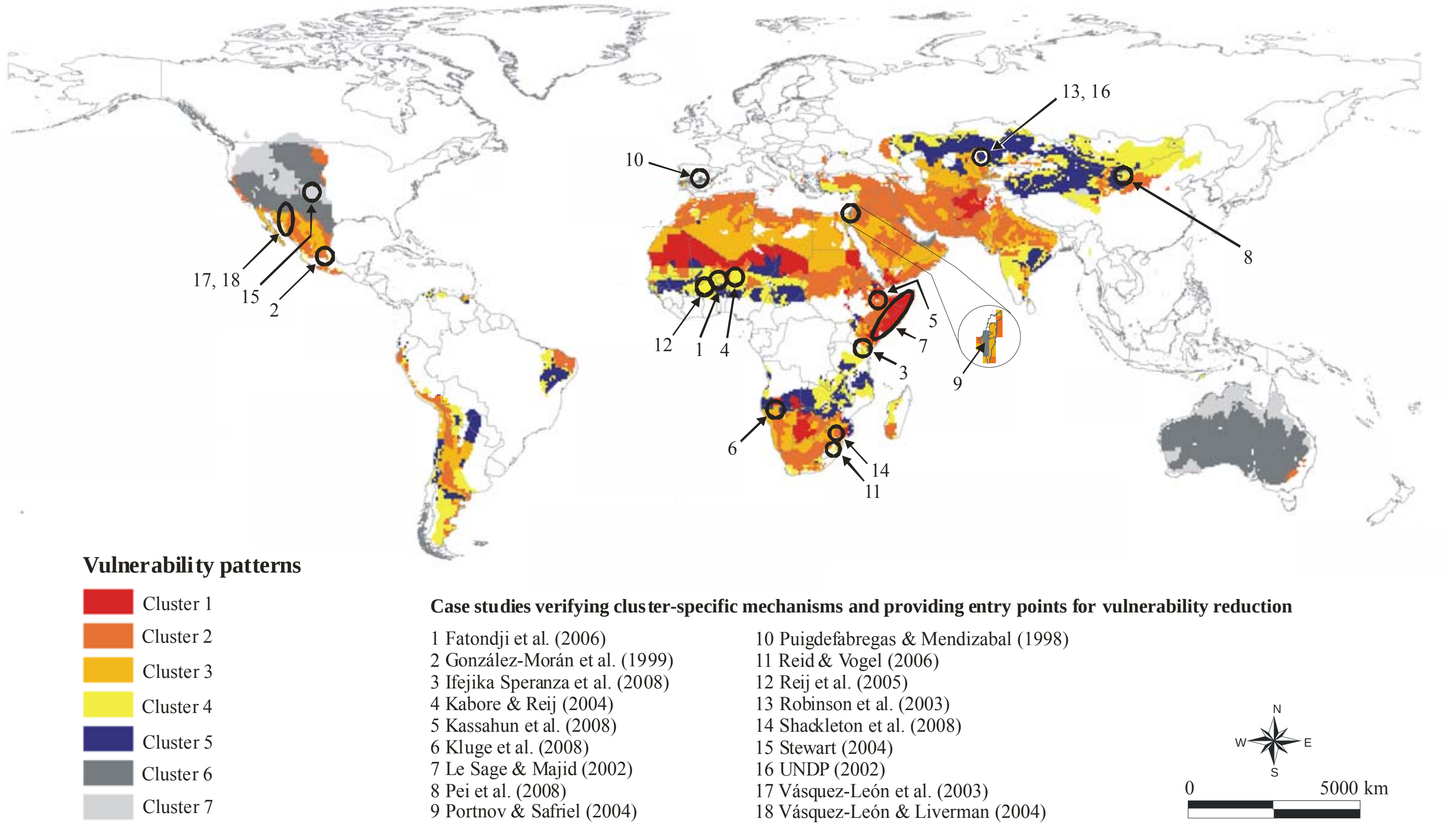

Figure 3. Spatial distribution of the typical vulnerability patterns across global drylands with case studies that verify cluster-specific mechanisms and provide entry points to reduce vulnerability.

4.2 Entry points to reduce dryland vulnerability

The typical vulnerability patterns suggest 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 clusters with exploiting livelihoods and restricted human wellbeing. Since agricultural production is important to secure human wellbeing, this aspect receives particular attention. Thereby the severity of vulnerability may guide the prioritisation of interventions at global level. Selected case studies demonstrate how cluster-specific approaches can be successfully translated into practice (for their location see Fig. 3).

From the indicator values at the cluster centers we deduce the entry points for vulnerability reduction (Tab. 2). 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 provide 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 the widespread isolation also suggests improvements throughout the clusters.

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

Table 2. Entry points for vulnerability reduction according to the indicator values at the cluster centers. (Symbols mean: ↑↑↑ = particular attention needed, ↑ = improvement needed, ● = stabilisation needed).

Starting with the most vulnerable regions, cluster 1 would require particular attention in almost all vulnerability dimensions (Tab. 2). As basic intervention, there are two options to better adjust livelihoods to the marginal water resources: decreasing the water withdrawal or increasing the 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 will be overcome, it would be essential to assess how the water situation can more pragmatically be improved by lowering the 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 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 water withdrawal.

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

To release pressure from the over-used 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 in the Northeast of South Africa the marketing of traditional brooms, furniture and locally produced beer provided additional sources of income for the poorest segments of communities (Shackleton et al., 2008). More elaborated safety nets, diversified livelihoods and increased food security improved the people´s wellbeing. A shift of water-intensive agricultural production to less water deficient areas may provide another strategy. Both options should however carefully be evaluated in the given socio-economic context of each region to avoid newly emerging, more pressing dependency on the markets.

A more advanced human wellbeing allows extending efforts to better adjust livelihoods by applying more labour 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 over-grazing is the shift from continuous grazing to the more demanding livestock rotation. Following this approach, soil degradation was reduced in North China (Pei et al., 2008). The before mentioned zai technique applied in Burkina Faso (Reij et al., 2005) also requires more labour input. As yields however rapidly increased, the higher labour input was accepted and the technique was widely adopted on degraded lands. In this vulnerability pattern it is essential to explore how the 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 type of intervention is expected to reduce vulnerability in these regions. Two examples are given that verify this hypothesis. First, the land rehabilitation approach applied in Burkina Faso was transferred to villages in Southwest Niger (Kabore & Reij, 2004, p.23) which also belong to cluster 4. Improving the technique, there again soils could be recovered, food supply increased and livelihoods improved. Later, the same approach also yielded improved soils and agricultural production in other locations of cluster 4 in Southwest Niger (Fatondji et al., 2006). Thus the cited approach helped in overcoming the most important soil constraints in these regions which appeared to be similar in the sense of our cluster analysis.

The case of Niger underlines the importance of the sub-national level 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 have to be further adjusted to particular local conditions. For example different social groups such as illiterate, women or 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 above outlines one way of dealing with the complex vulnerability-creating mechanisms in drylands. It is the first attempt to quantitatively analyse dryland vulnerability at sub-national resolution and with global coverage. The proposed cluster approach enabled us to deduce similarities among the diverse livelihood contexts. It results in typical vulnerability patterns that give distinct combinations of vulnerability-creating mechanisms and their respective policy implications. The results are verified 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 suggest thematic and spatial priorities for vulnerability reduction. Thereby the sub-national level of analysis allows recognising heterogeneity within countries to help focus respective 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 differential vulnerability reduction efforts and monitor changes in the related vulnerability causes data sources need to be developed that are sufficiently resolved in space and time.

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 preserved natural resources and in cluster 7 with 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, indicators should be updated based on the vulnerability-creating mechanisms when relevant sub-national data are globally available. Further the analysis would benefit from an even more rigorous verification. 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 – Cluster Analysis

The cluster analysis was performed using a sequence of each 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 & Walther 2005). We developed an algorithm 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 specific indicator combinations and (b) the ratio of the between-cluster variance and the inner-cluster variance (Calinski & Harabasz, 1974).

In our new approach, we assume that if a pre-given number of clusters fit the data structure, a stochastically initialised cluster algorithm will tend to generate more often a similar result than in the case of an inadequate number of clusters (Fig. 4). Therefore, we firstly generate two cluster allocations on the N dryland grid elements for a defined cluster number m. Secondly, the number of grid elements with identical cluster allocations in both cluster runs are counted. This number of overlap divided by the total number of grid cells leads to the consistency measure.

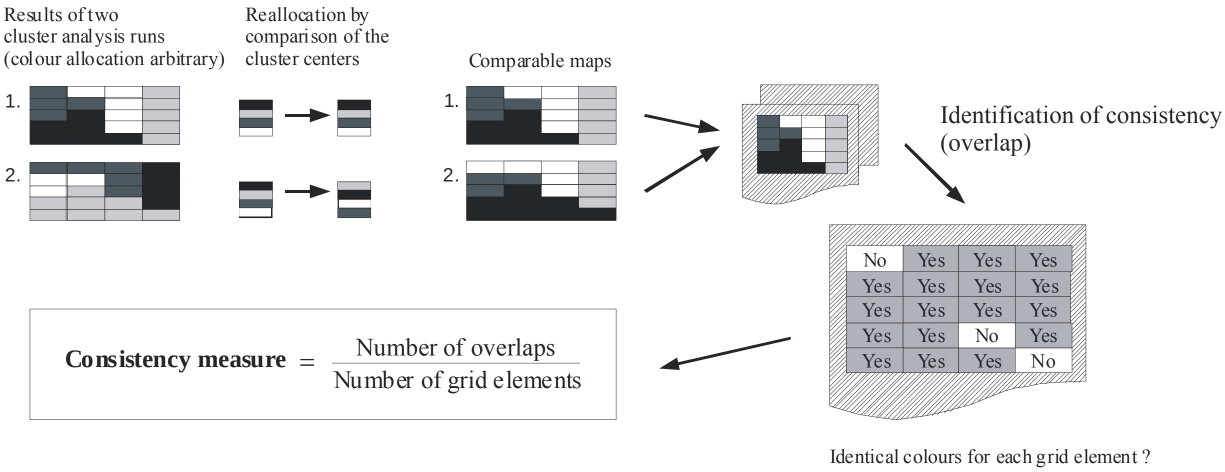

Figure 4. New approach developed to calculate the consistency of cluster reproductions. An example is given for two cluster analysis runs identifying four clusters.

This procedure was repeated 200 times for pre-given cluster numbers to identify the cluster number which maximises the consistency measure. Table 3 gives the consistency measure for cluster numbers 2-10. Thereby the stochastic element was realised by repeating the algorithm with varying initialisations produced by the hierarchical cluster algorithm. Here, cluster numbers 3, 5 and 7 show relative maxima for the consistency measure.

Cluster number	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Consistency measure	0.819 (0.01)*	0.987 (0.00)	0.893 (0.01)	0.908 (0.01)	0.861 (0.01)	0.874 (0.01)	0.848 (0.01)	0.847 (0.01)	0.848 (0.01)
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)

* Standard deviation given in brackets

Table 3. Consistency measure and ratio of the between-cluster variance and the inner-cluster variance for cluster numbers 2-10. The values represent averages for 50 repetitions of the cluster-specific measures based on 400 cluster allocations among all dryland grid elements. To show the reliability of our method we present the standard deviation describing the variability in the measures among the 50 average values resulting from the repetitions.

On the other hand, the variance ratio shows a stronger increase from cluster number two until seven while for larger cluster numbers the gain in the variance ratio becomes smaller (Tab. 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 number. 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 preserved natural resources which provides interesting insights for the discussion of vulnerability patterns.

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