Dryland vulnerability – Typical patterns and dynamics in support of vulnerability reduction efforts

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Abstract

The pronounced constraints on ecosystem functioning and human livelihoods in drylands are frequently exacerbated by natural and socio-economic stresses, including weather extremes and inequitable trade conditions. Therefore, a better understanding of the relation between these stresses and the socio-ecological systems is important for advancing dryland development. The concept of vulnerability as applied in this dissertation describes this relation as encompassing the exposure to climate, market and other stresses as well as the sensitivity of the systems to these stresses and their capacity to adapt. With regard to the interest in improving environmental and living conditions in drylands, this dissertation aims at a meaningful generalisation of heterogeneous vulnerability situations.

A pattern recognition approach based on clustering revealed typical vulnerability-creating mechanisms at global and local scales. One study presents the first analysis of dryland vulnerability with global coverage at a sub-national resolution. The cluster analysis resulted in seven typical patterns of vulnerability according to quantitative indication of poverty, water stress, soil degradation, natural agro-constraints and isolation. Independent case studies served to validate the identified patterns and to prove the transferability of vulnerability-reducing approaches. Due to their worldwide coverage, the global results allow the evaluation of a specific system's vulnerability in its wider context, even in poorly-documented areas. Moreover, climate vulnerability of smallholders was investigated with regard to their food security in the Peruvian Altiplano. Four typical groups of households were identified in this local dryland context using indicators for harvest failure risk, agricultural resources, education and non-agricultural income. An elaborate validation relying on independently acquired information demonstrated the clear correlation between weather-related damages and the identified clusters. It also showed that household-specific causes of vulnerability were consistent with the mechanisms implied by the corresponding patterns. The synthesis of the local study provides valuable insights into the tailoring of interventions that reflect the heterogeneity within the social group of smallholders.

The conditions necessary to identify typical vulnerability patterns were summarised in five methodological steps. They aim to motivate and to facilitate the application of the selected pattern recognition approach in future vulnerability analyses. The five steps outline the elicitation of relevant cause-effect hypotheses and the quantitative indication of mechanisms as well as an evaluation of robustness, a validation and a ranking of the identified patterns. The precise definition of the hypotheses is essential to appropriately quantify the basic processes as well as to consistently interpret, validate and rank the clusters. In particular, the five steps reflect scale-dependent opportunities, such as the outcome-oriented aspect of validation in the local study.

Furthermore, the clusters identified in Northeast Brazil were assessed in the light of important endogenous processes in the smallholder systems which dominate this region. In order to capture these processes, a qualitative dynamic model was developed using generalised rules of labour allocation, yield extraction, budget constitution and the dynamics of natural and technological resources. The model resulted in a cyclic trajectory encompassing four states with differing degree of criticality. The joint assessment revealed aggravating conditions in major parts of the study region due to the overuse of natural resources and the potential for impoverishment. The changes in vulnerability-creating mechanisms identified in Northeast Brazil are well-suited to informing local adjustments to large-scale intervention programmes, such as "Avança Brasil".

Overall, the categorisation of a limited number of typical patterns and dynamics presents an efficient approach to improving our understanding of dryland vulnerability. Appropriate decision-making for sustainable dryland development through vulnerability reduction can be significantly enhanced by pattern-specific entry points combined with insights into changing hotspots of vulnerability and the transferability of successful adaptation strategies.

Zusammenfassung

Die Grenzen ökologischer Funktionen und menschlicher Lebensweisen in Trockengebieten werden häufig durch natürlichen und sozio-ökonomischen Stress, wie extreme Wetterereignisse und ungerechte Handelsbedingungen, weiter verengt. Zur Förderung der Entwicklung in Trockengebieten ist es daher wichtig, die Beziehung zwischen den Stressfaktoren und den sozio-ökologischen Systemen besser zu verstehen. Das Konzept der Vulnerabilität, welches in der vorliegenden Dissertation angewandt wird, beschreibt dieses Verhältnis durch die Exposition, Sensitivität und Anpassungsfähigkeit von Systemen im Hinblick auf Klima-, Markt- und anderen Stress. Bezüglich des Interesses, die Umwelt- und Lebensbedingungen in Trockengebieten zu verbessern, zielt diese Dissertation darauf ab, die vielschichtigen Ursachen und Veränderungen von Vulnerabilität sinnvoll zu verallgemeinern.

Eine clusterbasierte Mustererkennung zeigte typische Mechanismen auf, welche Vulnerabilität auf globaler und lokaler Ebene verursachen. Dabei stellt die globale Studie die erste flächendeckende Untersuchung von Vulnerabilität in Trockengebieten mit sub-nationaler Auflösung dar. Die Clusteranalyse identifizierte sieben typische Muster basierend auf der quantitativen Beschreibung von Armut, Wasserknappheit, Bodendegradation, natürlichen Produktionshemmnissen und Isolation. Die Gültigkeit der ermittelten Cluster und die Übertragbarkeit von Anpassungsmaßnahmen innerhalb ähnlicher Gebiete wurden anhand unabhängiger Fallstudien belegt. Die flächendeckende Erfassung erlaubt es, die Vulnerabilität eines Systems in seinem größeren Kontext zu bewerten, auch in weniger gut durch Fallstudien dokumentierten Gebieten. Weiterhin wurde die Klimavulnerabilität von Kleinbauern bezüglich ihrer Nahrungsmittelsicherung im peruanischen Altiplano untersucht. In diesem lokalen Kontext wurden vier Cluster von Haushalten gemäß ihrer Produktionsrisiken, landwirtschaftlichen Ressourcen, der Bildung und ihres nicht-landwirtschaftlichen Einkommens unterschieden. Eine erweiterte Gültigkeitsprüfung unter Nutzung unabhängig erhobener Informationen stellte heraus, dass wetterbedingte Schäden mit den ermittelten Clustern korrelieren und dass haushaltsspezifische Schadensursachen mit den durch die Muster angezeigten Mechanismen übereinstimmen. Die lokale Studie liefert wertvolle Hinweise auf bedarfsgerechte Eingriffe unter Beachtung der Heterogenität innerhalb der sozialen Gruppe der Kleinbauern.

Die notwendigen Bedingungen zur Erkennung typischer Muster ergaben fünf methodische Schritte. Ihre Darlegung soll die Anwendung der gewählten Methode in zukünftigen Vulnerabilitätsstudien anregen und erleichtern. Die fünf Schritte umfassen die Ableitung relevanter Ursache-Wirkungs-Hypothesen, die Quantifizierung der Mechanismen, die Bewertung von Robustheit und Gültigkeit sowie die Ordnung der ermittelten Muster nach dem Grad der Vulnerabilität. Dabei ist die genaue Beschreibung der Hypothesen eine wesentliche Voraussetzung für die Quantifizierung der grundlegenden Prozesse sowie eine einheitliche Interpretation, Gültigkeitsprüfung und Ordnung der ermittelten Muster. Besondere Beachtung finden skalenbedingte Aspekte, wie beispielsweise die ergebnisorientierte Gültigkeitsprüfung in der lokalen Studie.

Weiterhin wurden die in Nordostbrasilien ermittelten Cluster im Hinblick auf wichtige endogene Prozesse in den dort vorherrschenden kleinbäuerlichen Nutzungssystemen untersucht. Diese Prozesse umfassen die Aufteilung der Arbeitskraft, die landwirtschaftliche Produktion sowie Einkommens- und Ressourcendynamiken. Sie wurden in einem qualitativen dynamischen Modell erfasst, welches eine zyklische Trajektorie mit vier unterschiedlich problematischen Entwicklungszuständen ergab. Als besonders problematischer Aspekt verschärfte sich die Vulnerabilität in weiten Teilen des Untersuchungsgebietes durch die Übernutzung natürlicher Ressourcen und die Möglichkeit weiterer Verarmung. Die in Nordostbrasilien gezeigten Veränderungen sind dazu geeignet, groß angelegte Entwicklungsprogramme, wie zum Beispiel “Avança Brasil”, angemessen an lokale Gegebenheiten anzupassen.

Insgesamt ermöglicht es die Kategorisierung einer begrenzten Anzahl typischer Muster und Veränderungen, die Vulnerabilität in Trockengebieten besser zu verstehen. Eine nachhaltige Entwicklung von Trockengebieten basierend auf der Minderung von Vulnerabilität kann durch musterspezifische Ansätze zusammen mit Hinweisen zu Veränderungen im Schweregrad und zur Übertragbarkeit erfolgreicher Anpassungsstrategien wirkungsvoll unterstützt werden.

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1 General introduction

1.1 Motivation

Drylands display a close human-nature interdependence based on their particularly marginal natural resources. Water scarcity and related constraints on primary production and nutrient flows are typical characteristics of dryland regions (Safriel et al. 2005). According to their decreasing level of aridity, drylands can be classified into four sub-types comprising hyper-arid, arid, semi-arid and dry subhumid regions (Middleton & Thomas 1997). Altogether, they cover 41% of the Earth's surface and are inhabited by 36% of the world population including an estimated one billion poor people in rural areas (Dobie 2001, Safriel et al. 2005).

In the past, people have developed sophisticated livelihood systems, such as those based on locally adapted crop and livestock rotation, drought-tolerant crop species as well as irrigation practices, in order to adapt to the inherently low land productivity and insecure water availability (Peterson et al. 2006). Furthermore, architecture and urban structures have been designed in order to regulate microclimate (Portnov & Hare 1999). However, stress factors, including climate variability and change, inequitable trade conditions and social exclusion, increasingly threaten the socio-ecological systems. In particular, they undermine traditional strategies for coping with the environmental and socio-economic insecurity inducing critical processes, such as soil and water degradation, food insecurity, forced migration and violent conflicts (e.g. Bantilan et al. 2006, Lee & Schaaf 2006).

The prevalent critical conditions are evidence that the potential for agricultural and societal development historically inherent in drylands (Diamond 1999) has largely been overstrained for a long time. The threats to ecosystem functioning and human well-being in drylands receive particular attention at the global level. The Fourth Global Environmental Outlook (GEO-4) identified drylands as one major context in which the interplay between environmental conditions and human development provokes specific problematic mechanisms (UNEP 2007). Other typical mechanisms are described in the GEO-4 assessment in the contexts of global markets, urbanisation and contamination, for example.

The basically local problem situations in drylands gain global relevance above all due to their widespread occurrence in a cumulative way. In addition, global drivers enforce broad-scale processes that manifest themselves at local scales. They affect socio-ecological systems in drylands to some extent triggering nested phenomena there. However, systemic linkages yielding feedbacks between great distances (Young et al. 2006) as illustrated in the case of coffee producers who are teleconnected via commodity chains (Adger et al. 2009, Eakin et al. 2009) play a minor role in drylands compared to the criticality of locally driven processes.

In view of the widespread prevalence of problematic conditions, the United Nations Convention to Combat Desertification underlines the development of environmental and living conditions in dryland regions as an area in need of advancement (UNCCD 2007). One important task in addressing this need is the design of interventions to minimise adverse outcomes of stress. This is a challenging task given that the processes that create problematic situations evolve in various ways depending on the local context. For example, heavily degraded soils constrain food security for farmers who strongly depend on agricultural production in some parts of Kenya (Ifejika Speranza et al. 2008). In another dryland region in Namibia, dysfunctional institutions fail to distribute the scarce water resources efficiently within similarly agriculture-reliant livelihood systems (Kluge et al. 2008). There, overuse of water impinges upon human well-being and generates conflicts over the scarce water. To further broaden the picture, growing population and lifestyle changes in parts of Israel have increased water consumption, thereby pressurising the limited water resources to the point of severe water scarcity (Portnov & Safriel 2004). Each of these case studies emphasises important mechanisms in a particular context. These mechanisms influence both the effects that environmental and socio-economic stresses have on dryland systems and also their capacity to deal with these effects. For example, a drought may significantly decrease agricultural production in farming communities that live on scarce water resources, particularly when lacking water reserves for irrigation purposes. Taken together, such case studies illustrate the heterogeneity of critical situations across drylands. However, the question as to whether there are characteristic processes with regard to the effects of stresses that recur within the diverse dryland mechanisms has yet to be systematically assessed at a global scale. Knowledge about such recurrent processes can provide valuable insights in order to enhance our understanding of dryland development and related decision-making.

In addressing this open field of research, this dissertation is devoted to categorising dryland systems according to typical patterns in their mechanisms that explain the outcomes of stresses. Vulnerability is employed as a concept to link the socio-ecological systems and stress factors that impact upon them. This concept is suitable for capturing the multi-dimensional character of the relationship between the systems and stresses, including specific stress factors and a system's response to them. The heterogeneous mechanisms that generate vulnerability in drylands are categorised using a cluster-based approach to reveal similarities between them. This categorisation allows the essence of dryland vulnerability to be grasped beyond individual cases, while at the same time representing the spatial and functional heterogeneity at an aggregate level. Thus, it provides an important entry point for reducing vulnerability since related decisions are usually taken at a higher than individual or local level.

In detail, identifying similarities enables the evaluation of key constraints and opportunities for dryland development. Such findings are valuable in prioritising interventions for vulnerability reduction given that funds available to advance dryland development are limited. Moreover, similarities provide useful insights for a potential transfer of successful adaptation strategies since their analysis is linked to the hypothesis that regions with similar properties require comparable strategies to reduce vulnerability. By deriving targeted intervention options, this dissertation essentially endeavours to support effective approaches towards sustainable dryland development.

The remainder of this chapter describes the research context of this dissertation. In the next section, important conceptualisations of vulnerability used in various research domains are thoroughly reviewed and the vulnerability concept used in this dissertation explained. The following section provides a detailed discussion of pattern approaches which have played an important role in the analysis of developmental dynamics and vulnerability. On the basis of this discussion, the pattern recognition approach employed in this dissertation is outlined. The specific research questions are then defined against this background and are detailed together with the dissertation's structure. The final section describes my contribution to the peer-reviewed publications that are included in this dissertation.

1.2 Conceptualisation of vulnerability

Typical mechanisms that shape the relation between socio-ecological systems in drylands and recurrent stresses, including exogenous and endogenous factors, are summed up as the so-called "Dryland Archetype of Vulnerability" (Jäger et al. 2007). An archetype of vulnerability as defined in the GEO-4 assessment combines recurrent processes that endanger the environmental and living conditions in a particular context. According to the Oxford Dictionary of English Etymology, the notion of being vulnerable refers to the potential to be wounded and openness to attack (Hoad 1996). In modern language, it indicates susceptibility to harm as a state of being likely to be adversely affected by a particular stimulus (Oxford Pocket Dictionary of Current English 2009).

More specifically, the GEO-4 assessment framed the concept of vulnerability as encompassing the effects of natural and anthropogenic stimuli impacting upon ecosystem functioning and human well-being (Jäger et al. 2007: 304). It includes the ability of ecosystems and people to adapt to these effects. This definition links in with recent approaches to conceptualising vulnerability to global change. However, the sciences do not completely agree on the meaning of vulnerability since different research traditions have developed particular perspectives on the related processes (e.g. Kasperson et al. 2005, Adger 2006, Birkmann 2006, Füssel & Klein 2006, Smit & Wandel 2006, O'Brien et al. 2007, Patt et al. 2008). Some of them focus mainly on either social or natural systems, while more integrative approaches analyse the vulnerability of coupled socio-ecological systems.

The theory of entitlements (Sen 1981 and 1990) as developed within the field of development economics has provided an important basis for investigating vulnerability as a socially-constructed phenomenon. The entitlement approach has been applied to explain food insecurity and famine as a function of socio-political, economic and institutional conditions and includes class, caste, empowerment and gender aspects. These conditions determine the capacity of people to cope with climate variability, economic stress and conflicts, among other factors (e.g. Bohle et al. 1994, Adger & Kelly 1999, Vogel & Smith 2002, Misselhorn 2005, Devereux 2007). A lack of entitlements may mean that food insecurity or famine are triggered only through a minor environmental stimulus or even an absence of a general food shortage. Overall, this research domain investigates vulnerability causes that generally lie beyond the sphere of influence of the people affected.

A succeeding research perspective seeks to understand how people organise their lives and which factors constrain or enhance livelihood opportunities in a dynamic and historical context. The livelihood approach (Chambers & Conway 1992, Scoones 1998) broadens the restrictive perspective on entitlements by assessing the ability of people to sustain their livelihoods when stressed (e.g. Eakin 2005, Eriksen et al. 2005, Barnett & Adger 2007). While emphasising the importance of understanding policies and institutions, this approach pays less rigorous attention to the inequalities in power relations.

Another approach examines vulnerability at the household level in terms of specific welfare damage in order to extend the analysis of poverty (e.g. Pritchett et al. 2000, Chaudhuri 2003, Calvo & Dercon 2007). Here, the likelihood of becoming or remaining poor considering stress in the future determines a household's vulnerability to poverty. This approach has the advantage of conceptually distinguishing vulnerability from poverty. However, the shortcomings of the headcount-based poverty measure lie in its being a mere count of the poor and uncertainties in defining an adequate poverty threshold. In addition, the poverty measure is ill-suited to representing risk preferences of poor households suitably. Overall, the perspectives on entitlements, livelihoods and welfare mainly reveal the importance of socio-economic differences in shaping vulnerability, while natural determinants play only a minor role in explaining the consequences of stress.

In contrast, the natural hazards approach to vulnerability directs attention towards environmental risk factors. Traditional natural hazard research determines the type and probability of natural stresses, thresholds of risk, the potential of exposed people to experience damage and possible adjustments (e.g. Burton et al. 1993, Cutter 1996, Brooks 2003). This approach to understanding vulnerability has provided valuable insights into human behaviour and has extended the considerations of human choice in disaster risk management. It has however been dominated by a focus on the interactions of technological factors and institutional conditions with natural events. In response to this specific view, political ecology and political economy approaches offer complementary insights into important political, socio-economic and cultural causes of vulnerability (e.g. Blaikie et al. 1994, Bohle et al. 1994, Adger et al. 2001, Bohle 2001, Wisner et al. 2004). They pay more attention to internal and actor-based aspects relating to inequalities of power or conflicts within societies than traditional natural hazard assessments. Thus, they go beyond external and structural determinants.

Due to the specific research traditions in the social and natural sciences in which the various approaches to vulnerability have evolved, conceptualisations differ in terms of the complexity of the components considered. While vulnerability to food insecurity and poverty refers to the effects of multiple stress factors on human well-being as a single variable, a single natural hazard is considered in relation to several adverse consequences in the natural hazards domain (Patt et al. 2005a).

The essence of these diverse perspectives has been integrated into conceptualisations of the vulnerability of socio-ecological systems to environmental and socio-economic stresses (e.g. Turner et al. 2003a, Kasperson et al. 2005, Young et al. 2006, Füssel 2007, IPCC 2007). In particular, the focus on vulnerability to climate change (IPCC 2007) provides a comprehensive framework with which to assess the causes and consequences of vulnerability. Climate, as an intrinsically global phenomenon, is shaped by a range of natural conditions, human activities and actors. At the same time, it generates multiple stress factors impacting upon socio-ecological systems. Therefore, climate research is inherently linked to the analysis of multi-dimensional processes and their dynamics on various spatial and temporal scales.

The Intergovernmental Panel on Climate Change (IPCC) employs a concept of vulnerability that characterises the effects of climate stresses for coupled socio-ecological systems in a transdisciplinary way (IPCC 2007). The IPCC concept defines vulnerability as the susceptibility of a system to be harmed by climate variability and change including its exposure, sensitivity and ability to cope with or adapt to adverse affects.

Recent assessments apply the IPCC concept to analyse vulnerability in a range of scales, contexts and outcomes. The Advanced Terrestrial Ecosystem Analysis and Modelling assessment (ATEAM) is an example of an integrated approach which was used to investigate vulnerability in Europe (Schröter et al. 2005a, Metzger & Schröter 2006). It integrated state-of-the-art ecosystem modelling with an evaluation of human adaptive capacity. The potential impacts of multiple global change drivers on ecosystem services were modelled including the effects of changes in climate, nitrogen deposition and land use. Here, a loss in ecosystem services is considered a measure of damage. ATEAM analysed the capacity of various economic sectors to adapt to changes in ecosystem services, though without explicitly incorporating feedbacks from social systems to the ecosystems. Relying on active consultations with policy makers and the private sector, the assessment involved a stakeholder-guided selection of indicators and discussion of measurements and thresholds (De La Vega-Leinert et al. 2008). It served both to enhance the analysis of relevant processes and to produce results that are relevant and useful in improving the management of natural resources. Reflecting the need to compare the results at various levels, the potential impacts and adaptive capacity of the investigated sectors were finally combined into a mapping tool (Metzger et al. 2004). This mapping tool provides a flexible application through which individual users may compare the vulnerability or components of interest to them over time for regions and sectors at a very high spatial resolution.

Further applications of the concept formulated by the IPCC have operationalised vulnerability in many different ways depending on its interpretation in a given context, particular research objectives or perceptions of stakeholders and affected people (e.g. Yohe & Tol 2002, O'Brien et al. 2004, Brooks et al. 2005, Luers 2005). While stimulating debate, such diverse approaches create confusion in terminology and complicate the comparison between different studies. The intense debate about the meaning, definition and operationalisation of vulnerability has motivated the linguistic analysis and formalisation of vulnerability (Hinkel 2008, Ionescu 2009, Ionescu et al. 2009). In particular, the use of mathematical concepts to formalise vulnerability allows the integration of information from the diverse knowledge domains concerned with the investigation of harm and can be applied to a wide range of systems (Ionescu 2009, Ionescu et al. 2009). It has the potential to provide results that are useful for informing decision-making processes when meeting three requirements. These include a definition of the system, the stress factors under concern and criteria with which to compare the outcomes of stress (Ionescu et al. 2009). In placing emphasis on the comparability of outcomes, this approach seeks to make the IPCC concept more operational, though in a very formal sense. Overall, a formal framework can contribute to clarifying communication among scientists as well as between scientists and policy makers.

The diversity of vulnerability assessments and related methodological integrations has inspired comprehensive guidelines in order to adequately capture the complexity in vulnerability of socio-ecological systems to global change stresses (Schröter et al. 2005b). Furthermore, a structuring framework has been designed to enable generalisations through systematic comparison of independent vulnerability assessments (Polsky et al. 2007). Besides the challenges relating to the conceptualisation of vulnerability and implementation of frameworks, statements about vulnerability include uncertainties resulting from our incomplete knowledge as well as methodological and data constraints. Projections of the evolution of natural systems or human decision-making may raise expectations among potential users that cannot be fulfilled. Therefore, transparent approaches that clearly communicate the uncertainties are vital in understanding and reducing vulnerability.

The IPCC concept provides a useful approach to analysing vulnerability in this dissertation due to its system-oriented and multi-dimensional formulation, encompassing both exogenous and endogenous processes. This dissertation applies the IPCC concept to complex socio-ecological systems in drylands. It directs its attention towards the interactions between global environmental and socio-economic stresses and local socio-ecological systems. For the purpose of this dissertation, vulnerability is defined as a system's potential to experience harm when exposed to stress. Exposure describes the type and degree of stresses that impact on the system. Among the stresses, climate and market forces receive special emphasis since they may severely impinge upon ecosystem functioning and human well-being. Exposure units include coupled socio-ecological systems at the level of administrative and other spatial units as well as at the household level. The degree to which a system will be affected by the stress is referred to as its sensitivity. For example, a drought may reduce crop yield severely when a high share of drought-intolerant crops have been cultivated. Sensitivity relates to a specific exposure, so that systems may be sensitive to a particular stress factor, but not to others. Vulnerability furthermore depends on the ability of a system to evolve in such a way as to minimise damage caused by stress. This ability indicates a system's adaptive capacity, including short- and long-term adjustments. For example, farmers may engage in water harvesting in order to better deal with drought. Improvements in water availability imply that crops will suffer less from shortages in the natural supply, thus lowering the sensitivity of the agricultural system to drought. However, harvesting water requires labour and knowledge, among other factors, which are linked to the farmer's capacity to adapt. This example demonstrates that a system's sensitivity and adaptive capacity are closely interwoven. Thus, these vulnerability components are addressed jointly in this dissertation. Finally, the residual damages of stress exposure mediated by a system's sensitivity and adaptive capacity depict the vulnerability outcomes.

This dissertation directs its attention towards endogenous processes shaping vulnerability at global and regional levels. The study of dryland systems on the global scale investigates generic vulnerability-creating mechanisms based on quantitative indication of natural and socio-economic properties. These properties determine the systems' sensitivity and adaptive capacity to a set of environmental and anthropogenic forces, including drought and inequitable trade conditions (Chap. 2). At the regional level, the assessment in Northeast Brazil relates to specific endogenous dynamics in smallholder systems (Chap. 4). It discusses how exposure to climate or economic stress factors, exemplified by drought and a drop in producer output prices, act upon endogenous development in smallholder systems. The evolution of smallholder systems is further used to assess endogenously driven changes in their vulnerability to recurrent climate, market and other stresses (Sect. 5.2). Refining the focus, the local analysis in the Peruvian Altiplano (Chap. 3) specifically addresses the vulnerability of marginalised smallholder systems to weather extremes. It determines the climate exposure in a specific agricultural campaign. The outcomes of this stress exposure are shaped through the sensitivity of the agricultural systems to weather extremes and the smallholders' capacity to manage the consequences. The outcomes are evaluated with regard to the smallholders' food security. With regard to the aim of revealing typical patterns in the mechanisms that generate vulnerability to particular stresses, the next section outlines the pattern recognition approach employed in this dissertation.

1.3 Pattern analysis

Specific processes that shape vulnerability locally derive from complex causal networks with diverse background conditions and dynamics. However, distinct processes recur within the multitude of problematic situations in drylands and elsewhere. Their recurrence has inspired extensive research on patterns of developmental processes and vulnerability. The discussion of pattern analyses in the following section provides the background for the pattern recognition approach employed in this dissertation.

A precursor of pattern analysis, the syndrome approach to global change, provides an overview of recurrent non-sustainable human-nature interactions across the world (WBGU

1996, Schellnhuber et al. 2002, Lüdeke et al. 2004). It decomposes global change dynamics into co-evolutionary trends that appear repeatedly in typical combinations. Thereby, syndromes reduce the multitude of interactive problematic processes described in case studies to a small number of cause-effect patterns. This is done without striving for a disciplinary first principle explanation of yield or profit maximisation, for example. Overall, syndrome analysis aims at improving our understanding of non-sustainable dynamics of global change, including the overuse of natural resources, urbanisation, rapid economic growth, industrial contamination and waste disposal.

Syndrome research integrates qualitative and quantitative system analysis to measure the disposition of a region towards a specific syndrome and the intensity of a syndrome in a given region (Schellnhuber et al. 1997, Lüdeke et al. 1999, Petschel-Held et al. 1999, Kropp et al. 2001). While the intensity indicates the presence and severity of a syndrome, the concept of disposition refers to the proneness towards a syndrome and is thus closely related to the idea of vulnerability. The ensemble of conditions which favour interactions in the syndrome-specific mechanisms determines the disposition of a region towards a syndrome. These conditions encompass environmental and socio-economic characteristics, such as climate, soil properties, political systems, traditions and culture. In addition to the disposition and intensity, potential drivers are identified which could initiate or further enforce the problematic mechanisms. Thus, like in the vulnerability conceptualisation used in this dissertation, syndrome research considers exposure factors. However, it remains to be investigated in a spatially explicit way as to which specific factors or combinations of them initiate or reinforce a syndrome in a given region. For example, the basic mechanism of the Sahel Syndrome is constituted of the downward spiral of impoverishment, overuse of resources, declining yield and further impoverishment related to smallholder systems in dryland regions of developing countries (Petschel-Held et al. 1999). This mechanism can be triggered or enforced through exposure to weather extremes or inequitable trade conditions.

Typically, a network of core trends and their relations, called an influence diagram, is used to describe the main dynamics of a syndrome. Such an influence diagram serves as input to compute the evolution of trend variables, that is to say the development of a socio-ecological system, using qualitative differential equations (Kuipers 1994). Qualitative modelling allows the formal representation of qualitative knowledge about relevant processes and feedbacks described by case studies in different regions (Petschel-Held & Lüdeke 2001). In particular, it enables the consideration of non-monotonous relationships between variables and is less demanding than parameterising a full numerical model. The modelled qualitative trajectories may involve unsustainable as well as desirable development paths, such as the recovery of soils resulting from a low intensity of agricultural land use (Petschel-Held et al. 1999). In a strict sense, such pathways leading to sustainability render the pathogenetic term "syndrome" as inappropriate in representing the full internal dynamic.

Though capturing important interactions between the biophysical and social spheres, qualitative dynamic models with a larger number of variables often result in qualitative trajectories that hardly achieve the aspired reduction of complexity and hence an appropriate generalisation of underlying processes. This is due to many ambiguities and bifurcations in the qualitative trajectories. Therefore, simplified model assumptions on human decision-making and social relations have to be applied. This significantly constrains the representation of the adaptive capacity of different actors. In contrast, the cluster-based categorisation of dryland conditions applied in this dissertation can accommodate a high-dimensional data space.

Nevertheless, the deduction of endogenous pathways from even simplified qualitative models facilitates reasoning about basic mechanisms and possible future development. In particular, it provides a suitable basis for evaluating intervention options to foster sustainability.

Interdisciplinary syndrome analysis has provided a systematic approach to operationalising vulnerability in a range of contexts, taking into consideration multiple stressors and related outcomes. The archetype approach to vulnerability as applied in the GEO-4 assessment (Jäger et al. 2007) is one major step in further developing pattern analysis. Like the syndromes, the archetypes of vulnerability abstract recurrent conditions from a multitude of observations to highlight typical vulnerability-creating mechanisms. This global assessment shows that ten years of further research on human development and vulnerability have confirmed essential mechanisms described by the syndromes of global change. The Dryland Archetype (Jäger et al. 2007), which is important for this dissertation, includes the poverty-degradation spiral, the typical mechanism of the Sahel Syndrome (Petschel-Held et al. 1999). Overall, archetype analysis explicitly considers opportunities which the environment offers to improve human well-being. Thus, it accounts more specifically for sustainable mechanisms than the syndrome definitions. In line with archetype analysis, the original syndrome approach has been further modified to explore core problems of sustainable development with a particular emphasis on potential adaptation to stresses, such as weather extremes, economic growth or conflicts (Hurni et al. 2004, Manuel-Navarrete et al. 2007). Moreover, it has served to improve conceptually the assessment of interrelations between vulnerability on local scales and processes operating on larger scales in the sense of nested mechanisms (Downing & Lüdeke 2002).

Pattern-oriented thinking and systematic case study analysis have been further applied in meta-analytical approaches. These have been used to characterise important processes that shape vulnerability in drylands and elsewhere, including desertification, deforestation, agricultural intensification and food insecurity (Rudel & Roper 1997, Geist & Lambin 2002 and 2004, Keys & McConnell 2005, Misselhorn 2005). These meta-analyses synthesise distinct patterns in the relative importance of causal factors based on frequency distributions and cross tabulation. These archetypical patterns improve the basic understanding of processes and feedbacks that result in similar outcomes, but manifest themselves in different ways at a local to regional level. The typical combinations of causal factors, such as agricultural activities, increasing aridity and infrastructure extension, help to frame the drivers of the investigated problems as multi-dimensional and interactive processes. Thus, they go beyond simple linear cause-effect relations. Overall, these analyses are based on case studies that represent only selected areas of the region under investigation. Therefore, they do not provide any reliable information about areas for which case study knowledge is absent. In addition, the severity of underlying causes can be compared neither between different causes or combinations of them nor between regions since they are not quantified. The investigation of dryland vulnerability in this dissertation relies on quantitative indicators. In addition, the analysis in Chapter 2 provides vulnerability patterns which cover the entirety of the investigated global drylands.

Taken together, the pattern approaches discussed above work on an intermediate functional scale. They identify patterns that are less general than a major, all-embracing theory, but apply to more than one individual case (Schellnhuber et al. 2002). Taking up the perspective of an intermediate functional scale, this dissertation aims at differentiating the global Dryland Archetype (Jäger et al. 2007) by investigating whether typical patterns of vulnerability to environmental and socio-economic stresses exist within drylands. The Dryland Archetype provides an overview of systemic vulnerability-creating mechanisms that distinguish drylands from other environmental and livelihood contexts. The global archetype focuses inevitably on aggregate assumptions about underlying processes, including the generally limiting effects of scarce water resources on agricultural productivity and thus human well-being in drylands. This aggregation is useful to understand functional similarities and differences from a broad-scale perspective at a global level. Nevertheless, it faces the challenge of adequately depicting the heterogeneity of problematic situations and feedbacks in underlying processes.

In the first part of this dissertation, typical patterns of dryland vulnerability are identified based on quantitative indication. For this, a cluster approach serves as an analytical tool to identify comprehensible categories and use them to specify typical mechanisms that explain vulnerability to climate, market and other stresses in dryland systems. Generally, a cluster analysis categorises cases according to the similarities of their attributes. Clustering provides a suitable basis since this dissertation aims at assessing typical vulnerability-creating mechanisms in drylands, rather than investigating statistically the frequency of distinct mechanisms.

Clustering is suited to identify structures in multi-dimensional data spaces spanned by various types of indicators as relevant for vulnerability in drylands and elsewhere. The focus on recurring indicator combinations characterises clustering as a nomothetic approach based on Windelband (1894/1998). In this dissertation, it supports the understanding of the causal structure of vulnerability to particular stresses to which individual cases submit as opposed to an unachievable description of every unique case. Clustering is well suited to the task of revealing the potentially non-linear characteristics of vulnerability-creating mechanisms. It can be applied in a range of contexts at any resolution, such as presented in the investigations of global drylands and smallholder households in the Peruvian Altiplano included in this dissertation. In view of the ongoing debate about vulnerability conceptualisations outlined above, clustering provides an opportunity for future applications to the different frameworks employed.

Clusters, or more specifically their centres, represent “general prototypes”. Such prototypes serve, for example in field guides, for the identification of plants to illustrate typical characteristics of plant species. Here, leaves, flowers and other parts of the plant are shown in a stylised way to highlight structural and functional particularities for a given species. Applied to this dissertation, this means that the prototypes, that is to say the cluster centres, depict typical indicator combinations characterising vulnerability. These indicator combinations serve to deduce general statements about all cases that belong to a given cluster and are therefore represented by its cluster centre. Like the plant illustrations, the clusters represent simplified, real world cases. These simplifications are a construct that may not necessarily exist in the identified form in reality. Nevertheless, the cluster-based categorisation of dryland vulnerability facilitates the recognition and understanding of typical underlying mechanisms. This dissertation uses the selected cluster approach in order to assess typical vulnerability-creating mechanisms with regard to specific research questions as outlined in the following section.

1.4 Research questions

Relying on a cluster-based categorisation of vulnerability-creating mechanisms, this dissertation aims at improving our understanding of the causal structure of vulnerability to environmental and socio-economic stresses in dryland systems. The findings serve to reveal opportunities to reduce vulnerability through preparing for potential stress and alleviating related damage. However, in order to better understand vulnerability and to support decision-making for vulnerability reduction appropriately, the typical vulnerability patterns to be identified need to provide relevant and valid insights.

Faced with a rich information base, the first question arises as to how to extract the relevant knowledge. The elicitation of vulnerability-creating processes is challenging since case studies often use differing terminologies and measurements to describe particular facets of vulnerability. Another essential question which then follows is how the elicited processes can be quantified. Ideally, data would be selected that cover all important processes well. But existing data may not correspond well to the required spatial and temporal resolution. While these two questions may concern any type of vulnerability assessment, there are further aspects which relate particularly to the pattern recognition approach. These concern the questions as to whether the identified patterns are methodologically robust and whether they bear comparison with observed vulnerability outcomes and underlying mechanisms. Finally, the ranking of the identified patterns is an important aspect which may inform the setting of priorities for vulnerability reduction. All these aspects are tackled cumulatively in the first research question formulated as follows:

Research question 1:
How do we identify typical patterns in the natural and socio-economic properties of dryland systems in order to enhance our understanding of their vulnerability to climate, market and other stresses?

The first research question scrutinises the selected cluster approach with a clear focus on an applicable methodology and practicable insights. As a fundamental first step, important vulnerability dimensions in drylands and their interrelations need to be established since clustering is a "neutral" method, thereby applicable to any type of data sets. A clear definition of the clustered data space is therefore required in order to firstly quantify the relevant processes and subsequently arrive at a consistent interpretation, validation and ranking of the identified clusters. Since the scale of analysis partially influences the overall procedure of pattern recognition, the selected approach is applied at two scales to address the first research question in detail: (a) an analysis of drylands with global coverage at sub-national resolution (Chap. 2) and (b) an analysis of subsistence-oriented smallholders in the local dryland context of the Peruvian Altiplano (Chap. 3).

The global analysis integrates endogenous processes that generate vulnerability to environmental and anthropogenic stresses relevant across drylands. The identified vulnerability patterns are validated against independent case studies and serve to derive spatially explicit intervention options. Regarding the interest in upscaling successful strategies to reduce vulnerability, this study addresses specifically the hypothesis that interventions are transferable among similar socio-ecological systems. On the other side of the scale spectrum, the local vulnerability assessment refines the focus of analysis by investigating distinct vulnerability-creating mechanisms at the level of smallholder households. While some of the factors that constitute vulnerability in the Peruvian Altiplano are globally relevant, such as climate variability, others describe local particularities, for example specific smallholder systems. The local study places emphasis on an outcome-based aspect to validate the cluster results. It explores whether the similarities in the vulnerability-creating mechanisms hold true in respect of damage from the exposure to weather extremes. In addition, it tests the cluster-specific mechanisms against reported causes of damage. Taken together, the applications of pattern recognition in the global and local analyses are discussed in relation to the first research question in Section 5.1. The discussion refers particularly to scale-dependent constraints and opportunities.

Adding to the spatial variation to be revealed by the vulnerability patterns, vulnerability varies over time. Conceptual work in the field of global environmental change emphasises the dynamic nature of vulnerability (e.g. Adger & Kelly 1999, Leichenko & O'Brien 2002, Turner et al. 2003a and b, Kasperson et al. 2005, Luers 2005, Füssel 2007, IPCC 2007, Ionescu et al. 2009). Accordingly, the processes that modify vulnerability may be grouped into two broad categories: exposure-related processes and endogenously driven processes without exposure.

The first category includes transforming effects of exposure factors operating outside or inside the system concerned (Füssel 2007) on coping, adaptive capacity and sensitivity. Coping strategies may well vary during a ongoing period of exposure, as illustrated by successive activities which agricultural communities employed to deal with a severe drought in eastern Africa (Eriksen et al. 2005). These activities reflected the intensity and duration of the drought in combination with differential economic opportunities and social relations. Overall, a drought may lower agricultural yields, but production may still suffice to meet food requirements when supplemented by reserves from the previous year. However, if seed demand for the coming year is not met due to the production loss, other resources have to be mobilised to fill that gap. A recurrent drought in the following year, even similar in magnitude, might result in a significant food gap due to the depletion of food reserves and other resources.

Moreover, the strength and type of exposure factors may fluctuate following global environmental and economic change or a re-orientation of livelihoods, for example from agricultural to off-farm activities. These shifts in one or more of the exposure factors may reshape the sensitivity to and the capacity to deal with other recurrent stresses, even when their magnitude remains constant. Analyses of dynamism in the agricultural sector include discussions on how economic change reshapes the capacity of dryland farmers to cope with climate variability and adapt to climate change (Leichenko & O'Brien 2002). Empirical work in this context reveals that processes, such as agricultural trade liberalisation, may impair people's ability to respond to climate risks as shown in smallholder communities in Mexico and Mozambique (Eakin 2005, Eriksen & Silva 2009). Other empirical work has expanded the focus to investigate the consequences of multiple stress factors for changing sensitivity and adaptive capacity (e.g. Belliveau et al. 2006, Westerhoff & Smit 2009, Sallu et al. 2010).

Integrated modelling has further advanced vulnerability analysis by considering alterations in multiple stresses based on scenarios of climate, natural resource use and socio-economic development (e.g. Gaiser et al. 2003, Schröter et al. 2005a, Hinkel & Klein 2009, Dougill et al. 2010). These assessments demonstrate how long-term trends in multiple stress factors may affect ecosystem services, such as water availability, agricultural productivity or carbon storage potential, and hence the people or sectors who are reliant on them. For example, the ATEAM assessment evaluates changes in sectoral vulnerability in Europe during the 21st century (e.g. Schröter et al. 2005a, Metzger & Schröter 2006, Metzger et al. 2006 and 2008). It considers the changing impacts of climate and socio-economic forces on ecosystems together with the changing capacity of sectors dependent on them to adapt to these changes. As another example, integrated simulations in Northeast Brazil explore potential impacts of future climate change and socio-economic development scenarios on water resources, agricultural production and living conditions (e.g. Krol et al. 2001, Gaiser et al. 2003, Döll & Krol 2002, Krol & Bronstert 2007). The identified sensitivity of the marginal water resources to climate change as well as to shifts in land and water use is linked to vulnerability. Potentially aggravating conditions are implied by a general decrease in available water as a result of a possible decrease in natural supply, population growth and an increase in irrigated area.

The aforementioned modelling assessments do not consider the decision-making of individuals in depth. Taking into account this factor more rigorously can provide interesting insights in cases where the dynamics of vulnerability are shaped by the interacting decisions of several actors and where emerging socio-economic or technological options may provide entry points for vulnerability reduction. As a suitable approach to deal with such realistic situations, agent-based modelling enables vulnerability analysis to be linked with advanced techniques to simulate complex adaptive systems. It directs attention towards the dynamic behaviour of people in response to changes in stress exposure (Patt & Siebenhüner 2005, Ziervogel et al. 2005, Acosta-Michlik & Espaldon 2008). The range of potential responses is determined for stylised agents, such as traditional, diversified and absentee farmers. Besides individual preferences, the socio-economic and natural context in which actors make their decisions influences their potential responses. Hence, considerations on how alternative policy scenarios shape the decision-making context enable the identification of strategies that foster the actors' capacity to respond adequately to stress. However, agent-based approaches involve highly data-intensive steps to parameterise the models, thus restricting their application to well-documented cases.

The focus on changes in vulnerability has delivered valuable insights into the underlying processes from the perspective of exposed socio-ecological systems. Exposure-driven processes are however just one aspect of changing vulnerability, though an essential one. Endogenously driven processes which unfold independently of the impacts of stress exposure - such as population growth, changes in water demand and competition between different types of land use - make up the second category of changes and play an equally important role. They are typically integrated with exposure factors when assessing the vulnerability of socio-ecological systems (e.g. Gaiser et al. 2003, Tudela 2004, Schröter et al. 2005a, Manuel-Navarrete et al. 2007). Independent endogenous processes may have been addressed less rigorously since integrative system-oriented approaches to vulnerability are commonly conceptualised with regard to stress factors acting upon a system (Kasperson et al. 2005, Adger 2006, Smit & Wandel 2006).

The ways in which an endogenous process modifies vulnerability depend on its relation to the overall local conditions. For example, population growth, up to a certain extent, may increase the available labour force which potentially facilitates the implementation of labour-intensive adaptation strategies as shown for soil conservation measures in Kenya (Tiffen et al. 1994). This can be interpreted as an endogenous process that alleviates the effects of stress. However, if the food requirements of the growing population exceed the productivity of natural resources and people are unable to purchase food from other places, population growth may evolve as an endogenous stress. To fully understand the dynamic nature of vulnerability, endogenous processes are essential for identifying key mechanisms that generate critical feedbacks as well as emerging opportunities.

This dissertation takes up the particular perspective of endogenously driven processes and investigates the resulting changes in vulnerability. For this, it determines both the status of vulnerability at a given point in time, in the sense of a baseline, and ongoing changes in sensitivity and adaptive capacity. Quantification of trends is often difficult due to the limited temporal resolution of available data. Qualitative dynamic modelling approaches are therefore useful to indicate relevant trends and hence to add mechanistic knowledge to the sparse observational data. This dissertation investigates endogenous aspects of changing vulnerability in the dryland region of Northeast Brazil by addressing the following research question:

Research question 2:
Which changes in vulnerability to climate, market and other stresses were caused by endogenous processes in dryland systems of Northeast Brazil?

The Northeast of Brazil is dominated by marginalised smallholder systems similar to the Peruvian Altiplano investigated in the local study (Chap. 3). To address the second research question, a qualitative dynamic model is applied in order to describe the relevant natural and socio-economic processes. The resulting endogenous evolution of the smallholder systems and the spatial indication of modelled states are discussed in Chapter 4. In addition, specific vulnerability-creating mechanisms are identified for Northeast Brazil by the cluster analysis on the global scale (Chap. 2). These mechanisms are investigated together with the endogenous processes to reveal changes in the vulnerability of the smallholder systems in relation to climate, market and other stresses (Sect. 5.2). The identified vulnerability changes serve to highlight critical as well as advantageous development aspects. These provide valuable insights for the prioritisation of intervention options aimed at improving environmental and living conditions.

Taken together, this dissertation comprises three peer-reviewed publications in Chapters 2 to 4 which provide the basis for addressing the two research questions posed above. Figure 1.1 illustrates the relation of these publications to the discussion of results with regard to the research questions in Chapter 5.

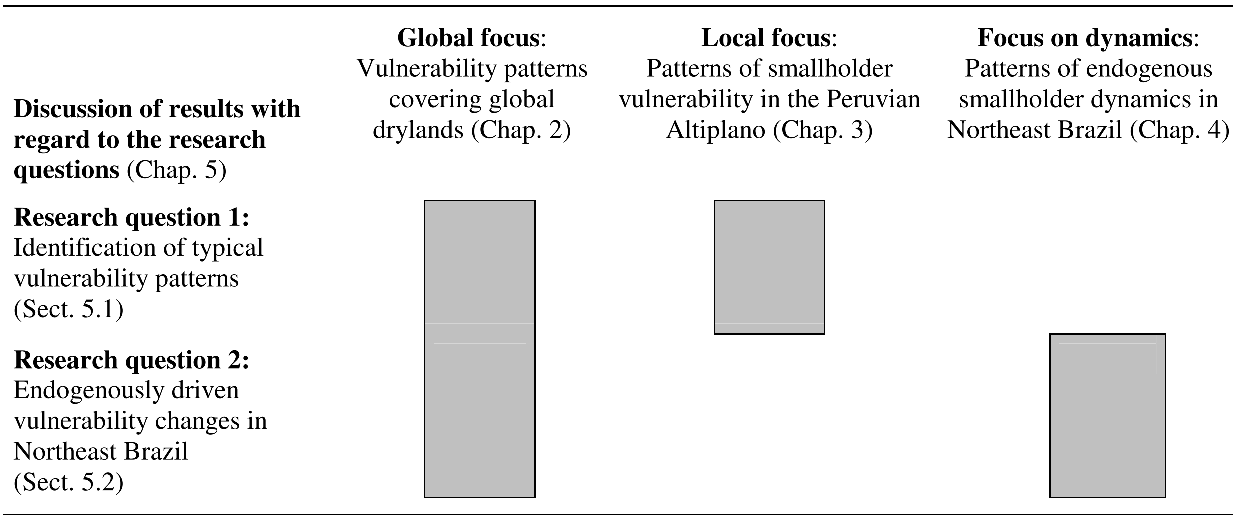

Figure 1.1 Relation of peer-reviewed publications included in this dissertation (Chaps. 2 to 4) to the discussion of results with regard to the research questions (Chap. 5).

Finally, by revealing the causal structure of the vulnerability of socio-ecological systems in drylands with regard to environmental and socio-economic stresses, this dissertation aims at improving the understanding of dryland development and at facilitating appropriate interventions to manage the outcomes of stress. In the climate change community, it has often been argued that strategies for reducing climate vulnerability need to be integrated into the wider development planning in order to be successful (e.g. Huq & Reid 2004, Agrawala 2005, Kok & De Coninck 2007). This integration, also called mainstreaming, is not only determined by available knowledge, but furthermore relies strongly on institutional factors. Major institutional barriers, including a lack of awareness, political commitment, information management and institutional continuity, may significantly constrain the success of integration efforts. Among others, these constraints are apparent in the mainstreaming of adaptation to climate stress into country-specific development assistance (e.g. Lasco et al. 2009, Sietz et al. 2011a). Recognising the pronounced diversity and complexity of development concerns, this dissertation particularly endeavours to establish an efficient approach to assessing dryland vulnerability and related intervention options in order to facilitate the necessary integration in practice.

1.5 Author's contribution to the publications included in this dissertation

This dissertation includes three peer-reviewed publications which I wrote as the lead author (Chaps. 2 to 4). The following paragraphs detail my contribution to the single papers.

Paper 1 (Chapter 2): Sietz, D., Lüdeke, MKB. and Walther, C. (2011) Categorisation of typical vulnerability patterns in global drylands. Global Environmental Change 21: 431-440.

In discussions with Gerhard Petschel-Held and Matthias Lüdeke, I developed the methodological approach for this pattern analysis. Based on a systematic literature review, I compiled the vulnerability-creating mechanisms, collected and prepared the input data, performed the cluster analysis and interpreted the results. Together with Carsten Walther, I adapted the existing R-routines to the specific tasks and he elaborated the consistency measure. Finally, I wrote the paper with helpful comments from my co-authors Matthias Lüdeke and Carsten Walther.

Paper 2 (Chapter 3): Sietz, D., Mamani Choque, SE. and Lüdeke, MKB. (2011) Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano. Regional Environmental Change, Published online: 15 November 2011, DOI: 10.1007/s10113-011-0246-5.

During my work with the International Potato Center in Peru, I developed the idea to apply the pattern recognition in a local context and refined the pattern approach with special emphasis on the validation of results. I compiled the input data from the ALTAGRO database, which my co-author Edgar Mamani consolidated, designed the questionnaire and participated in the household survey, carried out the cluster analysis, validated and interpreted the results. Finally, I wrote the manuscript to which Matthias Lüdeke contributed valuable comments regarding the discussion of climate exposure.

Paper 3 (Chapter 4): Sietz, D., Untied, B., Walkenhorst, O., Lüdeke, MKB., Mertins, G., Petschel-Held, G. and Schellnhuber, HJ. (2006) Smallholder agriculture in Northeast Brazil: Assessing heterogeneous human-environmental dynamics. Regional Environmental Change 6: 132-146.

The QUESTIONS working group had developed the syndrome approach to global change, initiated by Hans Joachim Schellnhuber, using qualitative dynamic modelling (Gerhard Petschel-Held and Matthias Lüdeke) when I joined PIK. For its application to Northeast Brazil, I systematically reviewed the relevant literature to devise the underlying model assumptions, discussed them intensively with my co-authors Bianca Untied and Günter Mertins, performed the qualitative modelling and spatial indication together with my co-author Oliver Walkenhorst and discussed the model results and effects of external shocks on the evolution of the smallholder systems. After discussing the structure with my co-authors, I wrote the paper with contributions by them to the introduction and methodology section.

2 Categorisation of typical vulnerability patterns in global drylands[1]

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 homogeneous. 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.

2.1 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 & 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 towards this aim by identifying typical patterns of dryland degradation in a meta-analysis of case studies.

To illustrate the aim of this study, 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

[1] This chapter and Appendix A are published in: Sietz, D., Lüdeke, MKB. and Walther, C. (2011) Categorisation of typical vulnerability patterns in global drylands. Glob. Environ. Chang. 21: 431-440.

described above. In response to this question, this study presents an approach to categorising 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 to ensure 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 further aims to contribute towards 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 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 among other things 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 study is organised in five sections: based on the compilation of specific vulnerability-creating mechanisms in drylands (Sect. 2.2), quantitative indicators are chosen to capture the most important vulnerability dimensions (Sect. 2.3.1). We employ a cluster analysis (Sect. 2.3.2) to identify typical vulnerability patterns and their spatial distribution at a global scale (Sect. 2.4.1). These patterns are used to deduce specific entry points for vulnerability reduction (Sect. 2.4.2). The study concludes with a summary and outlook (Sect. 2.5).

2.2 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 a 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 degree of 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 & 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 & 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 & 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. 2.1, 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 of income (Ferreira & 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 & 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. 2.1, right-hand side).

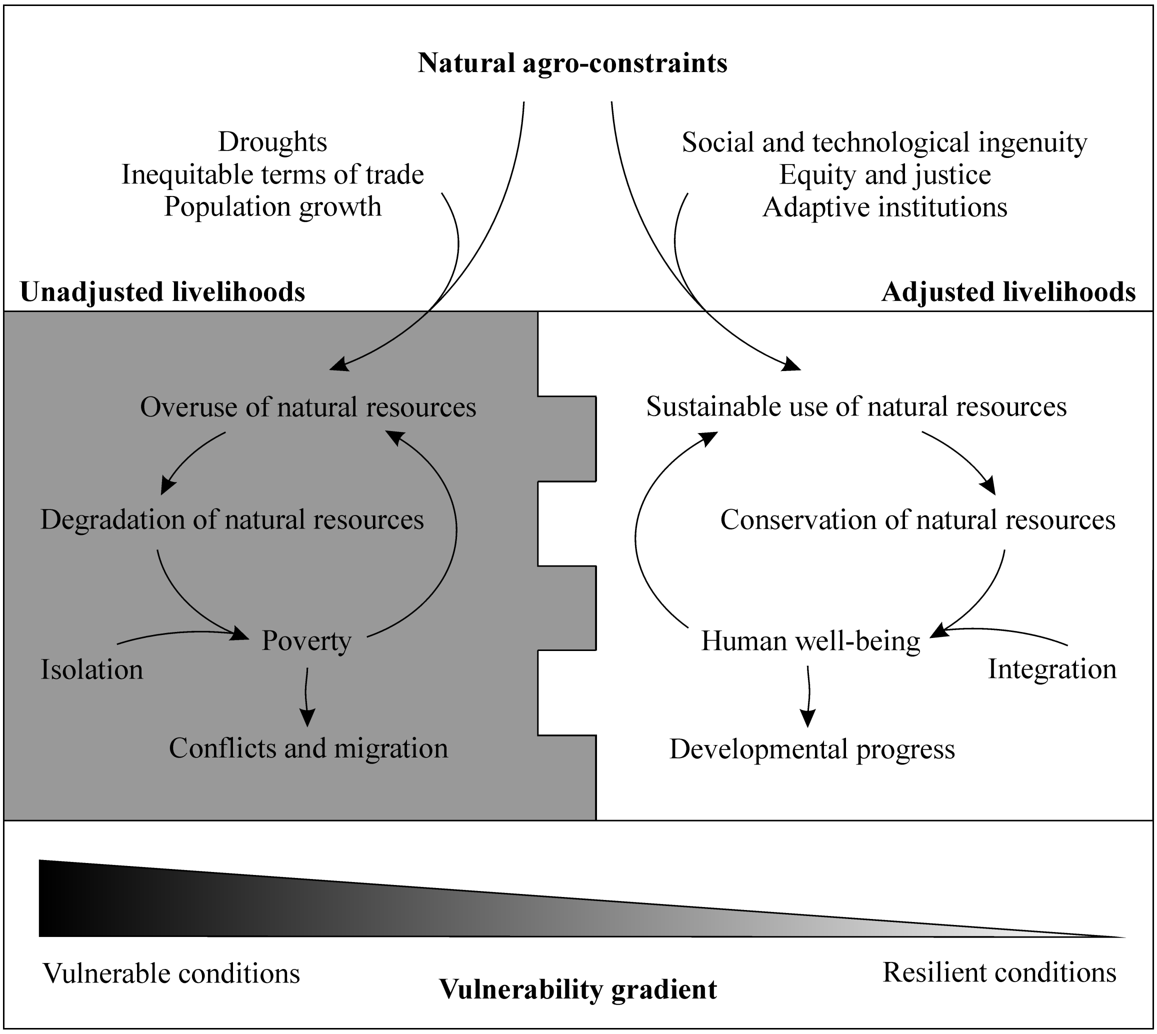

Figure 2.1 Impact trajectories of unadjusted and adjusted livelihoods on dryland vulnerability. A selection of important external and endogenous stimuli driving unadjusted or adjusted livelihoods is given. (Source: Developed on the basis of Reynolds et al. (2007) and Safriel & Adeel (2008))

Together, the two trajectories span a vulnerability gradient ranging from vulnerable to resilient conditions (Fig. 2.1). Dryland vulnerability develops between the extreme end points of this gradient with severity varying from place to place. While a given 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 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.

2.3 Data and methods

2.3.1 Quantitative indication of vulnerability

The mechanisms presented in Section 2.2 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 Figure 2.1. 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. 2.1, 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 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 (Tab. 2.1). 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 (Tab. 2.1). 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 this process 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 & Oldeman 1997, FAO 2009).

Though the natural agro-constraints, the fourth vulnerability dimension (Tab. 2.1), 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 2.1 summarises the five vulnerability dimensions and respective indicators.

Table 2.1 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\`x2.5\`	40-2,031 deaths per 10,000 live births	2000; CIESIN (2005)
Degradation of natural resources				
Water stress	Water scarcity	0.5°x0.5° based on major river basins	1-4	1995*; Alcamo et al. (2003)
Soil degradation	Severity of human-induced soil degradation	0.5°x0.5° based on polygons of FAO world soil map	0-4	1988-1989; Oldeman et al. (1991) 1996; Van Lynden & Oldeman (1997) 2007-2009; FAO (2009)
Natural agro-constraints	Agropotential	5\`x5\`	1-9	1996*; GAEZ (2000)
Isolation	Road density	0.5°x0.5°	0-0.25 km/km^2	2000; ESRI (2002)

*) including 1961-1990 climatology

Some of the indicators needed adjustment. First, infant mortality and agropotential were resampled to the 0.5°x0.5° resolution to integrate them with the other indicators (see Tab. 2.1). Then 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 conditions of and access to health care systems, for example (Rutstein 2000). To incorporate this adequately, we assume that the typical values for industrialised countries reflect the natural component well. 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 inverted, 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 & 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.

2.3.2 Cluster analysis

The selected set of vulnerability indicators (see Tab. 2.1) can be integrated in various ways to combine the relevant dimensions of dryland vulnerability. In this study, 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: Tab. 22.1). A total of 19,938 grid elements at 0.5°x0.5° 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 reflects well the discussion of vulnerability causes and consequences provided in Section 2.2. Further, large variance variables tend to have a higher discriminatory power in a cluster analysis, although variables with a small variance are not necessarily non-informative (e.g. Chang 1983, Yeung & Ruzzo 2001). 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, resp.), whereas 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. These findings are considered in discussing the results of the cluster analysis (Sect. 2.4.1).

Among the vulnerability indicators, infant mortality has clearly an exceptional position. It is the only purely socio-economic indicator. It reflects aggregate 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 & Lambin 2004). The cluster analysis (for mathematical detail see Appendix A) generates seven clearly separable clusters which depict typical combinations of the vulnerability indicators.

2.4 Results and discussion

2.4.1 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. 2.2). First, the indicator values of each cluster are piled, so that each cluster is characterised by a column as depicted in Figure 2.2a. 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 Figure 2.1. Figure 2.2b 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 Figure 2.3. As a first rough structure, it displays a divide between developing/transitional countries (Clusters 1 to 5) and industrialised countries (Clusters 6 and 7). In the following discussion, case study evidence is given that validates the cluster-specific mechanisms and their spatial distribution (their location is indicated in Fig. 2.3).

Cluster 1 represents the most vulnerable regions according to the highest indicator sum (Fig. 2.2a). 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. 2.2b and 2.3). 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 & 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 to 5 all show lower poverty, but differ significantly in the degree of livelihood adjustment (orange-blue colours in Figs. 2.2b and 2.3). 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 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. 2.2b).

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. 2.2b). 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 water permanently 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. 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 of heavily degraded croplands limiting 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 to increase the average livestock size, Robinson et al. (2003) concluded that seasonal rotation of livestock during the 1980s-1990s was an important factor contributing towards 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. 2.2a) depicting the lowest poverty indices (dark and light grey colours in Figs. 2.2b and 2.3). 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 & 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, resp.). 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 & Liverman 2004). In the municipality of Alamos (Sonora), water is particularly scarce due to the diversion of rivers for agricultural purposes outside 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.

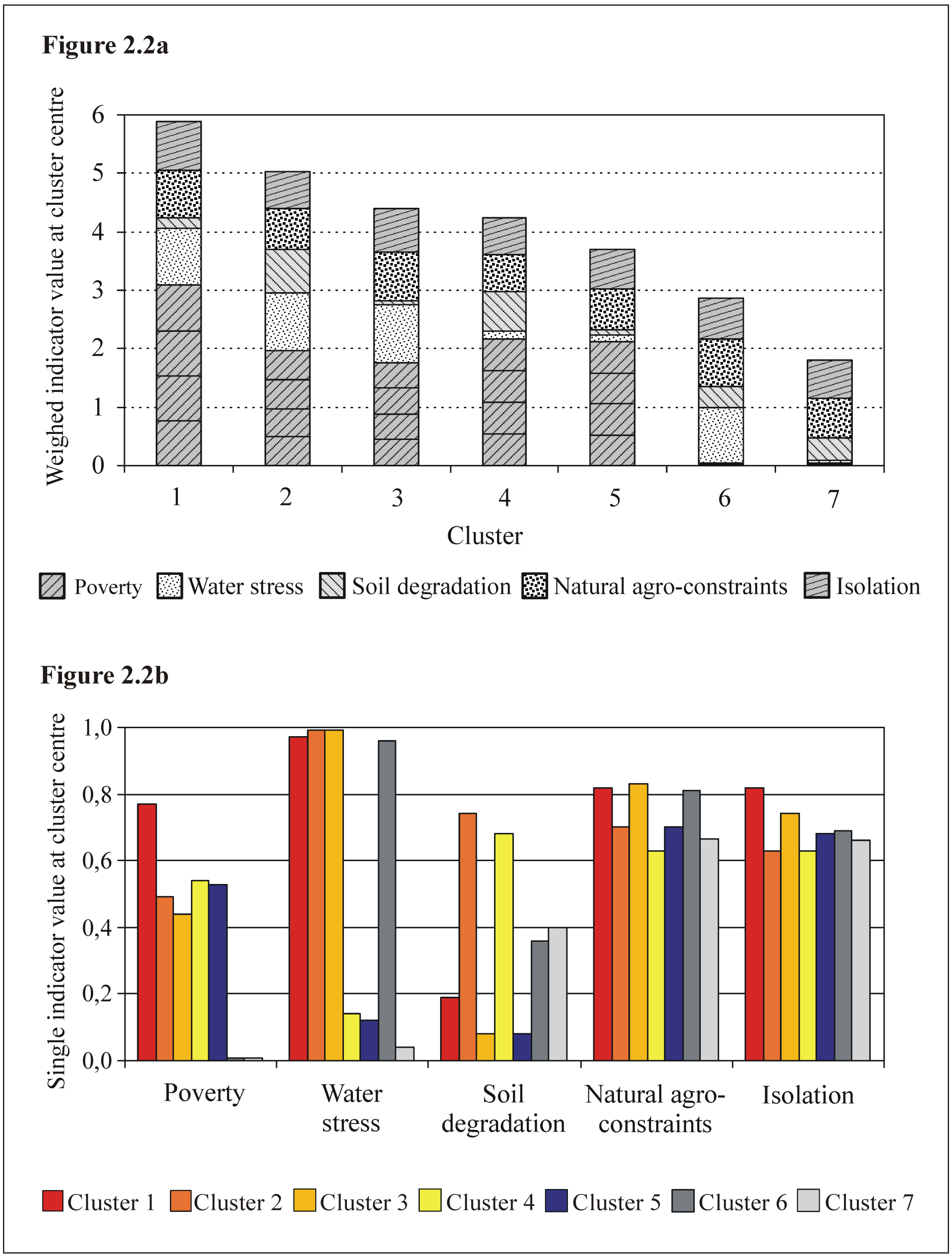

Figure 2.2 Typical patterns of dryland vulnerability as result of the cluster analysis depicting the combinations of the five indicators at the seven cluster centres. Poverty is weighed four times (see Sect. 2.3.2), so that the indicator is given accordingly in Figure 2.2a. To facilitate cross-cluster comparison, single indicator values at the cluster centres are given for each vulnerability dimension in Figure 2.2b.

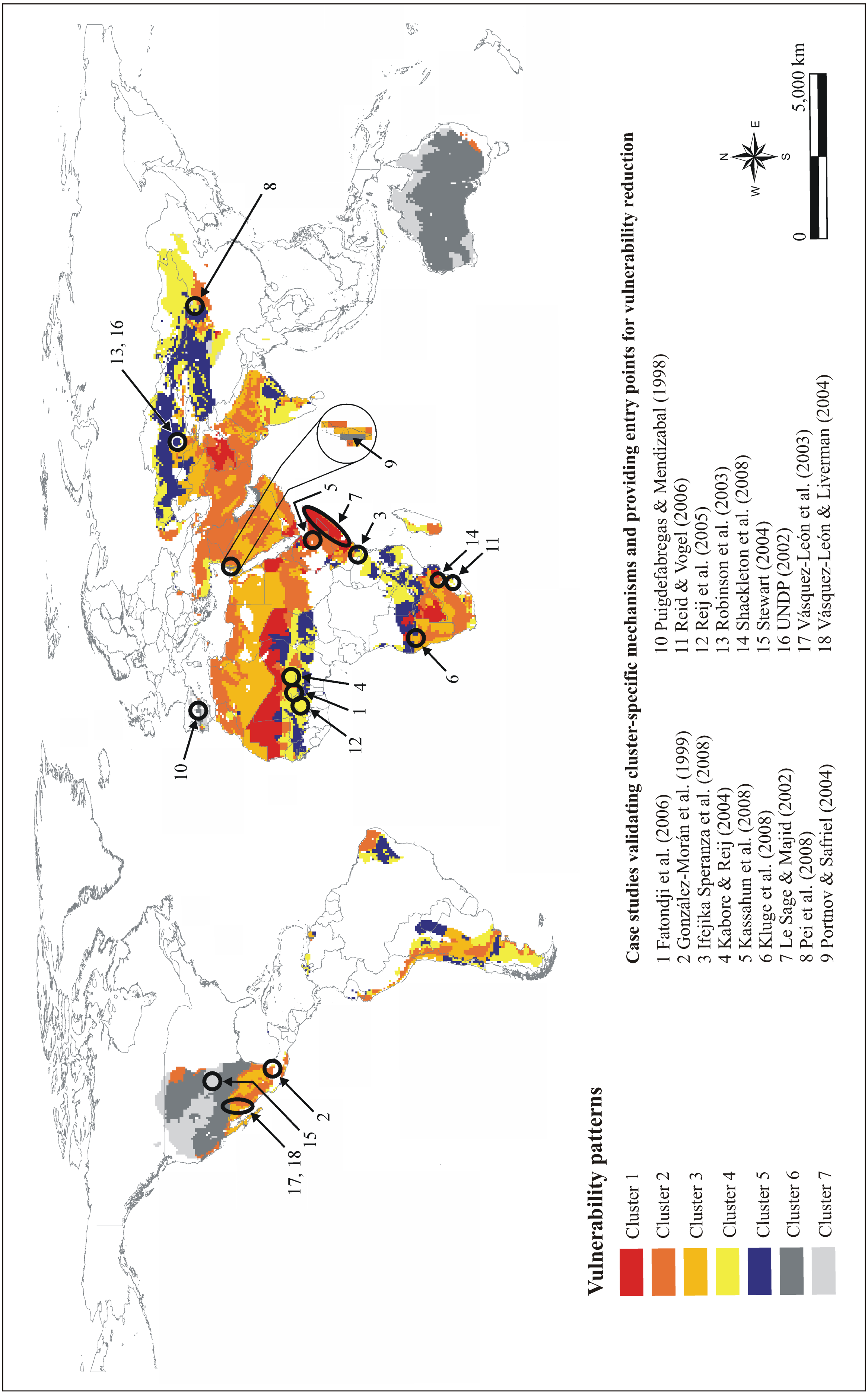

Figure 2.3 Spatial distribution of the typical vulnerability patterns resulting from the cluster analysis of drylands across the globe. Exemplary case studies are mapped that validate cluster-specific mechanisms and provide entry points to reduce vulnerability.

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. 2.2b). This is in line with the smaller variance in these indicators (see Sect. 2.3.2). 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 (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 ability to assimilate shocks.

2.4.2 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. 2.3).

Table 2.2 Entry points for vulnerability reduction according to the indicator values at the cluster centres. (Symbols mean: ↑↑↑ = particular attention needed, ↑ = improvement needed, ● = stabilisation needed)

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

We deduce the entry points for vulnerability reduction (Tab. 2.2) from the indicator values at the cluster centres. Thereby, dimensions with high indicator values (0.67-1) would require particular attention (↑↑↑), whereas 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 2.2 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 (Tab. 2.2). 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 water requirements, rainfall and market conditions (Shideed et al. 2005, Deng et al. 2006). 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 & Reij 2004: 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 in order to prioritise 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.

2.5 Conclusions

The pattern approach presented in this study 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 into 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.

3 Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano[2]

Abstract

Smallholder livelihoods in the Peruvian Altiplano are frequently threatened by weather extremes, including droughts, frosts and heavy rainfall. Given the persistence of significant undernourishment despite regional development efforts, we propose a cluster approach to evaluate smallholders' vulnerability to weather extremes with regard to food security. We applied this approach to 268 smallholder households using information from two existing regional assessments and from our own household survey. The cluster analysis revealed four vulnerability patterns that depict typical combinations of household attributes, including their harvest failure risk, agricultural resources, education level and non-agricultural income. We validated the identified vulnerability patterns by demonstrating the correlation between them and an independently reported damage: the purchase of food and fodder resulting from exposure to weather extremes. The vulnerability patterns were then ranked according to the different amounts of purchase. A second validation aspect accounted for independently reported mechanisms explaining smallholders' sensitivity and adaptive capacity. Based on the similarities among the households, our study contributes to the understanding of vulnerability beyond individual cases. In particular, the validation strengthens the credibility and suitability of our findings for decision-making pertaining to the reduction of vulnerability.

Resumen

Los medios de vida de los pequeños productores en el Altiplano Peruano son frecuentemente restringidos por eventos meteorológicos extremos como sequías, heladas y lluvias fuertes. Dada la malnutrición significativa a pesar de esfuerzos para el desarrollo regional, sugerimos una metodología para evaluar la vulnerabilidad de los pequeños productores ante eventos meteorológicos extremos con respecto a su seguridad alimentaria. Usando información de dos estudios regionales disponibles y una encuesta propia, aplicamos la metodología a 268 hogares de pequeños productores. Un análisis de conglomerados nos permitió identificar cuatro grupos de vulnerabilidad. Ellos representan combinaciones típicas de indicadores de hogares incluyendo su riesgo de pérdida de cosecha, recursos agrícolas, educación e ingresos alternativos. La correlación entre los conglomerados y un daño real, expresado por la compra de alimentos y forraje como resultado de la exposición climática, demostró la validez de los grupos identificados. Los grupos luego fueron ordenados según la cantidad de compra. El segundo aspecto de la validación estuvo referido a los mecanismos reportados que describen la sensibilidad y la capacidad adaptativa de los productores. Dadas las similitudes entre los hogares, nuestro estudio contribuye al entendimiento de mecanismos que generan vulnerabilidad más allá de los casos individuales. La validación de los conglomerados fortalece la credibilidad y aplicabilidad de los resultados para la toma de decisiones para reducir la vulnerabilidad.

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3.1 Introduction

As part of an Andean high plateau, the Peruvian Altiplano ranges from 3,800 to over 4,500 meters in altitude. Its highly variable, semi-arid climate is closely linked to weather extremes, such as droughts, frosts and heavy rainfall, which frequently challenge people's livelihoods. In 2007, several districts in the Peruvian Altiplano declared a state of emergency caused by frosts, hail and transient droughts in the midst of the agricultural season (INDECI 2009). Despite regional development programmes to improve the smallholder systems, poverty and undernourishment remain significant (FONCODES 2006). This situation is particularly precarious since the primary sector constitutes the most important area of economic activity (INEI 2006). Given this situation, we aim to enhance the debate on interlinkages between climate vulnerability and food security as a prerequisite for an adequate discussion of regional development. Therefore, we investigate as to whether there are typical characteristics of smallholder households that help to explain the causal structure of their vulnerability to weather extremes in relation to food security. Reference is made to smallholders in the administrative Region of Puno.

The smallholders living in the Peruvian Altiplano cannot be regarded as one homogeneous social group. Productive resources are heterogeneously distributed and livelihood options differ among the smallholders, all of which requires that the respective vulnerability-creating mechanisms be tackled appropriately. Addressing the heterogeneity of human-nature interactions at an intermediate functional scale, pattern approaches have been used to assess recurrent dynamics of global change and typical patterns of vulnerability at regional to global levels (e.g. Schellnhuber et al. 2002, Jäger et al. 2007, Manuel-Navarrete et al. 2007, Sietz et al. 2011b, see Chap. 2 of this dissertation). These assessments aggregate functionally similar processes to typical patterns which structure the understanding of underlying processes and provide insights into strategies that foster sustainable development.

Taking up the basic concept of pattern analysis, we assess typical vulnerability-creating mechanisms based on similarities at the household level. We extend the pattern approach in testing the validity of the identified patterns using outcomes of a specific exposure and reported mechanisms from independent information sources. Such a validated and manageable categorisation of the heterogeneous characteristics of smallholder households provides a solid basis for advancing regional development initiatives. Major initiatives have shown limited success (DRA 2005) partly because they were based on average environmental and socio-economic conditions. Therefore, such differential insights into the vulnerability of smallholders deliver valuable information for identifying particularly critical livelihood conditions and emerging food insecurity within the social group of smallholders.

3.2 Background

3.2.1 Climate vulnerability and food security

Climate vulnerability is considered as a function of exposure, sensitivity and coping/adaptive capacity (IPCC 2007). To operationalise the concept, one usually asks the questions "*who* is vulnerable to *what impacts?*" and "*what property* is affected by the vulnerability outcomes?". Our analysis focuses on smallholder households being exposed to weather extremes. We assess how households are affected in their food security property. We consider the effects of weather disturbance on the agricultural systems as sensitivity. Furthermore, the adaptive capacity of smallholders (the term as used in this study encompasses the coping capacity) describes the ability to adjust to weather extremes, manage damages or explore alternative livelihood opportunities.

Food security is often discussed in terms of four dimensions: food availability, access, stability of supply/access and utilisation (FAO 2000). Weather affects food security via crop production. While the impacts of weather on the production of food crops and the related building up of reserves directly influence the availability of food, the impacts on the production of fodder crops relate to the building up of livestock serving as savings. We consider those dimensions of food security which build the basis for nutrition and are at least partly within smallholders' control, i.e. food availability and access.

3.2.2 Assessing smallholder vulnerability at the local level

Concern over the degradation of ecosystem functions and limitations of human well-being has motivated a multitude of qualitative and quantitative approaches to assess vulnerability to various stress factors, including both climatic and non-climatic factors (e.g. Vasquez-León et al. 2003, O'Brien et al. 2004, Eakin 2005, Eriksen et al. 2005, Eakin & Bojórquez-Tapia 2008, Hahn et al. 2009, Sallu et al. 2010). These assessments contribute mechanistic and quantitative knowledge for decision-making processes and the monitoring of relevant characteristics. Such knowledge is particularly important for the evaluation of smallholders' vulnerability to which integrated dynamic modelling, such as that presented by Krol and Bronstert (2007) and Dougill et al. (2010), is scarcely applied due to the very high data demand involved in parameterising the models. In addition, the varied objectives of different actors and the uncertainties regarding the rules of human decision-making complicate an appropriate capturing of adaptation in such models.

Within the field of case study research, comparative analyses address specific mechanisms that shape the vulnerability of smallholders to climate variability and change. They employ inductive qualitative and quantitative methods, including interviews, focus group discussions and statistical analysis, to describe processes that determine vulnerability in particular local circumstances. The research on sustainable livelihoods (Chambers & Conway 1992, Scoones 1998) and political ecology (Blaikie 1985, Wisner et al. 2004) has contributed valuable perspectives to the investigation of the underlying processes. For example, smallholders attempted to access food and income during a severe drought in Tanzania and Kenya by collecting fruits, selling livestock and engaging in casual labour on other farms (Eriksen et al. 2005). Only very few households had access to skilled employment, received remittances or produced bricks and charcoal to generate income.

Vasquez-León et al. (2003) further extend the analysis of smallholder vulnerability in accordance with the political ecology approach in comparing rural livelihoods in similar climate conditions, but in the different socio-political and economic contexts on either side of the Mexico-USA border. They illustrate how historical inequalities in the access to natural resources and technological innovation as well as public policies, class and ethnicity determine the vulnerability of farming and ranching communities. For example, marginalised social groups, such as Hispanic farmers, smallholders and ejidatarios on communal land, were largely constrained in their access to land and irrigation systems. In addition, Hispanic farmers in the

USA faced language and literacy barriers to accessing agricultural subsidies. Altogether, such studies deliver rich details about specific expressions of drivers and consequences of vulnerability in diverse livelihood contexts. Thus, they provide the necessary knowledge for a further quantitative evaluation of vulnerability as performed in this study.

Since vulnerability is not directly measurable, indicators frequently serve to quantify the underlying processes. Indicators reduce the complexity of the processes under consideration. They are mostly applied to construct indices used to compare relevant attributes at the level of households or administrative units, including smallholder-dominated areas (e.g. O'Brien et al. 2004, Vincent 2007, Hahn et al. 2009). Such indices allow particularly differentiated insights in case they keep the constituent components and underlying assumptions transparent. For example, Hahn et al. (2009) construct a Livelihood Vulnerability Index to evaluate the climate vulnerability of two smallholder-dominated districts in Mozambique. As well as aggregating 31 indicators into a final index at the district level, these authors present all sub-components at various levels of aggregation. Regionally specific indicators, such as the share of female-headed households, may thereby stimulate debate about their influence on vulnerability. Furthermore, Hahn et al. (2009) apply a monotonous relation to capture the effects of the share of family members who migrate to generate income outside the community. However, while a higher share undoubtedly contributes to decreasing vulnerability, it aggravates the HIV/AIDS prevalence, thus pointing towards another regionally specific process. This relation would be therefore an interesting point of improvement for further exploring non-monotonous relations between individual indicators and vulnerability. This links to the intrinsically non-linear character of the cluster analysis applied in this study.

In contrast to such composite indices, Vincent (2007) develops an aggregate index of adaptive capacity for assessing the ability of rural households in South Africa to deal with changing water availability related to climate change. Here, the kin and friendship ties as well as the access to traditional and formal governance structures were incorporated as important determinants of adaptive capacity. However, merging indicators into one final index does not allow one to distinguish the contribution of such sub-components and thus restricts possible conclusions. Overall, the selection, weighing and aggregation of indicators involve subjective decisions which are linked to the uncertainty of final indices. A validation is therefore a crucial requirement for indicator-based assessments. If conducted, it is often restricted to the confirmation of the implied vulnerability-creating mechanisms by using independent information sources (e.g. O'Brien et al. 2004). Vulnerability outcomes are however an equally important aspect of validation and are thus an integral part of this study.

Other indicator-based assessments account explicitly for the uncertainty inherent in the evaluation of complex domains, such as vulnerability. They integrate quantitative, indicator-based information with qualitative statements and further combine them using fuzzy logic (e.g. Eakin & Bojórquez-Tapia 2008, Krömker et al. 2008, Cheng & Tao 2010). These assessments use fuzzy classification systems to group units of analysis into categories according to linguistic values of their attributes. These categories, for example high, medium and low vulnerability, are represented by fuzzy sets (Zadeh 1965) derived from verbal statements by experts.

A difficult part of fuzzy classification is to define a set of membership functions pertaining to the specific classification problem. Units of analysis have a degree of membership in specific classes. For example, a household can belong 20% to a low vulnerability class and 80% to a medium vulnerability class. Furthermore, a rule-based system (fuzzy inference system) is required to combine the membership functions of sub-components, such as sensitivity and adaptive capacity, into an overall index. Such an approach reflects the fact that experts usually express their knowledge in the form of qualitative conditional statements. For example, if the sensitivity of a household is low and its adaptive capacity is high, then the household's vulnerability is low.

In developing their indices of sensitivity and adaptive capacity as input for a fuzzy classification, Eakin and Bojórquez-Tapia (2008) as well as Cheng and Tao (2010) employ a systematic approach to reveal the relative importance of indicators. In this way, the contribution of each indicator to the overall vulnerability becomes clear and may encourage debate. For example, Eakin and Bojórquez-Tapia (2008) suggest that financial resources are more important for the constitution of adaptive capacity of smallholders in Mexico than their education. They disaggregate the overall index of livelihood vulnerability and discuss the constituting components of sensitivity and adaptive capacity for each class. Moreover, they validate the final index by revealing that the underlying class-specific mechanisms are consistent with the relative distribution of observed responses to climate stress. For example, multiple adaptation strategies were more frequently employed by households in the high vulnerability class than in the other classes. This reflects the necessity of considering any available option to compensate for constraints, such as their highly limited access to insurance, irrigation and credits.

Overall, fuzzy classification has the potential to contribute to the design of appropriate intervention options since it reflects the uncertainty in available knowledge and decision-making. It enables the qualitative comparison between the results of different conceptualisations of vulnerability and types of indicators. An important difference of fuzzy classification compared to the approach applied in this study is that it prescribes the structuring characteristics for categorisation via the membership functions.

Without such a pre-selection, alternative approaches investigate the structure of the data space spanned by selected vulnerability indicators using cluster analysis. They deliver useful insights into recurrent indicator combinations based on similarities among units of analysis, in cases where such a grouping exists. For example, clustering revealed typical livelihood strategies employed by smallholders in Mexico and Botswana (Eakin 2005, Sallu et al. 2010). These livelihood strategies point out mechanisms that shape the smallholders' sensitivity and adaptive capacity. Importantly, clustering keeps the constituents visible throughout the analysis, so that their contribution to the cluster-specific vulnerability remains transparent and can be evaluated. For example, households in southwest Botswana differed significantly in terms of their agricultural assets and access to infrastructure (Sallu et al. 2010). Those who generated a significant employment income could build up their livestock and improve their access to water and transport infrastructure. The accumulated assets and enhanced water availability increased their capacity to cope with precipitation variability, related water shortage and land degradation.

Clustering provides an appropriate method of revealing typical patterns of attributes accounting for variations between the investigated units. Cluster analysis thus delivers a feasible approach to analysing vulnerability since only a limited number of indicator combinations need to be interpreted and related strategies discussed. These typical patterns add structural knowledge to the understanding of vulnerability and decision-making for vulnerability reduction.

In this study, we apply a cluster analysis to assess typical patterns of smallholder vulnerability when exposed to weather extremes and focus our analysis on the food security aspect of vulnerability. We take the cluster approach further in two aspects. Firstly, we test whether the revealed similarities of households also apply to reported damages as a result of weather extremes, without having included a damage indicator in the cluster analysis. As a second validation aspect, we test whether reported vulnerability causes are consistent with the mechanisms derived from the identified clusters.

3.3 Study region

The study was conducted in the administrative Region of Puno in southern Peru. We considered smallholder households in eight districts primarily inhabited by Quechua people (Fig. 3.1). Their production systems are based on rain-fed agriculture in a variety of agro-ecological zones (Circunlacustre 3,800-3,900m, Suni Altiplano 3,830-4,500m and Puna 4,000-4,800m; see Tapia 1991, PISA 1993). The smallholders cultivate diverse food and fodder crops (potatoes - Solanum spp., quinua - Chenopodium quinua, broad beans - Vicia faba, barley - Hordeum spp., oat - Avena spp.) and keep livestock such as sheep, cattle and cameloids (PISA 1993). Some of the species and varieties, for example bitter potatoes, alpaca and llamas, are well-adapted to the challenging mountain climate. Generally, the Altiplano is characterised by a high interannual climate variability. This variability is closely tied to dynamics in the tropical Pacific whereby major temperature and precipitation anomalies are associated with the El Niño Southern Oscillation (e.g. Garreaud & Aceituno 2001).

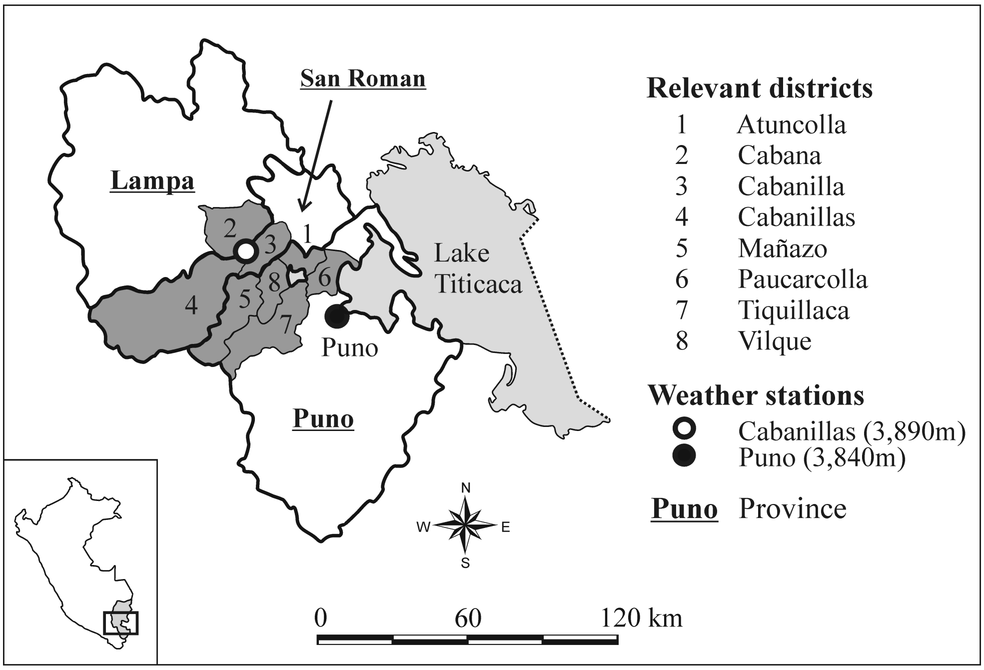


Figure 3.1 Location of the study region in the administrative Region of Puno (Source: Own design)

Despite the marginality of the Altiplano, three historical approaches permitted the development of ancient civilisations: elaborate irrigation and drainage systems, domestication of cameloids and freeze-drying of crops as a means of food security (e.g. Troll 1943, Ericksen 1992, Kolata 1993). Ensuring food security is thus possible, but requires a sophisticated management of available resources. Freeze-drying of tuber crops and cameloid husbandry are still commonly practised throughout the Altiplano. The freeze-drying process takes advantage of the main frost period from June to August. The resulting products, for example dark chuño and white tunta (moraya), can be stored over a long period due to the dry climate. However, the poorly developed irrigation systems, highly fragmented land properties as well as insufficient capacity building and technical assistance (DRA 2005) significantly hamper the adequate management of natural resources. Moreover, traditional adaptation measures, such as cultivation on terraces and raised fields (waru waru, sukacollo), have been substantially eroded since smallholders often cannot afford them or consider them to be inefficient. In addition to this, collectively determined rotation systems (aynoka, laymi; see Canahua et al. 2002) have often been replaced by individual decision-making.

3.4 Data

3.4.1 Vulnerability-generating mechanisms

This section sets the basis for the following analysis and discussion by outlining important mechanisms that generate vulnerability. Since empirical evidence about vulnerability has been scarcely reported for our study region, we draw our information from systematic community assessments performed in the Peruvian Altiplano as part of a larger assessment of climate resilient development in Peru (Sperling et al. 2008). These assessments cover parts of our study region.

Sperling et al. (2008) capture the perspectives of communities on their vulnerability to climate variability and change. The assessments involved focus group discussions with smallholders who are affected by extreme weather events and covered a range of smallholder systems in representing the diversity of vulnerability-generating mechanisms. They focused on the people's perceptions concerning the exposure to climate risks as well as their sensitivity and their adaptive capacity to those risks. Based on a qualitative evaluation of the vulnerability-related attributes, the team revealed the relevant underlying mechanisms.

Mechanisms that relate to climate vulnerability and food security in our study region concern the location, size and quality of land resources as the basis for agricultural production and livestock resources as savings accounts. Furthermore, the level of education and the access to alternative income sources give insights into the climate-sensitivity of food security. These processes provide a useful entry point for our analysis since they specify a generic pattern of vulnerability discussed in an analysis of global drylands (Sietz et al. 2011b, see Chap. 2 of this dissertation) in a local context. The vulnerability pattern identified for our study region reflects medium poverty and severely degraded water and soil resources compared to the global situation. The poverty dimension relates to the size of land and livestock as well as any alternative income in the local context, while the degradation of resources is linked to the quality of land. The location of land in our study however describes a locally specific aspect of climate vulnerability. In addition, the community assessments display the land ownership, access to credits, crop diversity as well as changes in climate and water availability as further vulnerability dimensions.

We briefly summarise the relevant processes identified by Sperling et al. (2008) and specify their relation to climate vulnerability and food security. As the first dimension, the high climate variability in the Altiplano is linked to the risk of harvest failure. The community assessments suggest the lack of opportunities to plant in different altitudes as an important aspect of vulnerability. While some pasture land at higher altitudes is located further away, most land in our study region is cultivated in close vicinity to the households. Therefore, the location of land in relation to production zones that sub-divide the broad agro-ecological zones becomes important. In our study region, three production zones exist to spread the risk of harvest failure, namely plains, hillsides and hills. The plains are more prone to frosts since cold air accumulates in the low-lying areas, whereas the hillsides and hills are more drought-prone due to water drainage. Importantly, if production is damaged in one production zone, the other zones may still provide sufficient yield. Access to more production zones hence increases a household's adaptive capacity.

Besides the harvest failure risk, the size of land resources, as the second vulnerability dimension, further determines the basis for food and fodder production. Cultivating on less land makes households more susceptible to completely losing the harvest. In addition, they are less able to accumulate food reserves for the coming year. Overall, the cultivated area may be constrained due to population pressure as well as a production loss in the previous year and a related seed shortage. As another important part of the production systems, the third vulnerability dimension refers to the livestock constraint. Livestock constitutes a savings account which can be used to buy food during emergencies. A greater stock size thus compensates, to some extent, for limited monetary assets. It also induces a higher capacity to maintain a critical number of livestock throughout an exposure time to rebuild the stock numbers afterwards.

Adding to the characteristics of the production systems, the fourth dimension relates to the productivity of natural resources. Households relying on less productive resources are less able to produce sufficient food and fodder from a given area. The productivity mainly reflects the quality of land, management practices and weather conditions. Productivity constraints are hence considered as an aggregate vulnerability dimension.

Educational effects on vulnerability constitute the fifth dimension. A lack of education decreases a household's coping and adaptive capacity. In emergencies, educationally deprived households are forced to accept poorly-paid work. They can then generate only limited income to cope with a food shortage. The education deprivation also limits the access to skilled climate-independent work and related alternative income as a long-term adaptation option. The sixth dimension, a lack of alternative, i.e. climate-independent, income, reduces the capacity of households to obtain food when production fails. A strong tie to on-farm activities thus implies a high climate-sensitivity of food security.

Finally, some pasture land is rented in our study region. Challenges in the tenancy due to unreliable agreements or high rents entail consequences that accumulate in the size of livestock, so that they are observable in the livestock constraint. As a further dimension, the access to credits is generally constrained in our study region and thus does not reveal a distinction between households. Moreover, the smallholders investigated here commonly cultivate a diversity of food and fodder crops, so that this aspect does not distinguish well between the households. Lastly, changes in climate and water availability relating to the onset and duration of rain, for example, point to dynamic aspects of exposure. These need to be analysed over a longer period and thus go beyond the scope of our study.

Overall, the described sensitivity and adaptive capacity mechanisms together determine whether smallholders are able to maintain their food situation when the production systems are disturbed by weather extremes. To capture the disturbance, weather anomalies are considered as exposure components (see Sect. 3.4.3).

Taken together, the processes revealed by Sperling et al. (2008) lay out important determinants of the climate vulnerability of smallholder systems in our study region. However, it remains unknown as to whether they occur in characteristic combinations. Therefore, we apply a cluster analysis to investigate whether typical patterns exist in these processes.

3.4.2 Quantitative indication of sensitivity and adaptive capacity

The mechanisms generating sensitivity and adaptive capacity outlined in the previous section are quantitatively indicated at the household level. Another regional assessment, the ALTAGRO project, provides the respective data. Starting in 2005, the project established a data base (ALTAGRO 2006) to monitor development progress in 25 communities.

The ALTAGRO (2006) data base contains detailed quantitative information for 527 smallholder households collected through household questionnaires. The data refer to the 2005/06 agricultural campaign. Ten categories describe the smallholder households covering personal information about the family members (e.g. occupation, education level, age), production systems (e.g. crop and livestock assets, labour input, processing and commercialisation of produce), weather conditions, food reserves, income, some expenses and credits. The households were randomly selected in four areas across the administrative Region of Puno reflecting representative smallholder livelihood conditions.

Agronomists with sound field experience conducted the household surveys. They had been engaged in participatory work with agricultural communities over a long period, some of them in the area in which ALTAGRO intervenes. Moreover, they had a good command of the local indigenous languages Quechua and Aymara. The surveys were mainly conducted at the smallholder domiciles (95%) and in some cases at the location of grazing areas or other ongoing activities. Overall, surveyors reported that the smallholders thoughtfully responded to the questions despite the length of the questionnaire. They observed further that recalling the requested aspects was feasible since the survey was carried out in August 2006, that is to say at the end of the agricultural campaign 2005/06. Finally, the collected data were reviewed and consolidated by ALTAGRO personnel based at the collaborating non-governmental organisation Centro de Investigación de Recursos Naturales y Medio Ambiente (CIRNMA) in Puno. They checked the collected data base for consistency in ranges and logic relations of variables. In particular, biases could arise in the surveys through enumerating, counting or measuring errors. Incorrect values were detected and corrected, where it was reasonable, by cross-checking various observations, such as the total cultivated area against the sum of crop and pasture land. This review of the survey and processing conditions reveals that the data are reliable.

The following data are taken from the ALTAGRO (2006) data base to indicate the mechanisms relevant in this study. As the first dimension, the harvest failure risk is indicated by the number of production zones used for crop and pasture cultivation. The indicator considers plains, hillsides and hills. The second dimension of the area constraint is measured by the crop area as an important prerequisite for food production. The pasture area highly correlates to livestock keeping and is therefore reflected in the livestock measure. The third dimension, the livestock constraint, is characterised by the number and types of animals. To compare various animal species, we calculated standardised livestock units in relation to an improved cattle variety based on the livestock-specific metabolism (Kleiber 1961). Average livestock weights were estimated using 20 representative animals of each species in the study region. Since fodder production is an essential condition for livestock keeping, the respective indicator contains a reference to the area and productivity of pasture land. Furthermore, the productivity constraint, as the fourth dimension, is given for the major food crops potatoes and quinua. It averages the household's productivity across species, varieties and production zones for each crop. Again, we concentrate on food crops since the productivity of pastures is already included in the livestock measure. The fifth dimension of education deprivation relates to the number of years that a household head attended school. School attendance is classified according to the four levels: no formal education, primary, secondary and higher education. Finally, the lack of alternative income as the sixth dimension is quantified by the sum of annual monetary income from local off-farm activities and remittances. People usually receive remittances from household members who migrate for climate-independent labour, for example mining and commerce. Table 3.1 summarises the indicators used to assess vulnerability.

Table 3.1 Indicators of households' sensitivity and adaptive capacity. The range of the area and livestock constraints as well as lack of alternative income is provided after winsorisation, see description below. (Data source: ALTAGRO 2006)

Dimension of sensitivity and adaptive capacity	**Indicator**	**Range**
Harvest failure risk	Number of production zones used for cultivation	1-3
Area constraint	Crop area	0.1-1.3 ha/person*
Livestock constraint	Livestock units	0.1-8.0 livestock units/person
Productivity constraint	Potato productivity Quinua productivity	0.1-10.0 t/ha 0.2-1.8 t/ha
Education deprivation	Education level of household head	1-4
Lack of alternative income	Local off-farm income and remittances	0-2,400 Soles/year∗person

*) Average: 4 persons per household

The data given in Table 3.1 describe the attributes of 268 smallholder households located in our study region. In preparing the further analysis, we adjusted data sets with only a few extreme values to increase the influence of these data sets on the cluster partitions. For example, the majority of households possess eight or fewer units of livestock. The few households with up to 39 livestock units can be formally interpreted as single outliers which skew the overall data distribution of this indicator. To deskew such data sets and thus adequately focus on the majority of households, we winsorised the data sets, i.e. replaced the outlying observations (4%) with the next available less extreme observation (Barnett & Lewis 1994). This procedure was applied to the area and livestock constraints as well as the alternative income. All indicators were then normalised to a 0-1 range using the minimum-maximum values.

Prior to the cluster analysis, we determined correlations between the selected indicators and the variance distribution in the data space. Firstly, the correlation coefficients reached average absolute values of 0.11. The crop area and livestock units correlate most strongly here (0.46) reflecting the mixed production systems. Furthermore, variables showing a large variance may be intuitively expected to contain most of the structure information. Therefore, we explored the variance of the selected indicators using a principal component analysis (PCA). The PCA was performed using the statistics package R (RDCT 2009) following standard procedure based on Pearson correlations. The PCA shows minor loadings for both productivity indicators, whereas each of the remaining data sets has a significant loading (absolute values >0.53) in the first three components explaining 66% of the total variance. The productivity indicators have significant loadings only in the last two components. This finding would encourage a clustering without the productivity indicators given the above expectation. However, variables that contribute little to the overall variance of the data space may still contain important structure information (e.g. Chang 1983, Yeung & Ruzzo 2001). To test the relevance for our clustering, we compared the cluster results obtained by including and excluding the productivity indicators (see Sect. 3.6.1). Finally, we inverted all indicator values, so that now high values point to climate-relevant constraints in the smallholder systems contributing to vulnerability.

3.4.3 Climate exposure

The climate exposure is determined by precipitation and temperature conditions as the main natural production factors. We refer to both the 2005/06 and the preceding agricultural campaign. Weather conditions during these two campaigns influenced crop production and available food reserves in the campaign under investigation. Furthermore, we use a well documented additional campaign to identify the conditions for drought and water stress. The necessary weather information is available in good quality for the 1996-2006 period for two stations located in Puno and Cabanillas (see Fig. 3.1). Table 3.2 shows the average precipitation and temperature for both stations.

Table 3.2 Mean precipitation and temperature for 1996-2006 at Puno and Cabanillas stations (Data source: Servicio Nacional de Meteorología e Hidrología del Perú, SENAMHI)

	Mean values for 1996-2006												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation (mm)													
Puno	201	161	138	60	7	3	4	14	27	51	48	88	801
Cabanillas	166	165	112	56	6	1	3	11	19	54	55	91	738
Mean temperature (°C)													
Puno	10.8	10.7	10.6	9.7	8.1	6.8	6.8	7.9	9.3	10.4	11.0	11.5	9.5
Cabanillas	10.6	10.5	10.5	9.8	8.6	7.3	6.9	8.1	9.6	10.6	11.1	11.3	9.6
Minimum temperature (°C)													
Puno	5.7	5.8	5.4	3.8	0.8	-0.9	-1.1	0.4	1.9	3.6	4.3	5.4	2.9
Cabanillas	5.3	5.5	5.2	3.7	1.1	-0.8	-1.5	0.3	2.1	3.7	4.2	5.1	2.8

Physiological modelling of production stress is not feasible in this study because appropriate data on evapotranspiration and soil conditions, for example, do not exist. Instead, in a first step, we calibrated observed precipitation anomalies against reported production damage. To make the two stations comparable, we determined relative anomalies compared to the average precipitation course over the period 1996-2006 through precipitation ranking. This ranking was then used to identify driest and wettest periods which caused production damage. Since soil water content integrates previous precipitation events to some extent, we cumulated the daily precipitation records in a 20-day window. This window was moved as a running mean by steps of one decade (10 days). This choice is supported by the calibration campaign 2003/04 described below. Covering the rainy season from December to March, we obtained cumulated precipitation values for 12 time segments (Fig. 3.2). This number of time segments still allows for sufficient resolution of intra-seasonal anomalies.

The 2003/04 campaign serves to calibrate the anomalies in the light of production damage (Revista Agraria 2004, INDECI 2010). At the beginning of 2003/04, the relevant provinces Puno and San Roman reported 490ha and 306ha of affected agricultural land and some 70ha lost in each province due to torrential rainfall. These damages correlate with the relative precipitation anomalies given in Figure 3.2 (lower part). Here, the wettest time segments are found in late December for both stations and an additional segment at Cabanillas station in early January. At the end of the campaign, an early harvest was reported in both provinces due to a lack of precipitation. This emergency concurs with the driest segments identified in late February in Cabanillas and in early March at both stations. To facilitate comparison with other regions, Figure 3.2 includes absolute precipitation values in the upper part.

To describe the exposure in the campaigns relevant for our study, we use the above information. In 2005/06, we find the driest time segments in December and February at both stations, while the wettest segments are found in January and March (Fig. 3.2, middle part). In 2004/05, the driest segments occurred during December/January and mid March, with an additional wettest segment in mid February at Cabanillas station. Overall, both stations recorded precipitation anomalies in the same magnitude as the calibration campaign. The study region was thus also exposed to drought and water stress during the 2005/06 and the previous agricultural campaign. Climate exposure was similar throughout the study region since the number of precipitation anomalies at the two stations is comparable in each campaign.

Contrary to the precipitation conditions, no general frost exposure was identified for the relevant campaigns as the minimum temperature did not fall below 0°C at the two stations (Data source: SENAMHI). Considering that temperature is measured 1.5 meters above ground and that the air may be around 1°C colder at canopy height (Morlon 1987), the 0°C threshold refers to a general frost sensitivity. Commonly grown bitter potato and quinua species are however more frost resistant withstanding temperatures as low as -3°C to -8°C (e.g. Canahua et al. 2002, Bois et al. 2006).

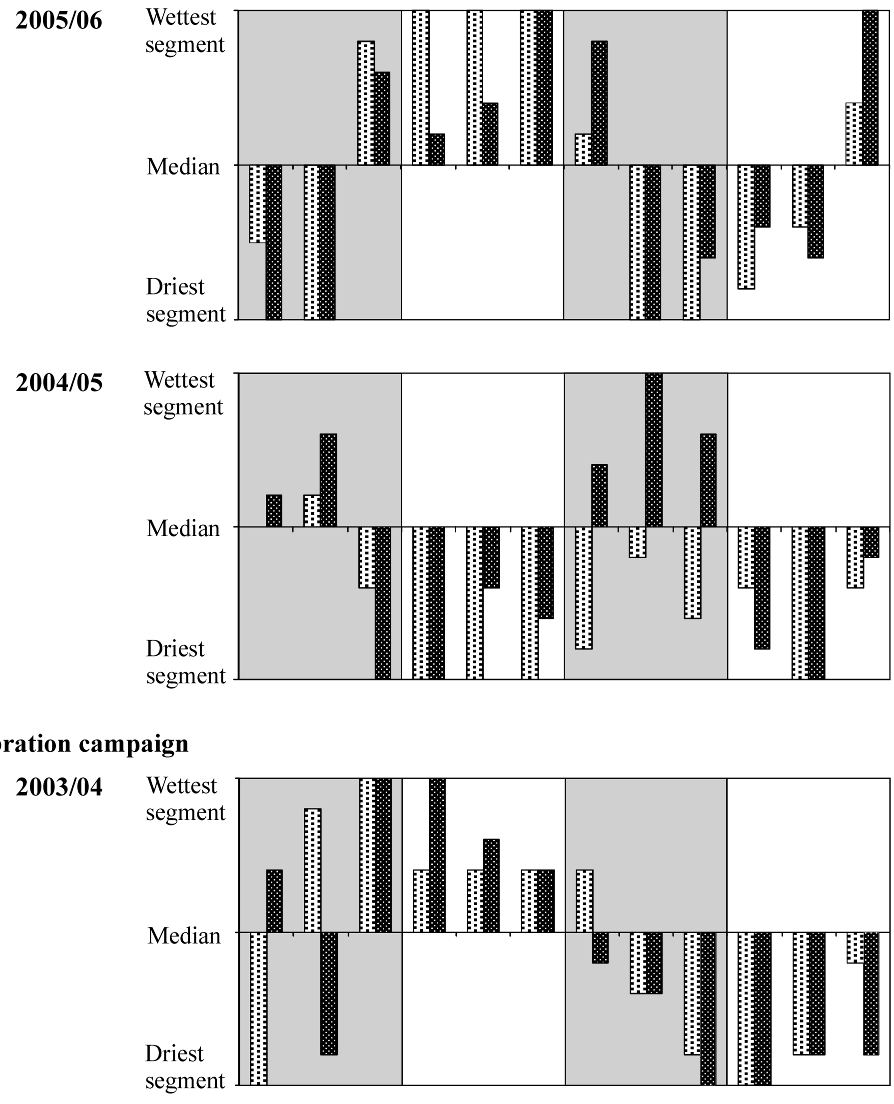
In conclusion, climate exposure was precipitation-driven during the relevant campaigns. Similar precipitation and temperature conditions at both stations indicate a similar climate exposure throughout the study region. Therefore, a potential spatial variation in the exposure does not have to be considered in the further vulnerability analysis.

Precipitation (mm) 1996-2006

	Station	December 21.11.-10.12.	December 1.12.-20.12.	December 11.12.-30.12.	January 21.12.-9.1.	January 31.12.-19.1.	January 10.1.-29.1.	February 20.1.-8.2.	February 30.1.-18.2.	February 9.2.-28.2.	March 19.2.-10.3.	March 1.3.-20.3.	March 11.3.-30.3.
Wettest segment	Puno	95	87	128	148	199	214	167	182	181	182	185	143
	Cabanillas	110	126	127	163	190	190	155	235	215	158	134	107
Median	Puno	30	39	62	93	120	141	115	133	99	92	82	92
	Cabanillas	34	58	80	83	107	102	102	134	94	77	73	34
Driest segment	Puno	7	26	25	39	91	79	87	50	41	49	54	40
	Cabanillas	17	27	24	23	49	48	51	61	70	35	20	46

Relative anomalies

Relevant campaigns



Weather stations: Puno (Puno Province) Cabanillas (San Roman Province)

Figure 3.2 Precipitation anomalies during the rainy season December to March in 1996-2006. The upper part presents precipitation records for the wettest, median and driest segment of 12 time segments. These segments result from the cumulation of precipitation records in a 20-day window moved as a running mean by one-decade steps. In the middle and lower parts, the abscissa refers to these 12 time segments. The ordinate indicates the ranking of the 1996/97 - 2005/06 cumulated precipitation values. Note: For missing values in 2004, the 1st segment in Puno refers to nine campaigns. (Data source: SENAMHI)

3.5 Methods

3.5.1 Cluster analysis

The cluster analysis was performed using a sequence of a common hierarchical and exchange algorithm, i.e. hclust and k-means, using the statistics package R (MacQueen 1967, RDCT 2009). Based on stochastic initialisation, we calculated the reproducibility of partitions for a pre-given number of clusters to determine whether the algorithm detects stable or unstable (inappropriate) partitions. The share of households that were categorised in the same cluster in two partitions is expressed as "consistency measure". The higher this measure, the more reliable the cluster results. We calculated the consistency measure as the average of 200 pairwise comparisons of partitions with a given number of clusters. Ultimately, the consistency measure enables us to identify the optimal number of clusters to be analysed. Further methodological details are outlined in a previous application of the cluster approach to dryland vulnerability on a global scale (Sietz et al. 2011b, see Chap. 2 of this dissertation).

Applying this procedure, the partitions with two and four clusters present local optima in the consistency measure among partitions with 2-10 clusters (Fig. 3.3, left-hand side). Though partitions with two clusters yield the highest consistency, they only differentiate between the clusters according to the harvest failure risk. The other dimensions do not differ much, meaning that the discussion would be rather limited. Moving on to partitions with four clusters, the algorithm separates groups of households that clearly differ in five dimensions. Such a categorisation contributes interesting aspects to the interpretation of vulnerability clusters. In addition, the ratio of the between-cluster and the inner-cluster variance is a measure of the dissimilarity between clusters and their compactness. It increases more strongly for partitions with up to four clusters than for partitions with higher cluster numbers (Fig. 3.3, right-hand side). Therefore, we base our analysis on four clusters.

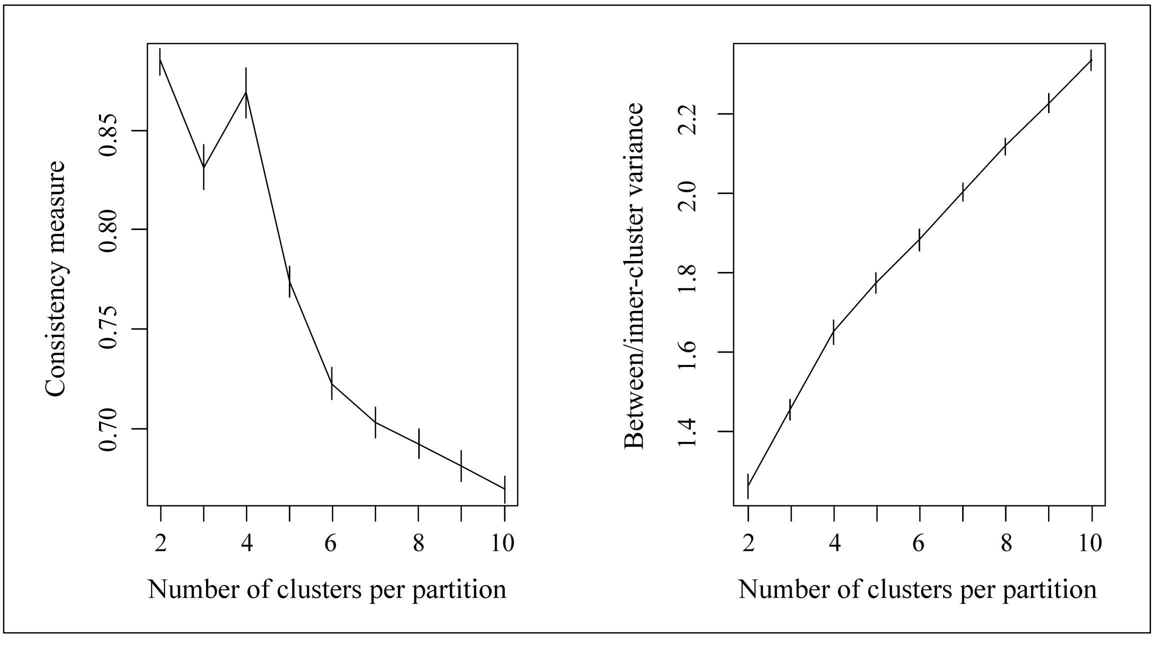


Figure 3.3 Consistency measure and ratio of between/inner-cluster variance for partitions with 2-10 clusters. Whiskers indicate standard deviations of 50 repetitions of 400 cluster runs, that is to say 200 pairwise comparisons for the consistency measure.

As the severity of vulnerability does not automatically result from the cluster analysis, an additional step was necessary. Here, we used outcomes of vulnerability to test the four identified clusters for validity and rank them as described in Section 3.6.1. Thereafter, these typical combinations of household attributes were interpreted and the implied vulnerability-creating mechanisms tested against empirical evidence. Both the outcomes and underlying mechanisms were collected in a household validation survey as described in the following section.

3.5.2 Household validation survey

The identified vulnerability clusters were tested for validity based on both outcomes resulting from the exposure to weather extremes and reported causes of vulnerability. The two regional assessments used to describe and quantify the vulnerability-creating mechanisms did not provide sufficient details for such a validation. Therefore, we conducted a Household Validation Survey (HVS) in collaboration with CIRNMA technicians. It was carried out in 33 randomly chosen households (12%) in February 2009. The engagement of local smallholders is a key component of this study. They are considered a necessary information source for providing details on the local conditions of climate sensitivity as well as constraints and opportunities for coping with adverse effects.

For the outcome-oriented aspect of validation, we assume that an increased purchase of food and fodder indicates damage since it forces the household to mobilise resources which may have been earmarked for other purposes. We collected data on the purchase of food and fodder in 2005/06 including monetary and in-kind exchange. The purchase was considered in relation to an average year to compare households in a standardised way. The average year indicates the necessary purchase which complements the household's production and reserves to maintain the average nutritional status. We assume that changes in 2005/06 were primarily caused by the identified weather extremes given that the productive resources and agricultural management are relatively stable over time.

As smallholders do not maintain records of their purchase, the data collection drew on their memory recall. This approach provides good estimates in the absence of other reliable data sources, though some limitations need to be considered. Most importantly, this method does not account for memory biases. To reduce such biases, the survey referred to the purchase of a specific crop in a given year. Firstly, smallholders were asked to reflect on the crop they harvested last, starting with the previous campaign and successively moving backwards to the 2005/06 campaign. This part of the survey was conducted with the aid of an abacus. Starting with the given number of ten beads indicating the average purchase, household heads or other adult family members removed or added beads to quantify their relative purchase in 2005/06. The survey considered the five major food and fodder crops: potatoes, quinua, broad beans, barley and oat.

The second part of the HVS focused on information about aspects of the smallholder livelihoods that help explain important causes for differences in purchase to support the interpretation and validation of the vulnerability clusters. This part involved semi-structured interviews exploring effects of weather extremes on the smallholders' livelihoods, access to land, production zones and income, availability of labour as well as social and economic opportunities to cope with production failure. The key questions about the households' purchase and its quantification are given in the questionnaire in Appendix B. Overall, each interview took around 45 minutes and was carried out in Spanish or Quechua according to the native language of the interviewees.

To test the consistency, we triangulated the responses with informal surveys conducted in the same smallholder households in 2007/08 and a recall of CIRNMA technicians who had engaged in long-term field work with the respective smallholders. As a result, we had to repeat two surveys for contradictory responses in the households initially selected. The information for the households finally surveyed was consistent.

3.6 Results and discussion

3.6.1 Outcome-oriented validation and ranking of vulnerability clusters

In this section, we consider the identified vulnerability clusters firstly as formal entities without regarding their contents; these will be discussed in the following section. Before going into the details of validation, we will review the results of the different cluster analyses, including and excluding the productivity indicators.

The initial cluster analysis considering all seven vulnerability indicators demonstrates that neither the productivity of potatoes nor that of quinua significantly differs between the households (maximum difference 0.09 and 0.03 for the normalised potato and quinua productivity, resp.). The limited contribution of the productivity indicators to the overall variance of the data space as described in Section 3.4.2 may partly explain this similarity. Furthermore, the comparison of clustering with and without the productivity indicators reveals an identical number of four clusters with a relative maximum in the consistency measure and a significant increase in the variance ratio for partitions with up to four clusters. Clustering without the productivity indicators yields very small differences of -0.03 for the respective consistency measure and 0.2 for the variance ratio as well as comparable indicator combinations at the cluster centres (average difference 0.01, maximum difference 0.03 in absolute terms). In addition, the cluster membership of almost all households (99%) persists. Therefore, the productivity is non-informative for our clustering, meaning that we will concentrate our discussion on the remaining five discriminating dimensions.

Recognising the sensitivity of any vulnerability analysis to the choice of indicators, we empirically examine whether the formal entities provide specific evidence about damages under the identified climate exposure. For this, the data on households' purchase collected in the HVS are related to the cluster membership of households. Figure 3.4 shows that each cluster corresponds to a relatively small range of the damage measure. Therefore, the similarities among the households revealed by the cluster analysis hold true with regard to the outcomes of the climate exposure. These similarities prove that the clusters provide specific information on climate vulnerability with regard to food security. Furthermore, the clusters clearly distinguish between the households in terms of the amount of purchase. The purchase ranges from above to below-average values pointing to the severity of vulnerability. The severity is used to rank and colour the clusters.

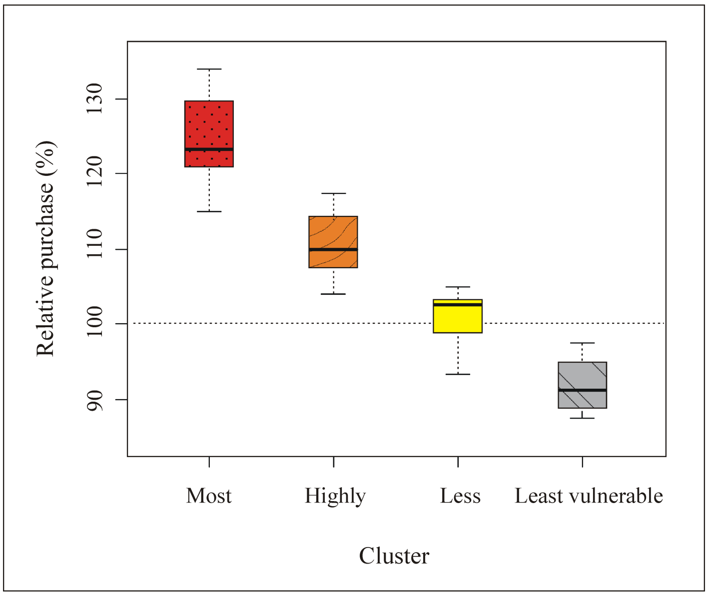


Figure 3.4 Relation between the vulnerability clusters and relative purchase in 2005/06. Clusters are ranked and coloured according to the severity of vulnerability as shown by the relative purchase. The dotted line indicates an average year. The boxplots give the 50% range of households including median values (bold line), while the whiskers show minima and maxima.

The above-average purchase in the most and highly vulnerable households (red and orange colours in Fig. 3.4) indicates that these households were sensitive and ill-adapted to the weather extremes. The less vulnerable households (yellow) were not affected much and the least vulnerable households (grey) purchased even less than average.

3.6.2 Interpretation of vulnerability clusters

We interpret the identified vulnerability clusters based on the indicator values at the cluster centres. These indicator values are representatives for all households categorised as a given cluster. The cluster profiles show that the specific sum of indicators (Fig. 3.5, upper part) reproduces exactly the cluster ranking according to the damage measure (see Fig. 3.4). This correspondence provides a bridge to vulnerability metrics (e.g. O'Brien et al. 2004, Hahn et al. 2009).

The clusters roughly divide the households into two broad types (Fig. 3.5, lower part). Either they rely on subsistence indicated by the higher education deprivation and lack of alternative income (most to less vulnerable clusters) or they integrate both on- and off-farm activities (least vulnerable cluster). Focusing on subsistence, the most and highly vulnerable clusters depict particularly resource-constrained households. The clusters however differ with regard to the harvest failure risk. The less vulnerable cluster assembles households with greater agricultural resources, but poorly distributed harvest failure risks. In contrast, the least vulnerable cluster indicates less educationally deprived households that generate a high alternative income. This means their food security is less sensitive to weather conditions.

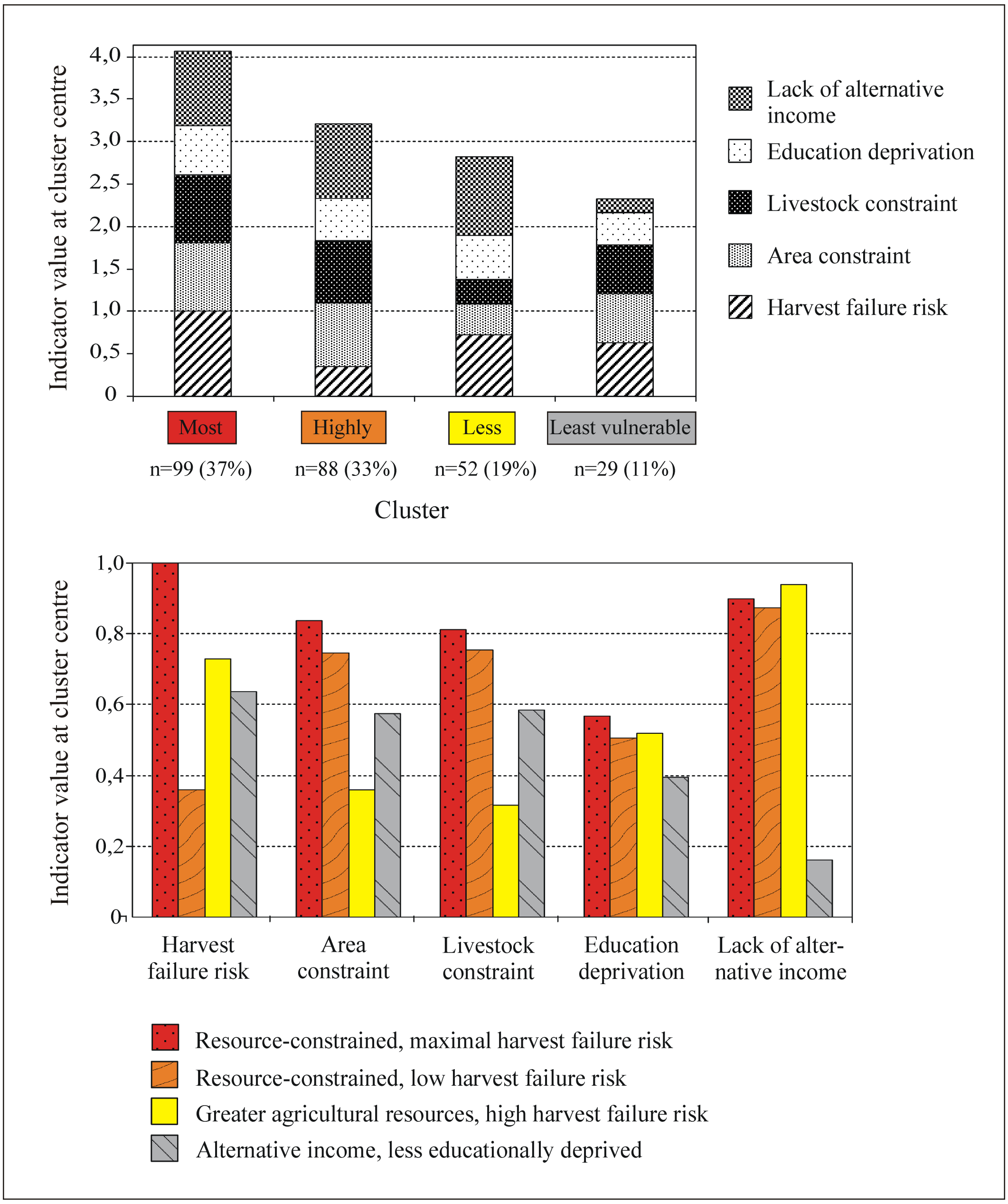


Figure 3.5 Vulnerability profiles with indicator values at cluster centres. Indicators are normalised according to their minimum and maximum, whereby high values contribute to vulnerability.

Table 3.3 Households' total income and involvement in extension services provided by CIRNMA (Data source: ALTAGRO 2006)

Cluster	**Total income (Soles/year∗person)**	**Extension involvement ≤ 4 years (% of households)**	**Extension involvement > 4 years (% of households)**
Resource-constrained, maximal harvest failure risk	1,065	61	39
Resource-constrained, low harvest failure risk	965	56	44
Greater agricultural resources, high harvest failure risk	1,503	38	62
Alternative income, less educationally deprived	3,972	67	33

In the remainder of this section, we will describe and interpret the identified vulnerability clusters in more detail. The empirical evidence independently gained in the HVS serves to validate the underlying mechanisms. The smallholders reported causes of climate vulnerability which deliver rich details that improve the understanding of particular mechanisms in the local context.

Resource-constrained households with maximal harvest failure risk. The most vulnerable cluster describes the maximal harvest failure risk together with pronounced area and livestock constraints. These households are educationally deprived and lack an alternative income. To specify the constraints, we cite two farmers from the Mañazo district who belong to this cluster. The competition for land resources greatly restricts their access to different production zones. Land still available is located far from their living places and sometimes has to be rented at high costs. Despite owning at least some land in plains and hills, they could not distribute the production risks well in the respective campaign. One of them followed his crop rotation which assigned the limited available area in the hills to fallow. The other farmer faced a labour shortage during sowing since he fell ill and his wife alone could not sow the rather distant intended area. They had no monetary assets to hire labourers for this task.

For the highly constrained area coinciding with a maximal harvest failure risk, the agricultural production fell short as result of the precipitation anomalies and related insect attacks (e.g. Gorgojo de los Andes). This causal relation was reported by the majority of interviewed smallholders that belong to this cluster. The purchase subsequently increased more than in the other clusters (see Fig. 3.4). However, although the households' expenses are unknown in detail and the purchase identified reflects both monetary and in-kind exchange, the generally limited income (Tab. 3.3) and livestock savings indicate that the most vulnerable households had a lower capacity to afford the increased purchase. The wife of one of the farmers mentioned above sought to overcome the deficit by knitting sweaters. But she was forced to compete with the saturated market supplying tourists in the city of Puno and could only negotiate a weak position. Within the family, one daughter living in Puno supported the parents financially.

Resource-constrained households with low harvest failure risk. Households in the highly vulnerable cluster are constrained in agricultural resources, education and income, similar to the most vulnerable cluster. But they distribute the harvest failure risks better. Farmers from this cluster in Cabana pointed out that their cultivation area consists of a high number of small parcels (8-13) located in various production zones. They prioritise the distribution of production risks when planning a campaign. This means that the area constraint is not necessarily a barrier for the balanced use of production zones. This finding contradicts the hypothesis on ample land resources as an implicit requirement for adequate risk distribution as mentioned by Sperling et al. (2008). Overall, the only slight increase in purchase in 2005/06 required rather small additional efforts. Some farmers exchanged parts of their cereal surplus harvested in the investigated campaign and remaining chuño reserves for quinua and beans which they did not produce in sufficient quantity.

Greater agricultural resources with high harvest failure risk. In contrast, the less vulnerable cluster indicates greater agricultural resources. Here, the longer involvement in CIRNMA's extension services compared to all other clusters has probably facilitated the accumulation of resources and income generation (Tab. 3.3). As a part of this, financial support and consulting services to improve cattle breeding and organic-quinua production receive special emphasis. A female farmer in Cabana explained that the extension service helped to improve her cattle stock by controlling breeding conditions and diseases. The well-developed cattle stock now supplies her with plenty of milk which she processes to cheese to sell at the local market. The income she generates with this allows her to increase her livestock further and acquire new land holdings. The female farmer however added that the labour-intensive animal husbandry absorbs a great part of the available labour force inducing labour shortages for the cultivation in different production zones. Generally, if households in this cluster lost parts of their harvest due to the identified precipitation anomalies, this was not a problem. They had enough reserves from the previous campaign.

Alternative income in less educationally deprived households. The least vulnerable cluster describes somewhat better educated people who more easily explore opportunities for skilled alternative income. Here, the alternative income contributes to the limited risk distribution. Some farmers from this cluster living in Cabanilla indicated that they engage less in agriculture and related reduction of harvest failure risk because they give more priority to skilled off-farm activities, including teaching and capacity building. They said that the resulting alternative income facilitates necessary purchase when their production fails. The below-average purchase (see Fig. 3.4) points to the opportunity that people use their higher income (Tab. 3.3) to meet changing family demands. For example, they sometimes substitute potatoes and quinua, as traditional foods, with rice and wheat products. As they are widely considered modern food, people like to include them in their diet. In addition, people who increasingly engage in off-farm activities sometimes reduce their agricultural assets, for example labour-intensive livestock. Under these circumstances, fodder requirements and the related purchase may slowly decline.

The prevalence of most and highly vulnerable households (Fig. 3.5) points to the urgent need to reduce climate vulnerability for improved food security. These households could not sustain their production even under the relatively modest exposure in the investigated campaign. Being limited by resources and income, the most and highly vulnerable households would benefit from extending the cultivated area and building-up of livestock. It would be helpful to identify further supportive conditions for well-distributed production risks and income generation. Under the given conditions, these households face substantial difficulties in innovating their systems. Increasing the livestock or the production of organic quinua, for example, demands a restructuring of the production systems to allocate the necessary labour and follow specific guidelines for organic growing. By organising in associations, individual households can negotiate a better market position to reduce costs for new inputs and receive more for their outputs. Capacity building and technical assistance would be important to support these processes with a simultaneous focus on building climate-robust production systems.

Considering the extreme El Niño events recurrently disturbing the Altiplano, the majority of the investigated households are probably unable to meet their food requirements during such periods as their capacity to deal with moderate stress is already low. Without major improvements, the undernourishment currently prevalent could unfold further and have adverse consequences for labour productivity and related income. As the undernourishment of mothers is linked to critical child malnutrition and higher rates of child mortality, it can transmit disadvantages across generations (Harper et al. 2003).

3.7 Summary and conclusions

This study has analysed climate vulnerability with regard to food security based on a cluster approach. Capturing multiple attributes of 268 smallholder households in the Peruvian Altiplano, we identified four vulnerability clusters. The typical patterns of vulnerability identified were validated against independently reported damages under climate exposure. At the same time, the damage measure allowed for a ranking of the clusters according to the severity of vulnerability. Given the similarities of both the vulnerability characteristics and the outcomes of the observed climate exposure, the clusters provide appropriate indication of climate-related causes of food insecurity in the smallholder households investigated. Moreover, independent empirical evidence about causes of climate vulnerability validated the cluster-specific mechanisms. This elaborate validation strengthens the credibility of our findings and the assumption that they are suitable for decision-making.

Our findings concur with previous studies on the consequences of resource scarcity, diversification of activities and income restrictions for climate vulnerability in smallholder households. For example, Valdivia and Quiroz (2003) report that livestock assets, the sale of dairy products and off-farm employment significantly increased the coping capacity of smallholders in the Bolivian Altiplano. They conclude that poor households deplete rather than accumulate assets, even with average precipitation conditions. As another example, smallholders in Mexico with limited land resources rather dedicated their land to maize production to meet subsistence needs (Eakin 2005). Though the price for maize was higher than for wheat and barley, the production of maize is more sensitive to frosts and droughts than mixed cropping systems. This links to a higher climate vulnerability. Adding to these findings, our results further differentiate within the group of resource and income-constrained households. Among them, we identified households that managed the risk of harvest failure better by extending their agricultural production into diverse production zones, thus improving their food self-sufficiency. Overall, the Peruvian Altiplano compares to other dryland regions in which ancient cultures evolved based on a sophisticated management of natural resources, but whose current inhabitants are poor and rely on overused water resources, frequently in combination with degraded soils, such as in central Mexico and the Middle East (Sietz et al. 2011b, see Chap. 2 of this dissertation).

The vulnerability patterns describe typical combinations of household attributes that translate into specific sets of strategies for reducing vulnerability. Entry points here for overcoming cluster-specific constraints include interventions that concern both the household level, such as climate risk management or the building up of agricultural assets, and the context in which people live, including access to education and alternative livelihoods. The management of climate risks in this case is an essential area of intervention. It strongly relies on weather information, expected consequences and available livelihood alternatives. In the context of risk management, the application of weather forecasts to adjust agricultural management has been intensively discussed. Their potential to positively influence decision-making depends on technical, institutional and cultural conditions as well as their legitimacy and credibility (e.g. Howden et al. 2007, Patt et al. 2007, Dilling & Lemos 2011). Important aspects include their spatial and temporal resolution, accessibility, the lead times, communication of uncertainties, their specificity to the users' needs and the users' perceptions of risks and benefits.

In the Peruvian Altiplano, forecast information has scarcely been integrated into the agricultural decision-making of smallholders, partly due to a lack of comprehension and mistrust of governmental institutions (Sperling et al. 2008). The smallholders rely more on the observation of local indicators, for example plants, animals and stars. However, only the precise observation of the brightness of the Pleiades stars is recognised as being able to provide quite reliable results in predicting rainfall variability in extreme periods associated with El Niño events (Orlove et al. 2000). Therefore, an improved communication of forecast information would be essential for better management of climate risks. For example, continued participatory workshops with smallholders in Zimbabwe demonstrated that iterative interactions with potential users can provide significant benefits by jointly interpreting the weather forecasts and translating them into specific management decisions (Patt et al. 2005b).

The validation outlined in our study complements newer studies that test the consistency of indices of vulnerability against independent data sets of observed or perceived vulnerability outcomes (e.g. Alcamo et al. 2008, Krömker et al. 2008, Fekete 2009). Being the first iteration of the cluster approach to analyse climate vulnerability at the household level, the secondary data set already provides an opportunity for validation. In a future assessment, it would however ideally cover a greater share of households. By testing the approach under different livelihood conditions and climate exposure, further damage dimensions may come to be meaningful. Finally, in view of newly arising stresses related to a stronger market integration, the food security of smallholders who increasingly engage in cash-crop production, such as organic quinua, or off-farm activities should be further examined under the influence of multiple stress factors, including demand, price and wage fluctuations.

4 Smallholder agriculture in Northeast Brazil: Assessing heterogeneous human-environmental dynamics[3]

Abstract

A qualitative model of smallholder agriculture with a few core variables and two allocation rules for labour and investment in agricultural resources was developed to cover spatial heterogeneity in Northeast Brazil. This region is characterised by large natural and socio-economic variance, recurrent droughts and widespread rural poverty. The resulting system dynamics essentially consist of a cycle of four qualitative states, each depicting a typical pattern of trends in smallholder agriculture. Municipal statistical data were used to identify the spatial distribution of these patterns for the 1990s and the internal transition likelihood between subsequent states. Additionally, the influence of external perturbations like droughts and producer price shocks on the smallholder system was investigated.

4.1 Introduction

Processes leading to environmental changes observable on the regional, i.e. sub-national level are often embraced by global processes (e.g. climate change, economic globalisation) or affected by local processes (e.g. farming activities, traffic conditions). Studying regional environmental changes has to take into account the systematic complexity of global changes as well as the functional heterogeneity of the local processes (Turner et al. 1990, Wilbanks & Kates 1999). The latter describes that human-nature interactions on a local level vary over the regional scale. These variations are the result of natural as well as socio-economic variances within the region. Regarding regional development policies, sub-regional differences in both dimensions - natural and socio-economic - have to be considered appropriately.

The syndrome approach deals with regional heterogeneity of global change, thus addressing processes which are structurally similar on a more aggregate level (Schellnhuber et al. 1997, Petschel-Held et al. 1999). This approach classifies typical patterns of human-nature interactions on the regional scale using methods to indicate these patterns in a geographically explicit form (Lüdeke et al. 2004) or model their dynamics (Petschel-Held & Lüdeke 2001). The basic idea of considering systems on a structural level below the level of interest is applied here to the regional level in order to identify basic patterns of local human-nature interactions. A differentiated analysis of regional environmental change is carried out in the Northeast of Brazil.

Northeast Brazil is a classic and well-documented example of the nexus between environmental degradation and rural poverty. For example, Northeast Brazil is considered as a hotspot for the risk of further desertification (Eswaran et al. 1999) and water availability continues to worsen due to poor hygiene and salinisation (Voerkelius et al. 2003). In addition, the region is susceptible to decreasing annual precipitation in the course of global climate change (Gerstengarbe & Werner 2003). Therefore, Northeast Brazil is not only well-suited for studying heterogeneous environmental changes within a regional context, but is also in need of

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scientific support in developing appropriate strategies to reduce the pressure on environment and people.

Developing such strategies requires predicting of further development with and without potential interventions. In this regard, formal modelling is frequently used, but often criticised for its shortcomings in representing the heterogeneity of the subject particularly concerning coupled human-nature systems. High resolution data are often not available to parameterise the model relations, and hence spatial heterogeneity is inappropriately represented. To deal with this problem, a dynamic modelling method is applied to Northeast Brazil which allows the development of the human-nature system to be deduced from general qualitative assumptions about the interrelation of variables - similar to an influence diagram (Stave 2002). The generality of the model assumptions inherently covers the spatial heterogeneity in the region. After algorithmic deduction of all dynamic behaviours which result from the assumed influence diagram, the present state and possible futures of a particular spatial unit are identified using a small number of indicators. This procedure is less data-demanding than parameterising a full numerical model.

The study describes the natural and socio-economic setting in Northeast Brazil in the next section. It then presents the conceptual framework and describes the model assumptions for smallholder agriculture. The following section elaborates on the resulting time developments, identifies the recent dynamic behaviour of the municipios of three federal states in Northeast Brazil - Pernambuco, Ceará, Piauí - and discusses the effects of external shocks. The final section concludes with a summary and perspectives for future research.

4.2 Smallholder agriculture and major problems in Northeast Brazil

Northeast Brazil is traditionally sub-divided into four natural units: the Zona da Mata, the Agreste, the Sertão and the Campos Cerrados (Fig. 4.1). To cover the major smallholder-related development, this study focuses on a transect across these four natural units involving the three federal states Pernambuco, Ceará and Piauí.

The Zona da Mata - a formerly forested coastal area - is characterised by a high agropotential principally used for large-scale sugar-cane production (Heidemann 1981) and a subsequently high population density (Andrade de Oliveira 1999). A transition zone regarding natural as well as socio-economic conditions towards the Sertão forms the adjacent Agreste (Kohlhepp 1994). Small-scale and large-scale cattle farming dominate the valleys, whereas small-scale food cultivation is concentrated within the brejos (Heidemann 1981). In contrast, the most problematic area in Northeast Brazil, the less populated semi-arid hinterland - the Sertão - faces uncertain rainfall and non-periodic droughts (Gomes 2001, Da Silva 2002). Overall, agricultural land use in the Sertão is characterised by smallholder crop production and extensive livestock farming. In the west, the Sertão adjoins the fertile areas of the Campos Cerrados which are cultivated by small as well as large landholders. In the beginning of the 1980s, soy-bean production was introduced by large landholders from south Brazil to supply the global market (Andrade de Oliveira 1999, CEPRO 2003).

Among the major land use actors, smallholders form an important social group within the rural area of Northeast Brazil. Approximately 90% of all agricultural units are smaller than 100ha, but they cover together only about 30% of the total agricultural production area (IBGE 1996). Smallholders in Northeast Brazil produce about 70% of the food crops supplying the domestic market, which include maize, beans, manioc and rice. Moreover, they produce cash crops, such as cashew, cotton, fruits and vegetables, involving irrigation measures along the São Francisco River in the south of Pernambuco and the Jaguaribe River in the northeast of Ceará (Voth 2002).

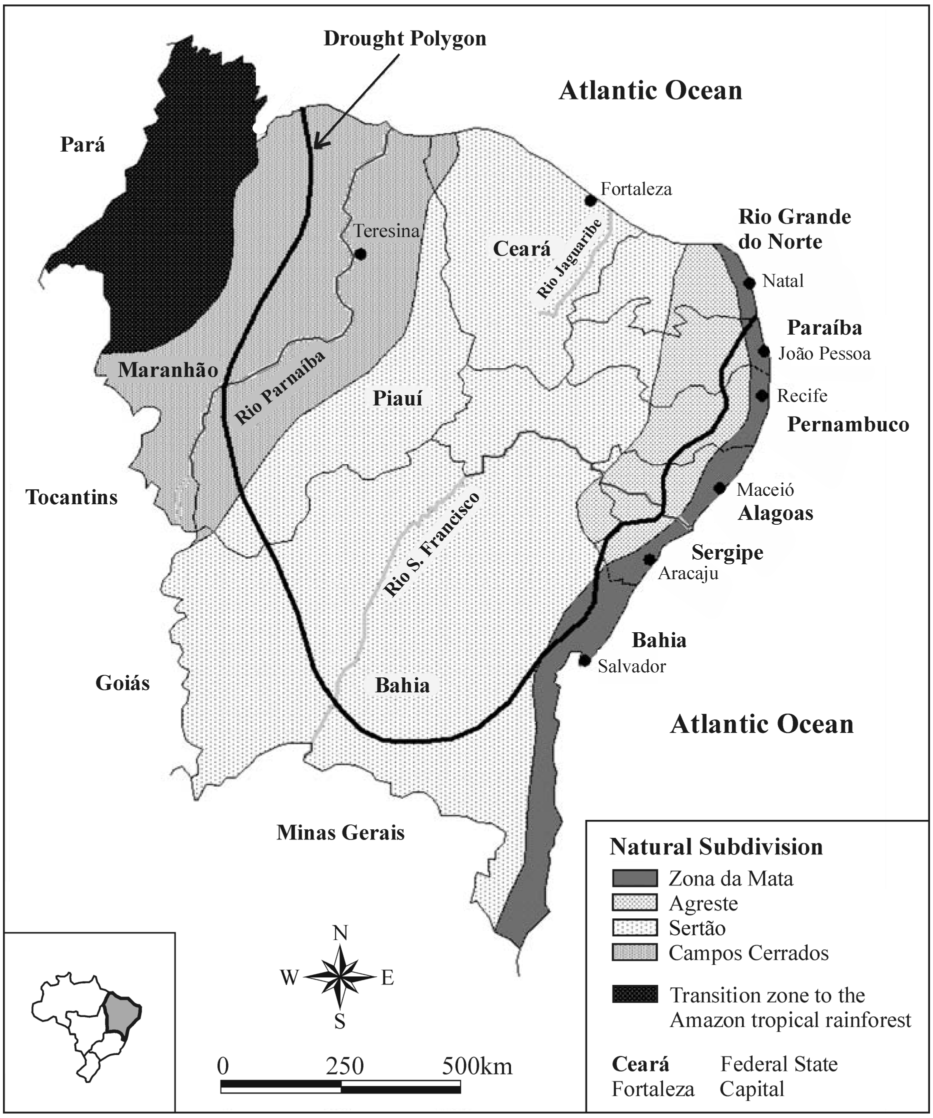

Figure 4.1 Natural sub-division of Northeast Brazil (Source: Rönick 1986)

The smallholders in the study region employ on-farm as well as off-farm livelihood strategies and therefore not only depend on the natural resources, but also on the socio-economic conditions. The limited access to productive land, water, infrastructure and markets caused by an inequitable distribution of resources tremendously limits the smallholders' agricultural production potential. Agricultural expansion into less favourable areas as a widespread livelihood strategy to maintain living standards however enforces pressure on natural resources and leads to further degradation, ultimately reducing agricultural yields (Gomes 2001). Furthermore, the transformation from the tenant-oriented into a rather wage-labour-oriented system throughout the region has detached many smallholders from their means of production

(Carvalho & Egler 2003: 25). Hence, local off-farm centres can play an important role in sustaining the smallholders' livelihoods by providing an additional source of income.

Within Brazil, the Northeast ranks highest among the regions suffering from severe rural poverty and out-migration. The unequal distribution of land, water and infrastructure, the lack of off-farm opportunities, the ongoing environmental degradation and recurrent droughts are the major underlying causes of stagnation and the decline of rural well-being (Mertins 1982, Carvalho & Egler 2003: 62). Increasingly aggravated rural conditions force many smallholders to migrate permanently to the regional and national urban centres in the Southeast and the Midwest of Brazil. Given this background, strategic decisions are crucial to foster rural development and improve rural livelihoods. Throughout the 1950s-1990s, vast efforts were made to reduce rural poverty and secure rural livelihoods. Within the various programmes, e.g. PROTERRA, POLONORTESTE, Projeto Sertanejo and PROHIDRO, land distributions, irrigation schemes, improved infrastructure, market integration and technical assistance were promoted as means of achieving poverty reduction. However, the schemes were neither effective nor efficient (Schwalbach 1993, Mertins 1997, Bezerra 2002: 41, Carvalho & Egler 2003: 19f.). Against the background of rural poverty and the serious environmental problems in Northeast Brazil, this study attempts to strengthen the poverty reduction debate.

4.3 Methodology

4.3.1 Conceptual framework

The phenomenon described above demands a modelling approach which couples environmental and socio-economic processes as well as their spatial heterogeneity. The model should be predictive in a well-defined manner as model-based reconstruction of observations is not an aim in itself, but a means for assessing potential future actions.

An important tradition in modelling smallholder households and their interactions with the resource base follows the line of economic optimisation approaches (Collins 1987, Barbier 1990, Barret 1991, Grepperud 1997). These approaches assume that the actors, i.e. the farmers, behave in such a way that the time integral over the discounted utility is maximised. This utility depends either directly on yield, in the case of purely subsistence-oriented farming, or on household income. The coupling with the resource base (e.g. soil quality) is realised by considering the influence of the farmers' actions on the resource and the feedback of the quality of the resource on the actual yield, for example. Whether the results of such a model are normative or descriptive with respect to the optimisation assumption is highly debated (Thaler 2000). Especially in developing countries where the conditions of economic activities change very rapidly, it can hardly be assumed that the actors will carry out long-lasting trial-and-error procedures to determine an optimal strategy. This is particularly the case if the success of a specific strategy can only be evaluated empirically after several years, for example considering resource conservation. Even if it is possible to fit such an optimisation model to the observed behaviour by parameter calibration, its predictive power would remain unclear. In contrast, the bounded rationality paradigm assumes a decision model which combines short-term optimisation and traditional rules (Jones 1999). In view of the discussion mentioned above, we therefore conclude that this descriptive approach is more appropriate to assess the human-environment dynamics in Northeast Brazil.

Current model approaches reflect the spatial heterogeneity of environmental and the socio-economic aspects very differently depending on the availability of data. Regarding natural resources, some models are based on spatially explicit data and relations close to natural science laws. On this basis, De Araújo et al. (2004) model the water availability in Northeast Brazil. Compared to this, modelling human actions is more complicated. Even in the most advanced models of smallholder agriculture based on optimisation (e.g. Holden & Shiferaw 2004) heterogeneity is poorly represented. This is due to both limited data and the normative assumption of inter-temporal optimisation as a basis for the description of the farmers' actions. The data limitation on socio-economic aspects becomes worse if the concept of bounded rationality is applied. As it relies much more on habits and traditional rules, it induces more heterogeneity than the hypothetical assumption of a utility-optimising farmer.

This study uses the bounded rationality approach by considering the rules in such a generalised way that the assumed spatial heterogeneity is covered. For this, the complex rules are reduced to their core which should mirror the whole investigated region. However, traditional mathematical methods cannot deal with such generalised rules because no explicit numerical functional dependencies can be developed. We thereby apply a new mathematical theory using qualitative differential equations (QDEs, see Kuipers 1994) to deduce possible time developments (trajectories) from rule systems that can be formulated in very general terms. The resulting trajectories consist mainly of sequences of trend combinations of the variables instead of numerical values. They typically contain branching points entering into different sequences that may be used to predict future developments. Compared to quantitative models, the results are solely deduced from generalised rules without adding partly uncertain information. Such methodological steps were firstly made in economic theory by discussing the properties of the equilibrium depending on the sign of the first partial derivatives of the functions used in the model (Varian 1984).

Although the resulting qualitative trajectories are deduced from qualitative assumptions on the relations between the variables, they can be validated by comparing them with the sequence of observed trend patterns. Additionally, the actual trend combination of variables in a given spatial or functional unit derived from appropriate data allows to define the initial qualitative state within the calculated trajectories. Hence, the following calculated sequences represent possible futures of the respective unit.

As different branches of development exist and the current position of a specific spatial or functional unit within the trajectories can be identified, the introduced method of qualitative modelling is closely linked to the syndrome approach (Schellnhuber et al. 2002). Branches of development which are either non-sustainable from the beginning or lead necessarily into a non-sustainable situation depict syndromatic developments. If the resulting trajectories include acceptable paths of development, the observed development should be influenced in a way that steers the system into an acceptable development branch in order to mitigate the syndrome.

This methodology is applied to model the decision-making process of smallholders in interaction with their resource base on the household level. It reflects the choice between different livelihood strategies. In the next section, the model will be described in detail.

4.3.2 Qualitative modelling of smallholder agriculture

The roots of the qualitative characterisation of the smallholder system in this study are the livelihood approach and the viewpoint of political ecology. The multitude of livelihood options from amongst which the actors can choose to mitigate adverse effects is stressed within the livelihood approach (DFID 2000), whereas political ecology encompasses structural pressures and the constantly shifting dialectic between society and natural resources within classes and societal groups (Blaikie & Brookfield 1987). Thus, model assumptions cover the allocation of labour force, the extraction of yields, the constitution of the budget as well as the dynamics of natural resources. As a first decision amongst different livelihood options, the smallholder has to allocate on-farm (l_y) and off-farm labour (l_w) as shown in Equation 1 (below). While for on-farm activities, the smallholder is the manager of his production resources, including soil, water and pastures, this is not the case for off-farm labour. The latter includes wage labour in the agricultural or other sectors, on a seasonal or annual basis. Labour time spent in the wage sector cannot be used for on-farm activities and vice versa:

$$l_t = l_y + l_w \qquad [1]$$

$$y = f(l_y, rq) \qquad [2]$$

with

$$\frac{\partial f}{\partial l_y} > 0$$

$$\frac{\partial f}{\partial rq} > 0$$

$$f(0,rq) = f(l_y,0) = 0$$

$$b = e_w * l_w + b_y \qquad [3]$$

with

$$b_y = y * e_p$$

$$b_w = l_w * e_w$$

where l_t: total labour available, y: yield, l_y: agricultural labour input, b: budget, l_w: off-farm labour input, b_y: on-farm budget share, rq: resource quality, b_w: off-farm budget share, e_w: effective wage per hour and e_p: effective producer price.

Besides the allocation of labour, the quality of the resources is a crucial production factor. Resource quality comprises both natural resources, such as soil fertility, water availability and quality of grassland, together with the climatic situation as well as technical resources, including technical equipment and irrigation technologies. The actual yield (y) is determined by the agricultural labour input (l_y) and the actual resource quality (rq) according to Equation 2. Multiplied with the effective price for agricultural produce (e_p) - involving producer output prices as well as access to markets and infrastructure conditions - the on-farm budget share (b_y) is constituted (Eq. 3). The total budget (b) of the household consists of both the income from the farming activities and the wage income. In practice, the wage income includes remittances by family members living in distant urban centres.

The qualitative structure of the smallholder system described so far has to be supplemented by hypotheses on the decision-making of the actors with respect to their choice of how to allocate the total labour available and how to reinvest parts of the budget obtained into the development of the resources. In line with evidence from Northeast Brazil (Mertins 1997: 7, CONDEPE 2001: 47), it is assumed that the labour allocation is governed by comparison of the labour productivity of on- and off-farm labour. This decision model is located between the strict inter-temporal optimisation approach and the cultural conservatism and thereby in the line of bounded rationality - a position corroborated by recent livelihood research (DFID 2000). To formalise the allocation rule, the actual value of agricultural income per agricultural labour input is compared with the wage per hour (Eq. 4). If the difference is positive, it is inferred that the wage labour share increases, otherwise it decreases. The opposite holds true for the development of on-farm labour. The effective price and the effective wage are assigned constant values owing to model constraints. However, the effects of changes in producer output prices are discussed in the section on external shocks.

$$\frac{dl_w}{dt} = e_w - e_p * \frac{y}{l_y} \qquad [4]$$

Aiming at sustainable resource use, the agricultural extraction needs to be compensated for by either natural regeneration or external measures. Without successful compensation, the resource base will degrade and reduce yield in the long term. This challenges the farmer to consider which part of the total budget will be reinvested in the maintenance of the resource base by, e.g. applying fertiliser or establishing erosion protection.

Therefore, the decision model for investment in resource improvement relates the budget (*b*) and the yield (*y*) - as indicator for the intensity of extraction - with the temporal change of the resource quality. The following general assumptions are made: the yield shows a threshold y_{ms} which reflects the maximum sustainable yield extraction without additional external inputs. Beyond this threshold, natural regeneration cannot balance the losses, i.e. without additional measures the resources will degrade. Concerning the budget, a threshold b_{ex} is supposed. Beyond b_{ex}, existential livelihood needs are fulfilled and investments in resource regeneration become possible (Fundaçao Getulio Vargas 2003, pers. comm.). Hence, a decrease in resource quality resulting from yield extraction exceeding the threshold y_{ms} may be compensated. Figure 4.2 shows the assumed trends of resource quality depending on all possible combinations of yield and budget. Thus, the investment decision is highly aggregate and does not explicitly cover other dimensions of decision-making, such as subjective priorities or knowledge.

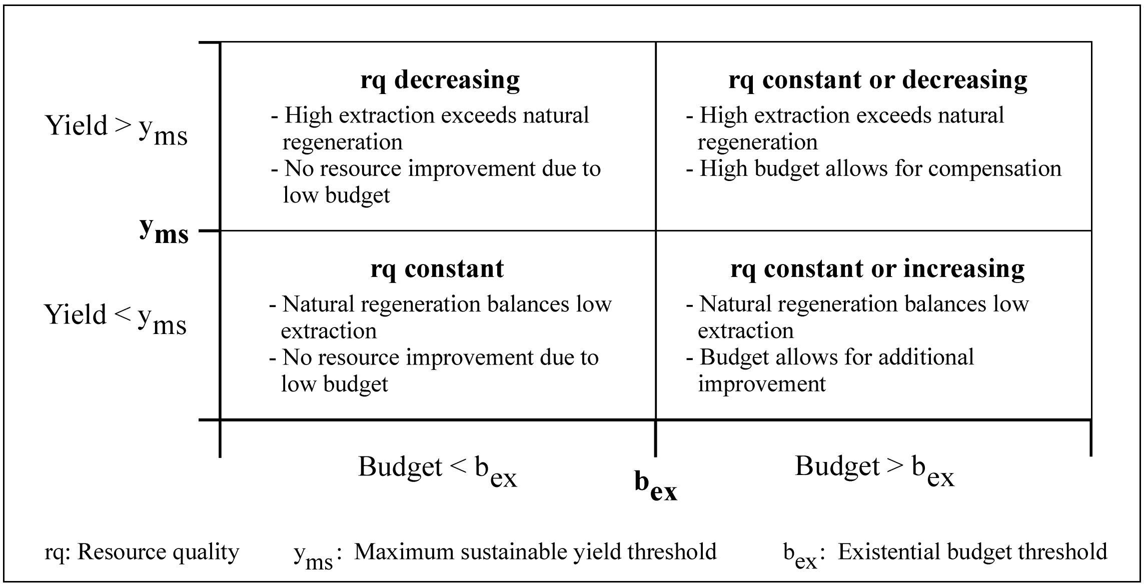

Figure 4.2 Model assumptions on resource quality (*rq*) trends depending on budget (*b*) and yield (*y*).

The above rules constitute a qualitative dynamic model of the smallholder system for the variables l_y, l_w, y, rq, e_p, e_w and b. It can be solved by using the QSIM algorithm (Kuipers 1994, Eisenack & Petschel-Held 2002) which computes the entire set of qualitative trajectories compatible with the model assumptions.

4.3.3 Spatial indication of smallholder dynamics

Due to available data, municipios were used as the smallest spatial unit to indicate the dynamics. Given the set of qualitative trajectories as presented in the following section, statistical data from the Instituto Brasileiro de Geografia e Estatística (IBGE) and the Instituto de Pesquisa Econômica Aplicada (IPEA) are used to indicate the qualitative state of the 591 municipios in the region for the years 1995-1999. As the model is based on household-level mechanisms, this choice implies the assumption of qualitative homogeneity of the smallholder households in a particular spatial unit. This is a weaker assumption than one had to make in the case of quantitative modelling. But in principle, it is also based on the concept of the "typical household". For the time being, initial steps have only been made to investigate the potential advantages of dynamic qualitative modelling with respect to the aggregation problem (Schellnhuber et al. 2002).

The calculated cyclic behaviour of the smallholder agriculture can be completely described by the trend combination of the two variables yield-oriented labour (l_y) and resource quality (rq) (see Fig. 4.3). While both trends show the same directions in States I and III, they are antipodal in the other States II and IV.

Statistical data for the years 1995-1999 are used to analyse the smallholder dynamics at the municipal level. This timescale takes the time horizon into account based on which smallholders take their decisions regarding labour allocation and investment as well as the natural processes of soil degradation and recovery (Pimentel et al. 1995, Brookfield & Stocking 1999). This subsection contains a basic description of data and analysis techniques used. Details concerning the indicators as well as the assessment of their uncertainties are provided in Appendix C.

The trends for *rq* and l_y are estimated for the years 1995-1999 based on the data listed in Table 4.1. The indicator for the yield-oriented labour l_y reflects the total amount of working hours per year devoted to agricultural activities in each municipio. The indicator is the sum of the contributions of six classes of agricultural activities to the total working hours. The six classes - cereal crops, roots and tubers, specialised crops, pastures, cattle and goats - differ with respect to their relative specific labour demand according to Andreae (1977). The trend for l_y between 1995 and 1999 is then computed via linear regression of annual data. The resource quality *rq* which encompasses both natural and technical components is reflected in the yield per hectare of cropland and the livestock density. Thus, the indicator for *rq* is constructed as the weighed average of the yield per hectare of all crops and livestock densities. Again, the trend for *rq* between 1995 and 1999 is determined via linear regression of annual data.

Table 4.1 Statistical data used. (PAM = Produção Agrícola Municipal, PPM = Produção Pecuaria Municipal, CAP = Censo Agropecuaria, CD = Censo Demográfico; Data sources: IBGE = Instituto Brasileiro de Geografia e Estatística, IPEA = Instituto de Pesquisa Econômica Aplicada)

Datum	Unit	Time resolution	Source
Harvest area for 62 crops	Hectare	1995-1999 (annual)	PAM (IBGE)
Yield for 62 crops	Tons	1995-1999 (annual)	PAM (IBGE)
Number of cattle and goats	Number	1995-1999 (annual)	PPM (IBGE)
Grassland: natural pastures and improved grassland	Hectare	1985, 1995	CAP (IPEA)
Farm size distribution (15 size classes)	Hectare/class	1995	CAP (IBGE)
Income distribution (16 income classes)	Capita/class	2000	CD (IBGE)
Share of rural population	Percent	1996	CD (IBGE)
People working in the primary sector	Number	1995	CAP (IBGE)

Besides indicating the qualitative states, the results of the qualitative modelling also allow quantifying the transition likelihood between the qualitative States II and III in the absence of external forces. The likelihood to leave State II grows with the share of smallholders whose income exceeds b_{ex}. The model results show that the system only passes from State II to III if the budget is above the existential level b_{ex} (this is not visible in Figure 4.3 due to the aggregation of states). The transition likelihood was indicated by the share of households in each municipio in which the head of household earns more than the existential budget. This corresponds to three times the minimum wage, i.e. reaching currently 500R$ per month (Fundaçao Getulio Vargas 2003, pers. comm.).

4.4 Results and discussion

4.4.1 Modelled qualitative smallholder dynamics

The model of smallholder agriculture in Northeast Brazil results in a number of trend combinations of the relevant variables (states) and the time evolution of the states (trajectories). The four presented states (Fig. 4.3) summarise closely related sub-states to highlight the main behaviour of the dynamic development. These sub-states are connected bi-directionally and therefore depict for example the oscillation of one variable, while the other trends are stable. Such a behaviour is symbolised by double arrows in Figure 4.3. In the following, these four summarised states are merely called states. The choice of colours in Figure 4.3 depicts the criticality of local conditions outlined below.

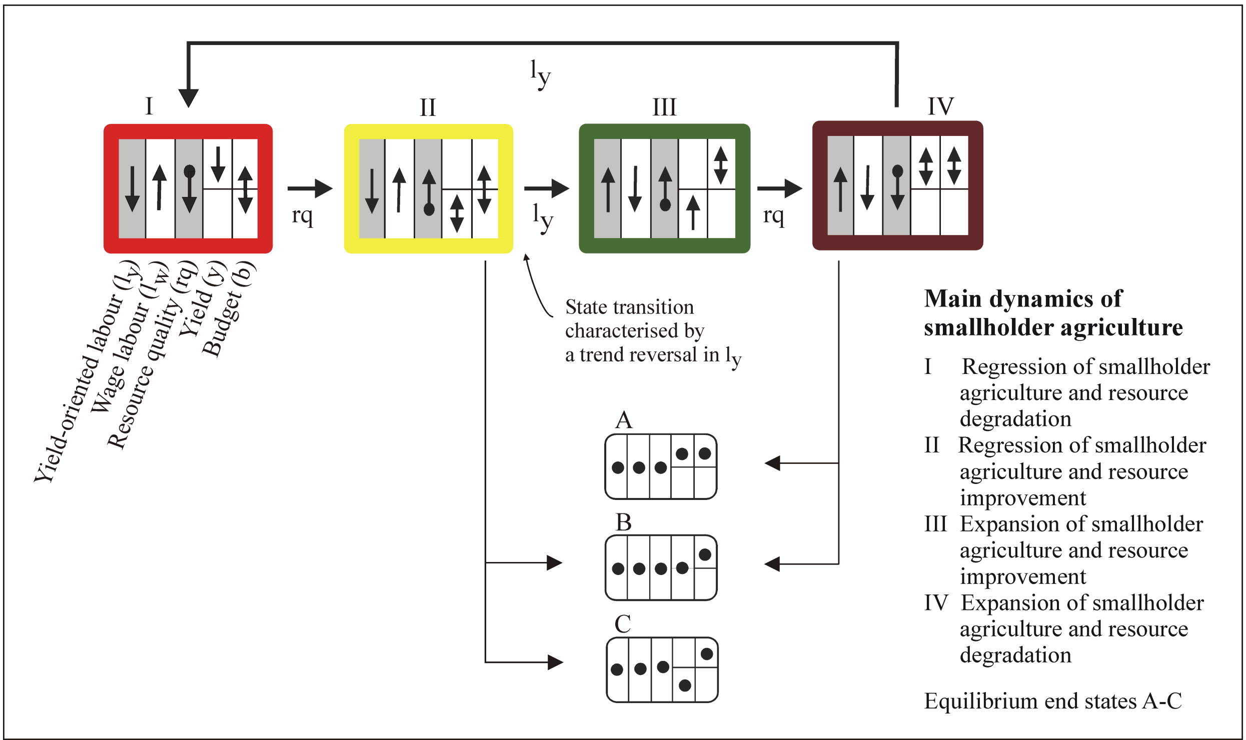

Figure 4.3 Modelled qualitative dynamics of smallholder agriculture with the five relevant variables. The boxes represent cycle states (I to IV) showing time evolutions - trends and magnitudes - of the variables. The colours reflect the criticality of local conditions. Trends are symbolised by arrows. In the case of yield and budget, their position refers to landmarks indicating their magnitude. Dots indicate that the variable is constant over time. In addition, the trend combinations of l_y and *rq* are shaded in grey. The model results include final equilibrium states (A to C). However, within the context of highly dynamic land use changes in Northeast Brazil, equilibrium states are of little practical relevance and are therefore not considered in the following discussion.

In view of smallholders' livelihoods, State I displays the most critical conditions. As socio-economic stress is reflected by an undetermined budget that can drop below the existential threshold, the smallholders' investments in resources are uncertain. Based on the syndrome approach (Schellnhuber et al. 2002), State I can therefore be interpreted as the syndromatic part of the trajectory. In contrast, State III depicts an environmentally and socio-economically desirable situation as resources may improve and the smallholders' budget is secured at a level higher than the existential budget. Still critical are States II and IV. While in State II resources may improve if compensation takes place, in State IV investments may only prevent the degradation without improving the resources. It follows a model-oriented analysis of the cycle including references to recent local developments, whereby special aspects of the states are particularly highlighted.

State I: Regression of smallholder agriculture and resource degradation. Even though the smallholders' on-farm activities are regressing (l_y↓), the production intensity is not adapted to the current local agropotential (yield > y_{ms}). If the budget is below the existential minimum (budget < b_{ex}), the resource quality is inevitably deteriorating (rq↓). Thereby, the degradation of resources reflects a deteriorating base of natural as well as technical assets. It thus reflects the damage to soils, water and vegetation, but also the divestiture of technical equipment or infrastructure. Only if the budget exceeds the existential level, further damage to resources can be prevented ($drq/dt = 0$). In this case, smallholders can invest part of their budget and are hence able to compensate for the overuse.

Unequal land distribution with limited access to productive lands and water in Northeast Brazil can be translated as a low level of maximum sustainable yield and consequently a high risk of overuse. Due to the resulting resource degradation, the agricultural activities become overall less profitable, so that smallholders tend to allocate their labour force rather to off-farm activities. The search for rewarding employment is often reflected in massive rural out-migration.

State II: Regression of smallholder agriculture and resource improvement. The production level is well adapted to the current local conditions (yield < y_{ms}). This can be the result of a low level of agricultural activity (low l_y) or efficient and resource-improving production techniques (high y_{ms}). Hence, the resource quality is at least stabilised ($drq/dt = 0$). An improvement of the resources can be achieved if the budget is above the existential threshold, so that smallholders can invest in the resources.

State III: Expansion of smallholder agriculture and resource improvement. State III shows increasing on-farm labour (l_y↑) and a budget above the existential threshold (budget > b_{ex}). Despite growing agricultural activities, the yield extraction stays below the maximum sustainable level (yield < y_{ms}). It hence creates the necessary precondition for the resources to improve. Efficient soil and water management techniques help to keep the production level below the maximum sustainable yield.

State IV: Expansion of smallholder agriculture and resource degradation. The expanding agricultural yield exceeds the local production potential (yield > y_{ms}). Thus, resource degradation can only be prevented if the smallholder invests part of his budget in resource conservation. A successful investment however presupposes knowledge about adequate conservation technologies. This may be hindered by eroding traditional knowledge as well as lacking access to information and extension services.

Transitions from one state to another can be crucial in terms of environmental and socio-economic well-being. Below, possible transitions and necessary preconditions are first discussed from the internal model perspective and then from the external viewpoint of intervention strategies. The transitions are basically characterised by changes in the *resource quality* and *labour allocation* (Fig. 4.3).

The passage from State I to II is characterised by the improvement of the *resource quality* as a result of decreasing yield extraction below y_{ms}. In contrast, the reverse applies to the transition from State III to IV. From a strategic perspective which seeks to secure rural livelihoods, this would mean concentrating efforts on maintaining or achieving yield extraction below a sustainable level (yield < y_{ms}) in order to combat resource degradation. However, this requires careful consideration of how to implement innovations, e.g. new production methods. If for example the land is not irrigated appropriately, severe damage, such as soil erosion, nutrient leaching and salinisation, is likely to occur. This may result in a declining quality of natural resources ($rq\downarrow$) and a potential overuse of the soils (yield > y_{ms}). Therefore, the transition from State III to IV is ultimately forced.

Changes in *labour allocation* indicate the transitions in the critical State I as well as to the desirable State III. The transition from State IV to I shows that, due to high yield extraction (yield > y_{ms}) and - without appropriate investment - degrading resources ($rq\downarrow$), yield-oriented labour is less profitable. It will successively be replaced by increasing off-farm labour. The reverse is true for the transition from State II to III. Indeed, the latter passage only takes place if the budget reaches a level above the existential threshold in State II.

In order to leave State II and support State IV, the ultimate goal is to make yield-oriented labour more attractive than off-farm activities and to create suitable grounds to maintain socio-economic well-being (budget > b_{ex}). However, the flanking measure to raise well-paid off-farm opportunities in order to sustain the families' livelihood may induce higher incomes which create suitable conditions to invest in their own resources (State II). This results in improving resource quality, which bears a great potential that on-farm labour will become more attractive and smallholders will allocate more labour to agricultural production. Hence, the transition from State II to III is accelerated.

Options to validate the model are narrow as few case studies cover a time period which allows to observe sequences of trend combinations of the model variables. However, combined with interviews performed in the study region, they provide insights which support the model results. Farmers in three development projects along the São Francisco River described environmental and socio-economic conditions which correspond to the modelled dynamics. 23-50% of the farmers reported specific trend combinations and transitions of model variables occurring in the 1980s and 1990s (Untied 2004, pers. comm.).

Ten out of 35 farmers in the project Bebedouro/Petrolina and five out of ten farmers in the project Apolônio Sales/Itaparica mentioned an inappropriate irrigation system which resulted in the salinisation of soils. The ultimately declining yields forced farmers to increase their off-farm activities, which reflects the behaviour of State I. After credits had been issued, the irrigation system could be enhanced and thus the resource quality improved (transition from State I to II). Subsequently, agricultural labour became more profitable and increased (transition from State II to III).

The transition from State III to IV was demonstrated in the project Nilo Coelho/Petrolina. Three out of eleven farmers described trends of amplified agricultural labour input and enhanced soil quality which were successively inverted due to inappropriate production techniques and lack of a drainage system. They emphasised the risk that resources could further decline and would be overused if no investment took place. This may imply that agricultural labour would be less profitable and might be reduced in favour of off-farm earning activities (transition from State IV to I). The statements of the farmers not cited here neither contradicted nor corroborated the modelled dynamics.

Another way to validate the modelled dynamics and thereby the underlying model assumptions would be to use quantitative time series of the variables. However, the statistical data obtained from IBGE and IPEA appeared to be too noisy to extract significant trend changes of the variables. These data still allowed us to identify the trends of relevant variables for the years 1995-1999. Indeed, this is less a validation than the identification of the actual dynamical state of the system.

4.4.2 Spatial distribution of smallholder dynamics

The spatial distribution of the four qualitative States I to IV (see Fig. 4.3) was investigated on the municipal level for the three federal states Pernambuco, Ceará and Piauí. The indication of trends is afflicted with uncertainty as the data on agricultural activities cover all farm sizes, but only the smallholder sector is of interest. Overall, decreasing on-farm activities in combination with an undetermined trend in resource quality (States I and II, resp.) are widespread (Fig. 4.4). Their predominance confirms the critical development of rural poverty and out-migration in Northeast Brazil.

Municipios within the critical State I can be found throughout the Sertão and Agreste as well as in northern Piauí and Ceará. Representatives of State II are located in the northern parts of Piauí, dispersed areas of Ceará and central parts of Pernambuco. Municipios showing the desirable State III are concentrated in Ceará, whereas State IV occurs predominantly in northwestern Pernambuco, southern Ceará and southeastern Piauí.

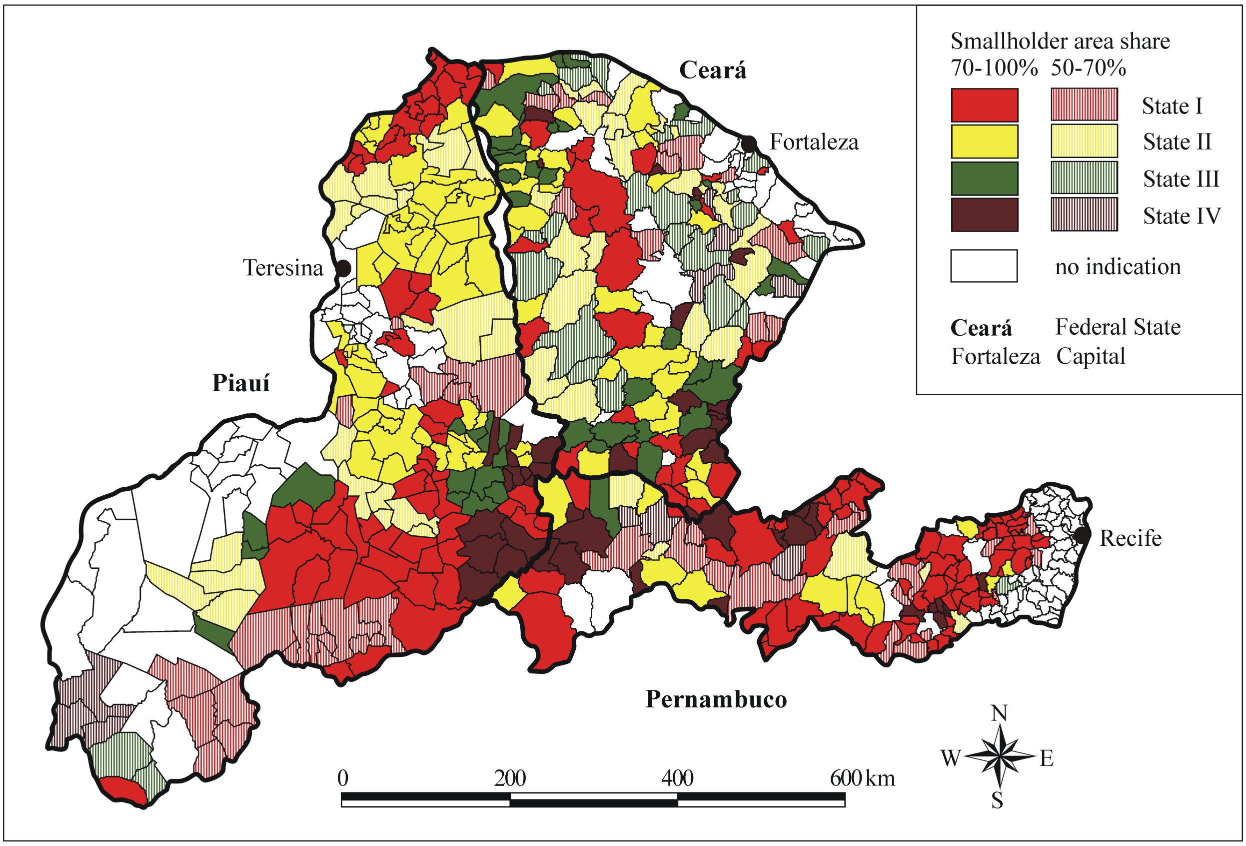

Figure 4.4 Spatial distribution of the four qualitative states at the municipal level for the three federal states Pernambuco, Ceará and Piauí. Trends refer to the years 1995-1999. The filled areas are characterised by a very high area share of smallholders (70-100%), the hatched ones by a high share of smallholders (50-70%). No indication was possible in areas dominated by large landholders or in mainly urban areas.

The uncertainty associated with the largeholder share is represented by the hatching in Figure 4.4. The lower the smallholder area share, the more uncertain is the indication. Regions with a very high smallholder area share (70-100%) are mainly situated in the more elevated areas (chapadas, brejos) in the Agreste and west Pernambuco, north and south Ceará and in southeast Piauí. Against this, regions with a high smallholder area share (50-70%) dominate in central Ceará and southwest Piauí. Modernised and capital-intensive agriculture, such as sugar-cane production in the Zona da Mata in Pernambuco, cashew production in the eastern part of the coastal zone of Ceará and soy-bean production in southwest Piauí, is characterised by a small share of smallholders and could therefore not be reliably indicated. No correlation was found between the qualitative state of a municipio and its uncertainty. In the remainder of this subsection, the calculated spatial distribution of smallholder dynamics is validated against case studies.

The major trends of State I are the decreasing yield-oriented labour and resource quality. Due to high population density and overuse in the Agreste and some parts of the Sertão, like the northern part of Pernambuco, degrading resources are highly probable. This corresponds to local information on high degrees of degradation (Lemos 2001, Instituto Desert 2003). Marginalisation as reflected in shortened fallow periods as well as the cultivation of steep slopes and drought-prone lands was highlighted as causing land degradation and declining yields (Mutter 1991: 368, Mertins 1997). Less profitable yield extraction and the subsequent decrease of on-farm activities are reflected in the observed patterns of rural out-migration throughout the Sertão and Agreste during the 1990s. Besides marginalisation, concentration of landholdings and unfavourable working conditions for smallholders, Häussler (1996: 24) further identifies lack of governmental services within the health care and nutrition sectors as driving migration forces in the Sertão region.

Major areas of rising off-farm labour and potentially increasing resource quality (State II) are located in the Sertão region. When the budget remains above the existential threshold and the smallholders are willing to invest in their resources, less pressure is put on soil and water. Hence, the resources can recover. Spatial examples for locally rising off-farm opportunities, as an option of income generation, are linked with emerging processing industries, such as agro-industrial complexes, gypsum mining in west Pernambuco (Mutter 1991: 367, Andrade de Oliveira 1999: 80), textile production in the Sertão of Piauí (Rheker 1989) and ceramic manufacture in northwest Piauí (Olimpio 2000: 89).

Expanding smallholder agriculture and rural well-being as characteristic of State III can be found in areas with a high natural agropotential, such as throughout Ceará. Apart from these naturally productive areas, irrigation measures (BNB 2000) along the Jaguaribe River in east Ceará and small dams (açudes) have supported production growth (Damiani 1999: 145, Elias 2002). Thus, yield-oriented labour is likely to increase as it becomes more profitable.

A decreasing or constant resource quality as shown in State IV is mainly calculated for the Sertão region and north Ceará. However, even though the smallholders' budget exceeds the existential threshold, it may not be invested because of other priorities or a lack of knowledge. There are areas where the impacts of mechanisation and application of agro-chemicals become obvious. Within the large irrigation perimeters of modern agriculture, crucial salinisation results from inappropriate irrigation measures and missing drainage systems (Instituto Desert 2003: 12). Under these conditions, failed extension services may even accelerate resource degradation.

From the model perspective, transitions only proceed under specific conditions related to the magnitudes and trends of some variables. Due to limited data availability, only the transition from State II to III can be indicated with sufficient reliability and will therefore be discussed in the following. Figure 4.5 shows the mean share of households in which the head of household earns more than the existential budget threshold, i.e. currently 500R$ per month. It can be used to indicate the transition likelihood for each municipio in State II. This indication is afflicted with uncertainty as the statistical data cover the income distribution of the total population, but only the smallholder sector is of interest.

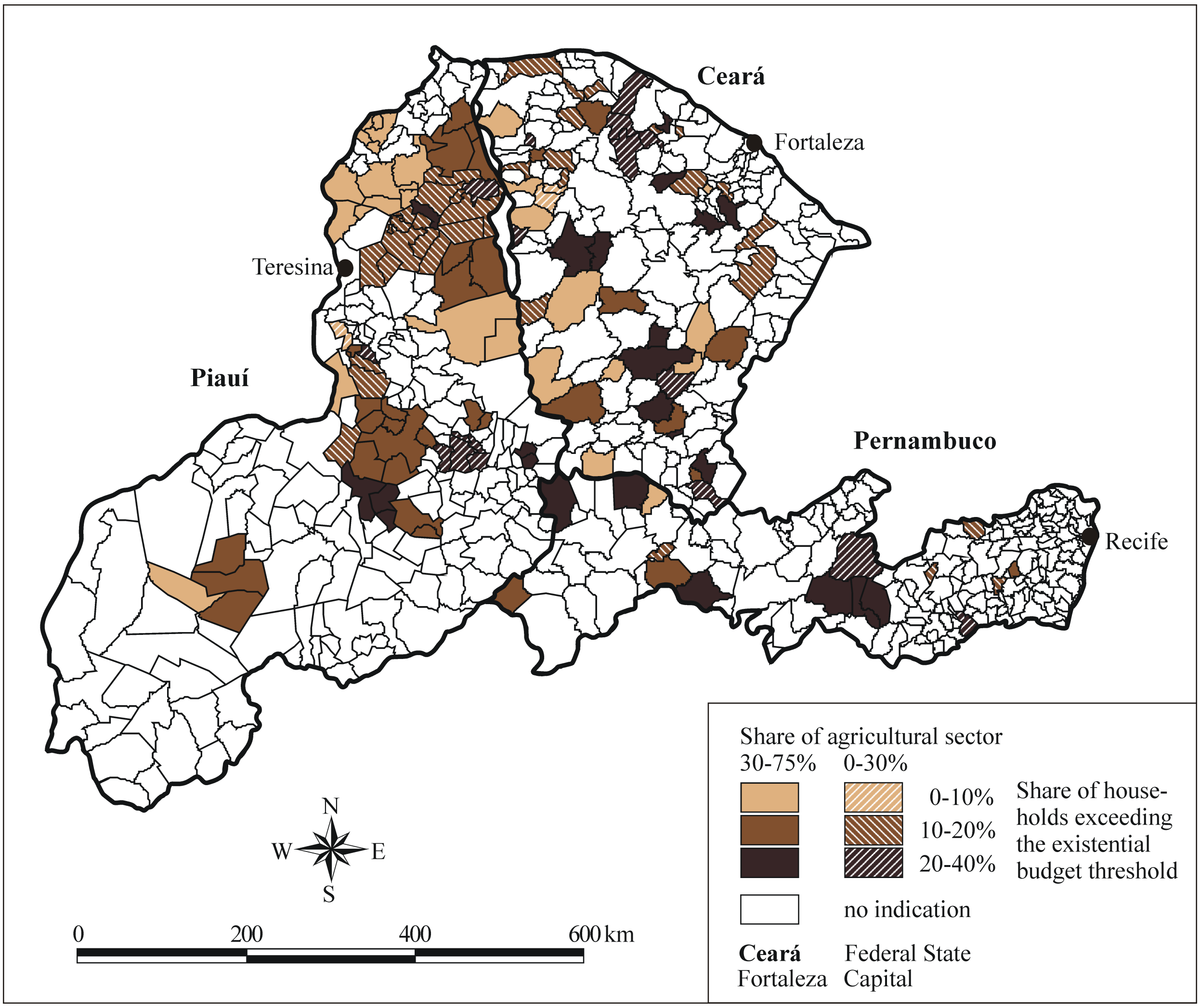

Figure 4.5 Spatial distribution of the transition likelihood from State II to III as indicated by the share of households in which the wage of the head of household exceeds the existential budget threshold. The indication of State II is based on trends of the years 1995-1999, budget data refer to the year 2000. The share of agricultural sector is the proportion of labourers in the primary sector (1996) within the total population. It serves as a measure for the uncertainty of the indication.

As Figure 4.5 shows, the share of households in which the head of household earns more than the existential budget threshold does not exceed 40% in the municipios of State II. The majority of the municipios depict a share of below 20%. Therefore, the internal transition likelihood from State II to III throughout Northeast Brazil is rather low. The preconditions for the transition are more favourable in Pernambuco and Ceará as a higher share of heads of households dispose of the existential budget (20-40%). In this regard, regions which offer better off-farm opportunities for generating income have a higher transition likelihood. Relevant municipios are located south of the Jaguaribe River in east Ceará, in the gypsum mining areas of northwest Pernambuco and close to the textile production areas of central Piauí. In contrast, the transition likelihood in the Sertão of Piauí and the western parts of Ceará is distinctly lower with less than 20% of household above the existential budget threshold.

The hatching in Figure 4.5 represents the uncertainty of the indicated transition likelihood: the higher the share of agricultural sector, the more certain the indication. Regions with a high share of the agricultural sector are mainly situated in west Pernambuco, south Ceará and large parts of Piauí. A lower share of the agricultural sector dominates in the northern parts of Ceará and Piauí.

4.4.3 External shocks

The model presented only captures the internal dynamics of smallholder agriculture in Northeast Brazil. External shocks, such as weather extremes and market fluctuations, will be discussed as exogenous perturbations to the model in three ways.

Changes in the absolute value or the trend of a qualitative variable. For example, a massive drop in producer output prices induces a switch in the relative attractiveness of agricultural versus off-farm labour within the model. The drop thus depicts a switch in the present labour trends from increasing agricultural work to increasing off-farm employment. However, changes which are reflected in the qualitative values have to be distinguished from those which do not imply a change in the qualitative value, even though affecting the system. An example of the latter would be a minor drop in prices without making off-farm labour more attractive than agricultural labour.

Changes in the real-world values of landmark values. The landmark value b_{ex} of the budget variable is defined as the particular income above which farmers would start to invest in their resources. Educational programmes to improve knowledge or decreasing investment prices for the means of new agricultural practices would make new conservation methods more accessible to the farmers. The model would reflect this by a decrease in the real-world value of b_{ex}. Thus, a budget below the landmark value might increase above it, so that farmers might start to invest without an actual increase in their budget.

Changes of the model structure. If qualitative relations are affected, they have to be adapted in order to retain the model's validity. A development programme which provides for example production techniques to improve the resources to those farmers who dispose of a budget below the existential threshold alters the respective model relations. In fact, the farmers were not able to invest in and improve their resources. However, this is not examined. Its consideration is shifted to further research.

In operational terms, the first two types of changes have the same effect. On the one hand, they induce leaps of variables to new qualitative states. These leaps then lead to changes in other, not directly affected variables according to the model relations. On the other hand, the change might not lead to a qualitative change of a variable, but can well put it at a greater distance to a relevant landmark value.

Important implications of two major shocks to smallholder systems in the region are further discussed: droughts - here considered as exceptionally low precipitation - and a drop in producer output prices.

Droughts. A drought has a direct effect on those variables in the model which encompass natural properties of the smallholder agricultural system, i.e. yield and resource quality. As the variable resource quality basically describes the long-term productivity of soils or vegetation, it is assumed that it is not directly affected by a short-term lack of rain. Thus, the effects of a drought are assessed by considering the yield only. Droughts affect the agricultural system in two ways: firstly, it directly reduces the yield and secondly, it may lower the maximum sustainable yield by increasing the susceptibility to degradation. Hence, a drought may force the yield above or below the maximum sustainable level, independent of whether it was above or below this level before. Furthermore, decreasing yields imply that agricultural labour becomes less attractive than before, and thus a trend of decreasing agricultural labour will not be reversed by a drought. Conversely, a trend of increasing l_y might turn around. But if yields are limited, loss still continues. Hence, the effects of a drought which changes the variables and trends are described with regard to the four possible model states in Figure 4.6 (see dotted lines).

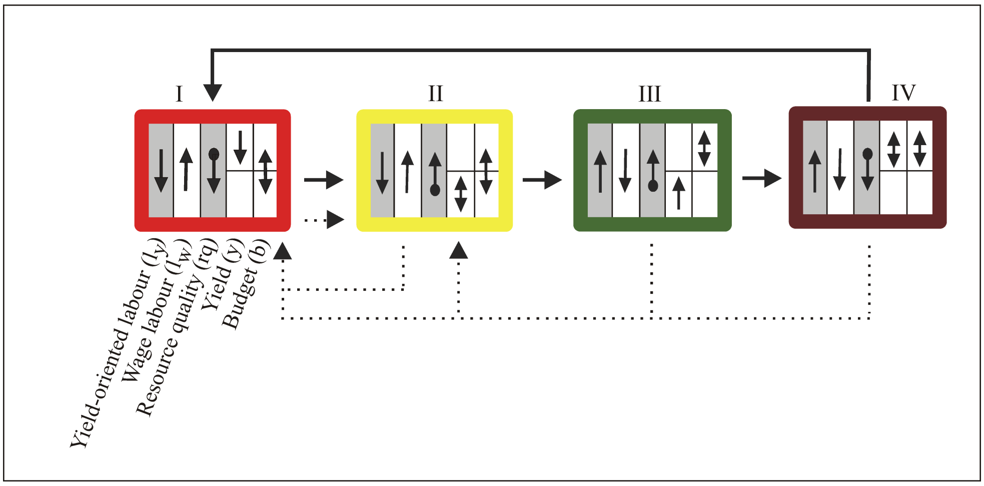

Figure 4.6 Possible state transitions and leaps due to a massive drought (dotted lines).

According to Figure 4.6, a drought induces state transitions or leaps to State I or II, independent of the original state. Thereby, the new state which is reached after a transition or leap depends on the relative reduction of the yield and the landmark y_{ms}. If the yield shifts from above to below the maximum sustainable yield and the wage labour expands, the system actually shifts to State II.

Drop in producer output prices. Falling producer output prices eventually result in less attractive agricultural labour. Thus, massive drops imply a reversal of increasing agricultural labour, whereas a decreasing trend will continue. Figure 4.7 shows possible transitions and leaps. If the system was hit by the price drop while being in States IV and III, it would move to the more critical States I and II, respectively. While the transition from State III to II is not possible from the endogenous model dynamics, the evolution from State IV to I has its endogenous analogue. Thus, this transition is accelerated by the price drop.

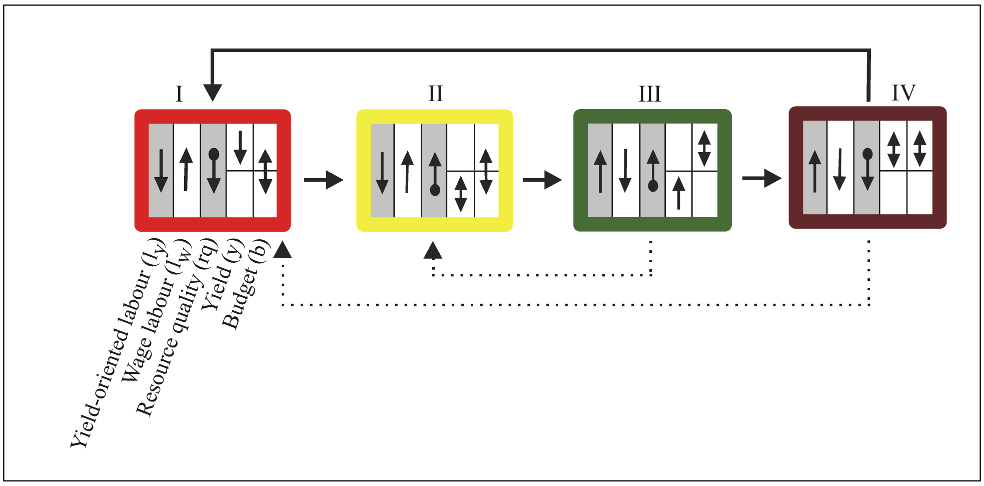

Figure 4.7 Possible state transitions and leaps due to a drop in producer output prices (dotted lines).

The analysis of droughts and price drops shows that both shocks favour the critical States I and II. Given the prevalence of droughts and price fluctuations in Northeast Brazil, it is an important reason for the dominance of these two states in Figure 4.4.

4.5 Summary and conclusions

A short introductory review of the role of smallholders in the Northeast Brazilian land-use system revealed their marginalisation in ecological, economic and social terms. It further motivated the closer inspection of this sector as an important contributor to the region's severe development problems. This socio-economic segment is characterised by a large heterogeneity as regards the natural conditions for farming and the farmer's decisions. After a short characterisation of mainstream model approaches for smallholder agriculture, an alternative method based on QDEs was introduced to handle this heterogeneity by subsuming it under general rules. These are close to a qualitative mental map of the smallholder system in the sense of an influence diagram. The allocation of labour between on-farm and off-farm work as well as the investment in resource conservation and improvement were chosen as relevant smallholder decisions. Furthermore, well-established general rules for the resource dynamics were added. Via the QDE algorithm, this mental map generated a specific cycle of four qualitative states depicting the development of the relevant variables, including labour allocation, resource quality, yield and budget. These states and the transitions between them could be interpreted in real-world terms and ranked with respect to their acceptability from highly problematic (State I) to desirable (State III). Case studies and interviews performed in the study region provided insights that support the modelled behaviour of the smallholder systems. Furthermore, the spatial distribution of the four qualitative states was identified on the basis of indicators on municipio level in the time period 1995-1999. This spatial distribution was compared with available case studies and appeared to be plausible. A theoretical, model-based assessment of external shocks comprising drought and drop of producer output prices was performed. It revealed that both types of shock - which occur frequently in Northeast Brazil - favour the critical States I and II, thereby contributing to the recent widespread prevalence of these states.

We have shown in this study how to proceed from a qualitative mental map of relevant mechanisms in smallholder agriculture to a data-based map of the actual spatial distribution of specific development states. Such a result bears the potential to assess spatially explicit policy interventions. Depending on the normative judgement of the actual development state and that of the successor as predicted by the model, the transition has to be either fostered or impeded. Potential policy interventions can then be translated into the model language, particularly how they influence the model variables and possible transitions. In order to perform such an analysis, three major constraints have to be overcome. First, after the comparison of the model results with empirical evidence as done here, a rigorous validation is needed presupposing sufficient data availability. Second, with regard to livelihood options, further model modifications, including the role of credits, paternalism and social networks, has to be addressed in order to open up the discussion of policy strategies. Third, changes in prices for agricultural commodities and wages have to be considered explicitly to better capture the Northeast Brazilian conditions. Further model refinement is planned to eliminate these shortcomings. However, it was illustrated how a policy analysis works on the basis of qualitative dynamic modelling and what its advantages are. Conclusions are based on the structural knowledge of the processes instead of their specific parameterisation which is hard to obtain with the necessary resolution and coverage.

With respect to the syndrome approach, the model gives an example of the trajectory-based definition of syndromes. Here, the paradigmatic case is the branching of a trajectory into a sustainable and a non-sustainable, “syndromatic” path (Schellnhuber et al. 2002). The modelled cyclic trajectory slightly differs from this branching with alternating sustainable and non-sustainable paths. It results in policy objectives which either support the transition to leave or hinder from joining the syndromatic part of the trajectory. Figure 4.4 presents an example of the dynamic, trajectory-oriented indication of the spatial distribution of a syndrome. This case refers to the Sahel Syndrome, for which the global distribution with less functional and spatial resolution is described by Petschel-Held et al. (1999) and Lüdeke et al. (2004). Here, the dynamic indication bridges the syndrome and the dynamic vulnerability concept. Being close to a critical branching point where the system may enter the syndromatic path translates into a high vulnerability of the system to exposures to which the system is sensitive.

5 Discussion of results with regard to the research questions

5.1 How do we identify typical patterns in the natural and socio-economic properties of dryland systems in order to enhance our understanding of their vulnerability to climate, market and other stresses?

This dissertation applies a pattern recognition approach to analysing dryland vulnerability. The following sections outline the prerequisites for recognising typical combinations of natural and socio-economic properties that shape the vulnerability of dryland systems to climate, market and other stresses. The experience gained from the vulnerability studies at the global and local levels (see Chaps. 2 and 3) illustrate the overall approach.

5.1.1 Vulnerability-creating mechanisms

The initial step in the pattern recognition approach is the systematic elicitation of knowledge about how vulnerability to particular stresses evolves in dryland systems. This knowledge elicitation involves collecting suitable information, analysing it for recurring processes and synthesising these processes into a comprehensive set of mechanisms that explain dryland vulnerability. The approach applies fundamental steps of grounded theory research - a qualitative approach for developing conceptual frameworks or theories (Glaser & Strauss 1967). The grounded methodology is suitable owing to its independence of any particular vulnerability framework. Moreover, it allows the integration of qualitative and quantitative information (Glaser 1978).

An information base about dryland vulnerability was compiled by means of both a structured review of case studies and meta-analyses as well as by utilising expert and stakeholder knowledge. As a start, I searched for peer-reviewed lead articles in the field of dryland vulnerability by conducting a combined keyword search for “vulnerability AND dryland” and “vulnerability AND arid” in the Scopus and Web of Knowledge databases. Particular processes and components of vulnerability discussed in these articles provided more specific keywords to refine the broad initial search. These comprised:

- *Stresses*: climate, drought, economic change, environmental change, global change, globalisation, growth, hazard, liberalisation, market, migration, perturbation, risk, stress, trade, urbanisation, variability and weather extreme;
- *Outcomes*: conflicts, degradation, desertification, disaster, disease, emigration, failure, famine, health, hunger, in/security, mal/nutrition, poverty, scarcity and water stress as well as
- *Components of vulnerability*: adaptation, adaptive, capacity, coping, response, sensitivity and strategy.

Through this search, I identified articles that include local to global analyses of socio-ecological systems or important components of them concerning a multitude of stress factors as well as vulnerability dimensions and outcomes.

In addition, consultations with regional experts and decision-makers for the Fourth Global Environmental Outlook (GEO-4) informed the study of global dryland vulnerability given in Chapter 2. These yielded multiple interlinkages between environmental processes and human development suitable for distinguishing the Dryland Archetype from other global archetypes of vulnerability (Jäger et al. 2007). The necessarily broad mechanisms defining the Dryland Archetype served as initial cause-effect hypotheses and were incorporated in the following procedure.

The collected information encompasses both general instances and particularly illuminating examples to achieve a comprehensive perspective on dryland vulnerability rather than a statistical generalisation. The included case studies and knowledge provided by experts and stakeholders depict conditions under which a certain process is observed rather than addressing the likelihood or frequency of such a process occurring. This information base was systematically analysed, so as to extract relevant processes and contextual conditions constituting diverse facets of dryland vulnerability. In this process, I coded emergent themes and then grouped them into classes of similar causes, feedbacks or outcomes of vulnerability. Finally, I integrated major classes into vulnerability dimensions and defined their cause-effect relationships.

The formulation of cause-effect hypotheses followed heuristic principles by sampling cases that broaden the scope of previously gained knowledge. It seeks to balance the efforts to integrate all the mechanisms observed with the necessary richness and specificity of detail in the hypotheses. Applying hermeneutic analysis, I explored context-specific meanings and the relation between the findings. Due to its focus on meanings and their connections, the hermeneutic methodology is consistent with the grounded theory approach. Altogether, the conceptual emergence driving the sampling is a suitable starting point since the purpose of this methodological step is to build hypotheses, not to test them. The course of analysis reveals the appropriateness of the hypotheses extracted. The hypotheses are adequate when the identified indicator combinations given by the cluster centres are interpretable in the light of the mechanisms elicited.

The formulation process involved constant comparison by interpreting new information in the light of knowledge generated from former cases and vice versa. It moved towards a saturation of the hypotheses (Glaser & Strauss 1967). Saturation was achieved when the main concerns of dryland vulnerability were accounted for, so that an inclusion of further information would not have significantly extended the vulnerability dimensions extracted, along with their connections.

In absence of appropriate peer-reviewed case studies in the Peruvian Altiplano, the local study (see Chap. 3) considered insights from comprehensive community assessments (Sperling et al. 2008), conducted partly in the investigated region, as working hypotheses. The local study focuses upon the vulnerability of smallholder systems that are exposed to weather extremes and examines its implications for smallholders' food security. The community assessments provide suitable insights for this study since they involved focused discussions with smallholders who have to deal with extreme weather events and who engage in climate risk management. In particular, they reveal the smallholders' perceptions of the exposure and sensitivity of their agricultural systems to climate stress as well as their capacity for dealing with it. The underlying processes refer to locally specific aspects of smallholder livelihoods, such as the harvest failure risk and availability of alternative livelihood opportunities.

The resulting vulnerability-creating mechanisms are explicitly outlined (see Sects. 2.2 and 3.4.1) to ensure transparency since vulnerability is not directly observable and a multitude of frameworks exist to explain it. On the one hand, the global study lays out the complete functional space in which vulnerability to a set of environmental and socio-economic stresses unfolds across drylands. Due to their global coverage, the generic mechanisms submerge specific processes relevant for particular social groups or occurring in only a few regions. On the other hand, concerning one important social group in drylands, the local study outlines specific processes that shape climate vulnerability of smallholders in relation to their food security. These processes are consistent with the generic mechanisms identified in global drylands.

Overall, well-defined mechanisms are necessary to adequately quantify vulnerability and interpret the identified patterns consistently. The mechanisms may feed back into the debate about dryland vulnerability, thereby bridging the scientific and the decision-making spheres. For this feedback, it is essential that stakeholders fully grasp the mechanisms to be able to comment upon them. Influence diagrams illustrating the relevant mechanisms as shown in Section 2.2 provide a useful communication tool in expert and stakeholder consultations.

Integrating expert and stakeholder knowledge provides valuable entry points for improving the relevance of the global and local findings for decision-making processes. The integration moreover creates opportunities to discuss different worldviews and perceptions. Differences in viewing the world among researchers and stakeholders may yield distinct mental maps (Nisbett 2003), and hence different conclusions. With regard to potential differences, I explicitly accounted for situational constraints and opportunities in the interpretation of the clusters identified in the Peruvian Altiplano, so as to be recognisable to stakeholders and to facilitate a common approach to vulnerability (see Sect. 3.6.2). Relevant aspects include land availability, labour shortages or processing of produce which were frequently expressed by the interviewed smallholders.

Finally, the elicited mechanism hypotheses represent the most important currently documented knowledge about dryland vulnerability in the global and local contexts investigated. They may be extended according to newly emerging insights by multiple iterations of the approach outlined. Feeding back into case study research, the mechanisms may stimulate investigations to further elaborate the knowledge established so far. After outlining the procedure for eliciting hypotheses on vulnerability-creating mechanisms to initiate the pattern approach, the following section lays the foundation for the quantitative analysis of vulnerability.

5.1.2 Quantitative indication of vulnerability

Quantitative data were chosen to indicate vulnerability to the selected environmental and socio-economic stresses drawing upon the well-defined hypotheses about vulnerability-creating mechanisms resulting from the first step. Indicators are quantifiable constructs describing dimensions which are not directly measurable. For example, infant mortality serves as an indicator for human well-being by counting the relative number of infant deaths at a given point in time (CIESIN 2005). Indicators provide simplified information about the complex underlying processes and allow comparison between the investigated units.

Indicators were chosen that are generic enough to adequately capture the relevant natural and socio-economic properties of the investigated systems as well as their interactions. The analysis of global dryland vulnerability requires universal indicators representing all dryland regions (see Sect. 2.3.1). The global indicators describe general mechanisms that shape sensitivity and adaptive capacity to a set of environmental and socio-economic exposure factors. The indicator for the degradation of water resources, for example, reflects the fact that people's livelihoods generally depend upon the availability of water resources, be it for agricultural, industrial or domestic purposes. In contrast, the local analysis in the Peruvian Altiplano indicates the harvest failure risk - a particularly important endogenous characteristic of smallholder systems - by means of the number of production zones involved in cultivation (see Sect. 3.4.2). This indicator mirrors locally specific opportunities to prepare for climate variability in this highly diverse mountain environment. Analyses of smallholder systems in other regions might require different indicators, such as the distance of fields to river plains or access to irrigation schemes.

Ideally, data used for indication would be well-resolved both spatially and temporally in order to differentiate the relevant mechanisms appropriately. Moreover, all data would be collected in the same spatial resolution and temporal intervals. However, available data show limitations in these aspects. If observations are insufficient for quantitative indication, modelling may provide a substitutional method, such as that used for indicating the overuse of water resources in the global analysis (see Sect. 2.3.1).

In particular, the global analysis had to cope with data scarcity due to its sub-national resolution. I have used the best globally available data bases for indication (see Sect. 2.3.1). For example, the dimension of resource degradation includes an indicator for soil degradation since a high proportion of livelihoods in drylands rely either on subsistence or cash-crop agriculture. I argue that people cultivating severely degraded soils have more difficulty producing sufficient crops to meet their subsistence needs and build reserves for the coming year under average conditions than those with access to well-preserved soils. These difficulties will be more pronounced during a drought, for example, and may result in an insecure food situation. Insufficient nutrition in turn translates into a low capacity for reducing adverse outcomes of climate exposure.

Existing data on soil degradation with global coverage however show only partial consistency (Sonneveld & Dent 2009). They clearly demand improved information about the extent and severity of soil degradation as well as the changes in this process. Thus, their inclusion in the analysis will stimulate the discussion of necessary refinements in future data collection efforts. Contrary to the data scarcity at the global level, the local analysis uses a detailed household survey (ALTAGRO 2006) for quantitative indication, conducted in a specific agricultural campaign in the Peruvian Altiplano (see Sect. 3.4.2). The set of indicators selected from this data base was sequentially modified demanding more iterations in this step of analysis. In addition, exposure to weather extremes during the agricultural campaign covered in the household survey was analysed in the local study. The analysis revealed that general climate exposure was equally distributed within the study region. For this reason, climate exposure did not require a spatially differentiating indicator.

The indication of the underlying processes is made transparent by explaining explicitly how the selected indicators describe the respective vulnerability dimensions and how they link conceptually to the understanding of vulnerability to particular environmental and socio-economic stresses. The traceable indication facilitates the recognition of underlying assumptions and hence supports the debate about their suitability.

The indicators span a data space whose structure is investigated by applying a cluster analysis. As a first step prior to the cluster analysis, the distribution of indicators was reviewed for outlying data points. Since the cluster analysis uses an algorithm based on a distance measure, outliers may distort the pattern recognition. This is particularly relevant for small data sets, such as those used in the local analysis. Here, some indicators include outlying data points (see Sect. 3.4.2). An evaluation of their origin shows that they reflect extreme, but valid disparities among the households. It resulted that 4% of the investigated households in the Peruvian Altiplano possessed a far larger cultivation area, number of livestock and/or alternative income than the remaining smallholders. I have therefore winsorised the data sets concerned, i.e. replaced the outliers with the next available less extreme observation (Barnett & Lewis 1994), in order to reduce the influence of these outliers on the overall data distribution. This procedure supports the pattern recognition since the adjusted data sets have a greater variance. As described further below, the studies in Chapters 2 and 3 demonstrate that large variance indicators differentiate between the vulnerability patterns better than small variance indicators.

For the clustering, indicators need to be comparable among each other. Therefore, they are firstly standardised by normalisation to the 0-1 range according to their minimum-maximum values. This procedure aims at giving all indicators equal importance, irrespective of their particular measurement units. Take the example of the two indicators for infant mortality and water stress used in the global analysis (see Sect. 2.3.1) and consider their real measurement units. If they were plotted in a two-dimensional diagram with units on either axis drawn to the same size, the infant mortality would have a very large effect on the data structure, while the water stress would contribute very little to it. This is due to the very large range in the indicator for infant mortality (40-2,031 deaths per 10,000 live births) as compared to the small range in the water stress indicator (1-4). The normalisation converts the indicators to unitless variables neglecting the different concepts represented by the real measurement units. This procedure is sensitive to outlying observations which need to be treated prior to the normalisation as outlined above. Normalisation is an option depending on the particular application, but there is no objective way of standardising. Other methods are based on standard deviation or mean absolute variation, for example (Milligan & Cooper 1988, Kaufman & Rousseeuw 1990).

Furthermore, the variances in the data space were determined by performing a principal component analysis based on Pearson correlations using the statistics package R (RDCT 2009). In the global analysis, the indicators for water stress and soil degradation have the largest variances among the indicators. They distinguish well between the identified clusters. In contrast, the small variance indicators for the natural agro-constraints and isolation do not differentiate the vulnerability patterns well. Taking up this finding, ways of refining future assessments with regard to the underlying mechanisms and indication have been proposed (see Sect. 2.4.1). In the same sense, the productivity indicators in the local analysis have a very small variance and do not significantly distinguish between the smallholder households (see Sect. 3.6.1). Instead, the very low mean values for both indicators highlight the overall marginality which is partially caused by degradation of natural resources in that region. However, investigating in detail the effects of small variance indicators on the cluster results remains important since other studies have shown that variables with a small variance may contain important information about the structure of the data space (e.g. Chang 1983, Yeung & Ruzzo 2001).

Adding to the pre-analysis, correlations between the indicators were explored. Weak correlations among the indicators point out dissimilarities in their combinations which are later manifested in the cluster characteristics. To cite two examples from the studies in Chapters 2 and 3 which contradict possible expectations: neither does a high poverty level generally link to severe soil degradation in the global analysis, nor does a high harvest failure risk relate directly to a high area constraint in the Peruvian Altiplano (see Sects. 2.3.2 and 3.4.2). Both studies underline that indicators which correlate as little as possible to each other particularly enrich the conclusions drawn from the clusters with differential insights.

In summary, quantitative indicators reduce the complexity of the observed vulnerability-creating mechanisms to relatively simple measures. They are thus an adequate means of communicating the assumptions and results of pattern recognition to decision-makers. Uncertainties related to the indicator selection as outlined in this section however often confine the absolute certainties desired in decision-making processes. It is therefore important to refine the quantitative indication of vulnerability until the pattern recognition approach yields methodologically robust and valid results that are fully interpretable. The following section determines how methodological robust vulnerability patterns can be identified.

5.1.3 Robust vulnerability patterns

After the selection and pre-analysis of the raw indicators, this methodological step evaluates the results of the cluster analysis with regard to the robustness of vulnerability patterns (clusters). One approach to analysing their robustness lies in the reproducibility of cluster partitions (Ben-Hur et al. 2002, Dudoit & Fridlyand 2002, Lange et al. 2003). Here, it is assumed that the cluster algorithm tends to yield similar results in stochastically initialised runs if the cluster number fits the structure of the data space. Thus, the cluster algorithm is initialised with randomly chosen sub-sets of the resampled data. The share of overlap between two partitions, that is to say the fraction of investigated units assigned to the same cluster, then determines the consistency of the cluster results. This consistency is an important measure to decide how many vulnerability patterns are further analysed. In contrast to the previous steps, this evaluation focuses on the identified combinations of indicators at the cluster centres and the membership of the investigated units in these clusters.

The consistency measure applied in Chapters 2 and 3 (see Append. A, Sect. 3.5.1) generally decreases with increasing cluster numbers - a trend favouring the analysis of fewer vulnerability patterns. Too few patterns however would greatly restrict possible conclusions because they would provide highly aggregate information. This may be convenient in an approach to determining rough patterns perhaps as a first approximation. However, I have selected partitions with larger cluster numbers that still yield high consistency since they promote more differentiated insights into the causal structure of vulnerability.

In addition, the development of cluster partitions with increasing cluster numbers demonstrates at which cluster number new clusters are separated and from which clusters they are demerged. The separation of new clusters provides valuable insights into regional patterns in the global analysis and differentiates the smallholder systems in the local study. In particular, the joint evaluation of the development path and the reproducibility of cluster partitions in the global analysis (see Append. A) allow a focus on a partition that differentiates adequately the dimensions of poverty and resource degradation and still yields a high consistency measure. The explicit distinction provides interesting insights for discussing the identified vulnerability patterns.

Finally, the ratio of the between-cluster and the inner-cluster variance is considered (see Append. A, Sect. 3.5.1). The higher the variance ratio, the more dissimilar and compact are the clusters which were identified. Together with the consistency measure and the degree of differentiation, the variance ratio supported the choice of cluster partitions for further analysis in

Chapters 2 and 3. Overall, this step of evaluation rests on methodological considerations. The identified vulnerability patterns are further reviewed in the light of vulnerability outcomes and reported underlying mechanisms as explained in the following section.

5.1.4 Validation of vulnerability patterns

The analysis of vulnerability patterns involved selection processes in Steps 1 and 2 which can be largely systematised. However, some subjectivity is inevitably involved. Due to the importance of these subjective decisions in pattern identification, the results need to be validated. For the purpose of validation, I have assessed whether they provide specific insights into vulnerability outcomes and their underlying mechanisms. The validation rests on an empirically-oriented procedure.

Since patterns are sought that are suited to supporting decision-making for vulnerability reduction, I scrutinised the patterns identified with a view to confirming two aspects of validity: empirical and application validity (Bossel 1994). Accordingly, patterns prove to be empirically valid if they correspond to reported outcomes of vulnerability and if the pertinent vulnerability-creating mechanisms are consistent and plausible. Furthermore, patterns prove to have application validity if the transferability of entry points to reduce vulnerability can be shown within a given cluster. Overall, the validation refers to the limited number of cluster centres as representatives of several investigated units, that is to say spatial units or households. The following paragraphs lay out a total of three different ways of validation as applied in the two studies in Chapters 2 and 3.

The study in the Peruvian Altiplano (see Chap. 3) demonstrates in two different ways that the clusters provide valid insights into the smallholders' vulnerability to weather extremes. Firstly, I treated the vulnerability patterns as formal entities, i.e. neglecting their interpretation. I compared these entities to specific vulnerability outcomes in terms of the purchase of food and fodder in the investigated agricultural campaign compared with an average campaign (see Sect. 3.6.1). Information on the relative purchase was collected specifically in a household survey conducted in a sub-set of the investigated households. The comparison of the identified clusters and the relative purchase reveals that the similarities of households given by the clusters hold true for the reported relative purchase (see Fig. 3.4). It shows the clear correlation between the identified patterns of vulnerability and an independent data set of reported differential vulnerability outcomes in a post-event situation. This relation highlights the relevance of the identified clusters for decision-making processes.

This form of validation was possible by concentrating on a specific exposure in a given region and placing the emphasis on a specific livelihood aspect. The relatively small data set of selected households used for the validation provides first valuable insights. Given the even exposure to weather extremes, a higher degree of damage reveals more sensitive households with lower adaptive capacity. Considerations of resources that can be mobilised in the households to compensate for food shortfalls would enhance the discussion of smallholders' adaptive capacity. The insights gained in the study could be further strengthened by extending the secondary data set and including further meaningful damage dimensions.

The outlined approach is in line with newer vulnerability assessments that test the consistency of indices of vulnerability and modelled damages against independently reported damages caused by specific exposure events. For example, in an approach to quantifying societal vulnerability to drought, Alcamo et al. (2008) modelled 14 indices of water stress in three case study regions. Here, modelling provides a substitute for areas with insufficient coverage of well-resolved observational data with regard to water withdrawal and availability. This enables a consistent comparison between the regions investigated. The indices explained the occurrence of a drought crisis with a varying degree of accuracy depending on the water use in a particular river basin. A large perennial river, such as the Volga, provides water permanently for people who live nearby. But people further away may not have access to this water. Therefore, a new, aggregate index was constructed out of a selection of the initial indices. Its correlation with the occurrence of a drought crisis was significantly higher than that of the initial indices. This aggregation is a valuable first step towards an improved understanding of the complex processes generating societal vulnerability to drought. Knowledge about the severity of drought events would help to differentiate the underlying processes further.

In another study, Fekete (2009) constructed an index of household vulnerability to floods based on a large set of demographic census data. He selected variables from the census data that could be validated against an independent data set of reported problems caused by a flood, including the necessity to leave one's home or seek emergency shelter. The most important principal components within this set of data served as vulnerability factors to build the overall index. The index refers to endogenous household characteristics excluding a reference to exposure. Due to the high complexity of the vulnerability factors and in the absence of a sound definition of the assumptions for selecting the initial set of indicators, the results of this study are however difficult to interpret in detail. A similar focus on vulnerability outcomes has been applied to assess the quality of a flood loss model (Thieken et al. 2008). Here, the modelled economic flood losses were evaluated against reported repair costs of rebuilding after a flood. The applied multi-dimensional loss model provides realistic estimates for financial damages after the extreme flooding in 2002 in Saxony - the event from which the model was derived. Results however deviate largely from observed damages caused by a less extreme event in 1993 in Bavaria indicating a limited transferability to different types of floods. Another study uses people's perception of experiencing a crisis when a drought occurs to test the validity of a drought susceptibility index due to the absence of exposure (Krömker et al. 2008). In collecting the people's perceptions, however, these authors did not explicitly define the magnitude or duration of an assumed drought. Their approach thus presents a broad approximation to validation. However, neither of these studies proved the validity of their assumptions, processes or model inputs.

In order to enhance the validation of cluster results in the local study, the outcome-based aspect outlined above is complemented in a second step. Here, the hypotheses used to define and indicate the relevant processes were tested. This test shows that the vulnerability-creating mechanisms implied by the identified clusters are consistent with reported processes that explain the household-specific damages caused by weather extremes (see Sect. 3.6.2). Empirical evidence for this test was collected in the same household survey mentioned above. The survey included an interview in which the smallholders provided valuable examples, stories and issues concerning their climate vulnerability and related food insecurity. They explained important aspects of the complex reality in which climate vulnerability evolves in this region. The narratives obtained add richness and details to the understanding of local vulnerability that quantitative data cannot provide. This validation approach runs parallel to a ground truthing of the spatial distribution of simultaneous climate and economic vulnerability in agricultural systems in India (O'Brien et al. 2004). Evidence from interviews with government officials and local experts, secondary data and household surveys confirmed particular mechanisms identified in this regional analysis. Similarly, another study uses judgements derived from a focus group of experts to prove empirically selected indicators of social vulnerability and adaptive capacity to climate stress as well as their relation to mortality risk on a national level (Brooks et al. 2005).

Working at the global level largely restricts an outcome-oriented validation, such as the one presented for the local analysis. This is due to spatial variations in stress exposure and limitations in independent observational data which are globally available, e.g. low spatial resolution and inconsistent methodologies (Guha-Sapir & Below 2002, Brooks & Adger 2003). Thus, the analysis of global drylands (see Chap. 2) uses independent case studies concerned with particular aspects of dryland vulnerability to confirm cluster-specific mechanisms and their spatial distribution (see Sect. 2.4.1) in the same sense as the validation of household mechanisms in the Peruvian Altiplano. Principally, there are numerous case studies describing stresses, causes and consequences of vulnerability in specific regions or locations which can be explored for relevant mechanisms and their outcomes specific to each pattern. However, case studies need to describe a combination of all or at least a substantial part of the investigated vulnerability dimensions covering the time interval of interest in order to be suitable. This requirement thus significantly reduces the number of useable case studies because they often concentrate on a few or even just one dimension of vulnerability.

In addition to its empirical validity, the global study proves by way of example the transferability of strategies for vulnerability reduction between regions which depict similar natural and socio-economic properties (see Sect. 2.4.2). In particular, the pronounced soil degradation, the most important vulnerability dimension causing food and subsequent livelihood insecurity in some regions of western Africa, could be overcome through an effective land rehabilitation strategy (Reij et al. 2005). This strategy was later transferred and adjusted to two other regions (Kabore & Reij 2004: 23) belonging to the same vulnerability pattern generating positive impacts there as well. This successful transfer highlights the fact that similarly problematic conditions identified by the cluster analysis link to similar intervention options. This proof of application validity is a necessary prerequisite for the intended upscaling of interventions at the global level. To further enhance the validation on the global scale, improved observational data and case studies are required which reflect appropriately the spatial and temporal differences of vulnerability outcomes and underlying conditions.

Altogether, the successful validation in the studies in Chapters 2 and 3 clearly strengthens the scientific credibility of the identified vulnerability patterns and demonstrates their value for estimating expected damages caused by stress exposure. In this step, working at different functional resolutions yielded different opportunities for validation. Particular opportunities resulting from the functional resolution are equally apparent in the pattern ranking as explained in the following section.

5.1.5 Ranking of vulnerability patterns

The pattern recognition approach requires an explicit step of ranking the vulnerability patterns since they are at first unrelated entities. This ordering aims at determining the relations of patterns according to the severity of vulnerability. It provides useful insights in order to prioritise spatial and thematic intervention options. Two aspects inform the ranking in Chapters 2 and 3: vulnerability outcomes and the distribution of indicators.

The vulnerability outcomes, i.e. the relative purchase of food and fodder, used for validation in the Peruvian Altiplano as outlined in the previous step, additionally inform the ranking of vulnerability patterns. The amount of purchase clearly differs between the clusters. Thereby a higher, above-average purchase indicates more severe vulnerability (see Fig. 3.4) which serves to rank the clusters. This outcome-informed procedure constitutes an advanced approach of ranking when compared with an indicator-based approach as it accounts for damage incurred under a certain stimulus.

The relative purchase describes one important dimension of food security in the smallholder households. It reflects the exposure and related production in the agricultural campaign under investigation and the previous campaign. The weather extremes investigated in 2005/06 and 2004/05 moderately influenced the smallholders' food security. Considering that vulnerability involves non-linear processes, it would be interesting to test if varying types and strengths of exposure result in a similar ranking of patterns. For example, dry atmospheric conditions may induce radiation frost and related production losses in the Altiplano (Morlon 1987). On clear nights with excessive outgoing radiation, favourable production zones on higher grounds which are generally less affected by local frost may lose this advantage. If such conditions prevail during the growing season, the difference in the vulnerability outcome between the most vulnerable and the highly vulnerable households may become insignificant since these households differ above all in the use of various production zones (see Fig. 3.5).

Due to a lack of methodologically consistent information about the nature and magnitude of stress exposure and related damages in the global analysis, the indicators at the cluster centres are summed up for an initial approximation to rank the vulnerability patterns (see Fig. 2.2a). The piled columns illustrate both the sum and distribution of vulnerability indicators for each cluster. Such a ranking provides relevant insights into hotspots of vulnerability assuming cumulative effects of underlying causes. This requires that all single indicators are arranged in the same way, so that higher values point towards more severe vulnerability, for example.

Overall, the ranking of the vulnerability clusters presents an approach which is inverse to a legend classification of vulnerability indices (e.g. O'Brien et al. 2004, Vincent 2004). Here, vulnerability indices are first calculated and then classified for mapping purposes according to statistic characteristics. This may be useful for illustration. However, the contribution of single indicators to the final indices remains hidden. In comparison, the transparency in the composition of clusters identified in Chapters 2 and 3 (see Figs. 2.2 and 3.5) provides an advantage over such merged vulnerability indices. Knowledge of the clusters' composition allows the differentiation of different causes of vulnerability in patterns with approximately equal indicator sums. This is the case for example in Clusters 3 and 4 in the global analysis (see Fig. 2.2).

Due to the small difference in their indicator sums, the ranking of clusters can be interpreted as a partial order. Partial ordering was applied by Ionescu (2009) and Ionescu et al. (2009) in developing a formal framework of vulnerability that enables the comparison of vulnerability measures used in different assessments. The ranking of the global vulnerability patterns in this dissertation displays a partial order relation since both Clusters 3 and 4 clearly indicate a less severe vulnerability in comparison to Clusters 1 and 2 and a more severe vulnerability in relation to the remaining clusters. The very small difference in their indicator sums points towards a similar importance of these clusters in prioritising intervention options. However, Clusters 3 and 4 differ significantly in the level of resource quality. While Cluster 3 indicates distinctively greater water stress and natural agro-constraints, Cluster 4 represents more pronounced soil degradation. This information helps to design adequate strategies for vulnerability reduction.

The indicator-informed ranking yields plausible insights into the severity of vulnerability in both the global and the local analyses. In the Peruvian Altiplano, this type of ranking is in line with the outcome-informed ranking. In this sense, the ranking of global vulnerability patterns could be strengthened through an additional test as to whether the damage potential specified by the indicator sums at the cluster centres is actually attained under exposure. As is the case for validation, this requires suitable observational data.

The ranking based on indicator distributions reflects the same weights of indicators as used for clustering. If single dimensions were to influence vulnerability more strongly than others in a certain context, an alternative approach to ranking might be considered. Assuming a leading role of single vulnerability dimensions, Kok et al. (2010) present multiple rankings of vulnerability patterns each focusing on one particular dimension. They thus deliver meaningful insights with regard to sectoral priorities. This approach to ranking however requires an additional decision on what is the most important dimension. This may pose difficulties in the case of several equally important dimensions or sectoral competencies.

5.1.6 Conclusions

The two studies presented in Chapters 2 and 3 demonstrate the conditions necessary to identify typical patterns in the natural and socio-economic properties of dryland systems that explain their vulnerability to climate, market and other stresses. They are summarised in five methodological steps. While the first and second steps are generally fundamental for studies that aim at providing well-informed insights into vulnerability, the following Steps 3 to 5 are specific to the pattern recognition approach presented here. They refer to characteristics of the typical patterns each treated as representative for a group of similar spatial or functional units. Though starting by building the mechanism hypotheses, the approach in practice involves numerous iterations between the five steps.

Prior to the cluster analysis, the first step requires sound empirical knowledge about causes and consequences of vulnerability in the concerned dryland systems in order to build hypotheses about the underlying mechanisms. Principles of grounded theory research combined with heuristic and hermeneutic elements proved suitable for systematically eliciting relevant hypotheses from the knowledge available. The precisely defined vulnerability-creating mechanisms are a prerequisite to indicating vulnerability quantitatively. To be successful, the selected data need to adequately represent the mechanisms at the temporal and spatial resolution under consideration. In addition, indicators with high variance in the individual data sets and weak correlations between each other discern the identified clusters potentially very effectively.

After performing the cluster analysis, the third step concerns the methodological robustness of the identified patterns to guide the selection of how many vulnerability patterns are inspected. It considers the consistency of repeated cluster partitions in combination with the degree of differentiation of vulnerability dimensions as well as the ratio of the between-cluster and the inner-cluster variance. In the fourth step, the identified vulnerability patterns need to demonstrate that they provide reliable indications as to how vulnerability unfolds in reality. They have to bear comparison with reported causes and, ideally, outcomes of vulnerability. For this validation, clusters need to be interpretable in the light of the vulnerability-creating mechanisms elicited in the first step. Moreover, independent observations of mechanisms or outcomes are required here. Finally, the fifth step rests on outcomes of vulnerability or, alternatively, on the indicator distribution to rank the patterns. The ranking is supportive for priority setting in decision-making on vulnerability reduction. As a further supportive aspect, the multi-dimensional information given by the indicator combinations at the cluster centres points towards strategic intervention options.

The studies in Chapters 2 and 3 outline a pattern recognition approach based on well-defined and formalised vulnerability-creating mechanisms. Thus, they follow a deductive way of data mining as opposed to inductive data mining. Inductive data mining is designed to identify relationships between variables without a priori hypotheses on the nature of those relationships. In contrast, the pattern recognition applied in Chapters 2 and 3 starts by building hypotheses about causes and consequences of vulnerability and hence by establishing grounded ideas of underlying mechanisms. This knowledge essentially allows a consistent interpretation, validation and ranking of the identified vulnerability patterns. Moreover, it is a precondition to standardising the collection of information to enable the comparison of vulnerability between different socio-ecological systems.

Reflecting scale-dependent opportunities, the studies in Chapters 2 and 3 concentrate on specific objectives. By proving the transferability of options for reducing vulnerability, the global study aims to inform decision-making on the upscaling of interventions when available funds are limited. Moreover, the spatial indication of vulnerability patterns allows comparisons between regions and the identification of vulnerability hotspots across global drylands. It enables decision-makers to evaluate a given region within its wider context. Emphasising different aspects, the study in the Peruvian Altiplano facilitates the comprehension of specific mechanisms which determine impacts of weather extremes on the smallholders' food security. Here, the outcome-based aspect of validation constitutes a crucial step in establishing the credibility of the patterns and hence their suitability for informing extension services and individual decisions. In this respect, working at the local level provides a clear advantage since, to a large extent, limitations in globally available observational data constrain such a validation on the global scale. Global data sets should therefore be further developed to provide data which reflect well the spatial and temporal differences in vulnerability outcomes in order to support a more rigorous validation for this type of study.

The five steps deduced from the analyses of vulnerability patterns partially overlap with an iterative and flexible methodological approach to arrive at stakeholder-relevant assessments of vulnerability to global change (Schröter et al. 2005b). This approach consists of eight steps, likewise including the development and formalisation of causal models of vulnerability. In addition, the 8-step approach outlines in rich detail the issues particularly relevant to improving the dialogue with stakeholders and the communication of results. Here, the robustness of the findings and their usefulness for decision-makers determine the overall success of assessments. In order to facilitate comparison between different assessments, Polsky et al. (2007) elaborate on specific aspects of the 8-step approach including a grounded approach to building cause-effect hypotheses and a structured approach to the indication of underlying processes. These aspects closely correspond to the first and second methodological step outlined in this section. However, the prerequisites for recognising typical vulnerability patterns provide more details on how methodological robustness can be evaluated (Step 3) and account more explicitly for the validity of the patterns identified (Step 4). In particular, the successful validation of the patterns against reported outcomes and mechanisms makes objections of reductionism more difficult. These objections are raised when vulnerability assessments are criticised for the limited number of indicators they use (e.g. Carr & Kettle 2009).

Although Schröter et al. (2005b) consider future changes in vulnerability, they limit their remarks on possible effects to changes in the exposure to global stresses. The five steps outlined in this section may incorporate changes in both exposure factors and endogenous characteristics of the socio-ecological systems. Dynamic perspectives would particularly concern Step 2 to indicate vulnerability quantitatively. This may involve the selection of trend indicators or the analysis of various time slices. An example of analysing changing vulnerability driven by endogenous processes is detailed in the following section (Sect. 5.2).

The conditions for arriving at relevant and valid vulnerability patterns summarised in the 5-step approach are well suited to complementing an influential pattern approach applied by the World Food Programme to analyse vulnerability to food insecurity (WFP 2009). The guidelines seek to improve our understanding of the causes of food insecurity at the household level, so as to inform appropriate responses. They detail a pattern recognition based on clustering principal components within a set of indicators. Though outlining the general procedures of statistical techniques, they fail to give specific guidance on the conditions under which the cluster approach yields meaningful patterns. The five steps established in this section provide a concise tutorial on how to complement essential elements.

Finally, the 5-step approach was outlined in such detail in order to facilitate and motivate the application of pattern recognition in other research studies concerned with vulnerability analysis. Such applications could promote the refinement of mechanisms in specific contexts and advance methodological adjustments. This would further increase the value of identifying typical patterns in the properties of socio-ecological systems for an improved understanding and management of the relation between these systems and particular stresses.

5.2 Which changes in vulnerability to climate, market and other stresses were caused by endogenous processes in dryland systems of Northeast Brazil?

The categorisation of vulnerability patterns outlined in Chapter 2 describes particular vulnerability profiles at a given point in time. Vulnerability, however, is not static. Instead, endogenous mechanisms may trigger changes in the vulnerability of socio-ecological systems independent of exposure to stresses. The Northeast of Brazil serves here as an example with which to investigate related processes.

5.2.1 Vulnerability changes in smallholder systems

This section explores vulnerability changes caused by endogenous processes in smallholder systems in Northeast Brazil during the late 1990s. It first investigates the vulnerability clusters from the categorisation of global drylands (see Chap. 2) for the three smallholder-dominated federal states of Pernambuco, Ceará and Piauí. The area of these federal states covered by the vulnerability clusters is referred to as the "study region" in the following discussion. The respective vulnerability profiles are categorised as Clusters 2 to 5 depicting high to medium vulnerability in the global comparison. These four clusters differ significantly in the quality of natural resources depending on how well human use was adjusted to the marginal resources. They concur in medium levels of poverty, agro-constraints and isolation.

The clusters indicate that the highest vulnerability in Northeast Brazil results from severe water stress and soil degradation described by Cluster 2 (Fig. 5.1, lower left part). These regionally most vulnerable areas account for about one third of the study region and prevail in Ceará and east Pernambuco (Tab. 5.1, Fig. 5.1, upper part). In contrast, land use in west Pernambuco, south and southeast Piauí is better adjusted to the marginal resources and supports relatively preserved water and soil resources there. These areas classified as Cluster 5 characterise the lowest vulnerability accounting for another third of the study region. In between these contrasting levels of vulnerability, specific facets of resource degradation relating to the overuse of either water or soil resources constitute medium vulnerability. Here, regions with pronounced soil degradation as indicated by Cluster 4 dominate the federal state of Piauí and occur in some parts of central and east Pernambuco. They add up to about one quarter of the study region. The remaining dispersed areas of Cluster 3 show heavily overused water resources mainly in Ceará and Pernambuco. In total, 91% of the vulnerability clusters are located in smallholder-dominated municipios above all in Ceará and Piauí (Tab. 5.2).

Table 5.1 Distribution of vulnerability clusters in the study region of Northeast Brazil according to the categorisation of global drylands (see Chap. 2)

Vulnerability cluster	**Federal state**			**Total area (km^2)**	**Area share (%)**
	Pernambuco (km^2)	**Ceará** (km^2)	**Piauí** (km^2)		
Cluster 2	11,390	104,730	370	116,490	37
Cluster 3	3,120	6,720	2,380	12,220	4
Cluster 4	11,550	510	74,740	86,800	27
Cluster 5	39,460	980	61,370	101,810	32
Total	**65,520**	**112,940**	**138,860**	**317,320**	**100**

Table 5.2 Cluster area share of smallholder-dominated municipios

Vulnerability cluster	**Area share (%)**								
	70-100% smallholder area per municipio				**50-70% smallholder area per municipio**				**Total**
	Pernambuco (%)	Ceará (%)	Piauí (%)	Total	Pernambuco (%)	Ceará (%)	Piauí (%)	Total	
Cluster 2	6	39	0	46	3	39	0	41	87
Cluster 3	11	34	7	53	13	21	12	45	98
Cluster 4	9	1	50	60	3	0	22	25	85
Cluster 5	25	1	36	62	10	0	21	31	93
Total	**13**	**19**	**0**	**55**	**7**	**15**	**14**	**36**	**91**

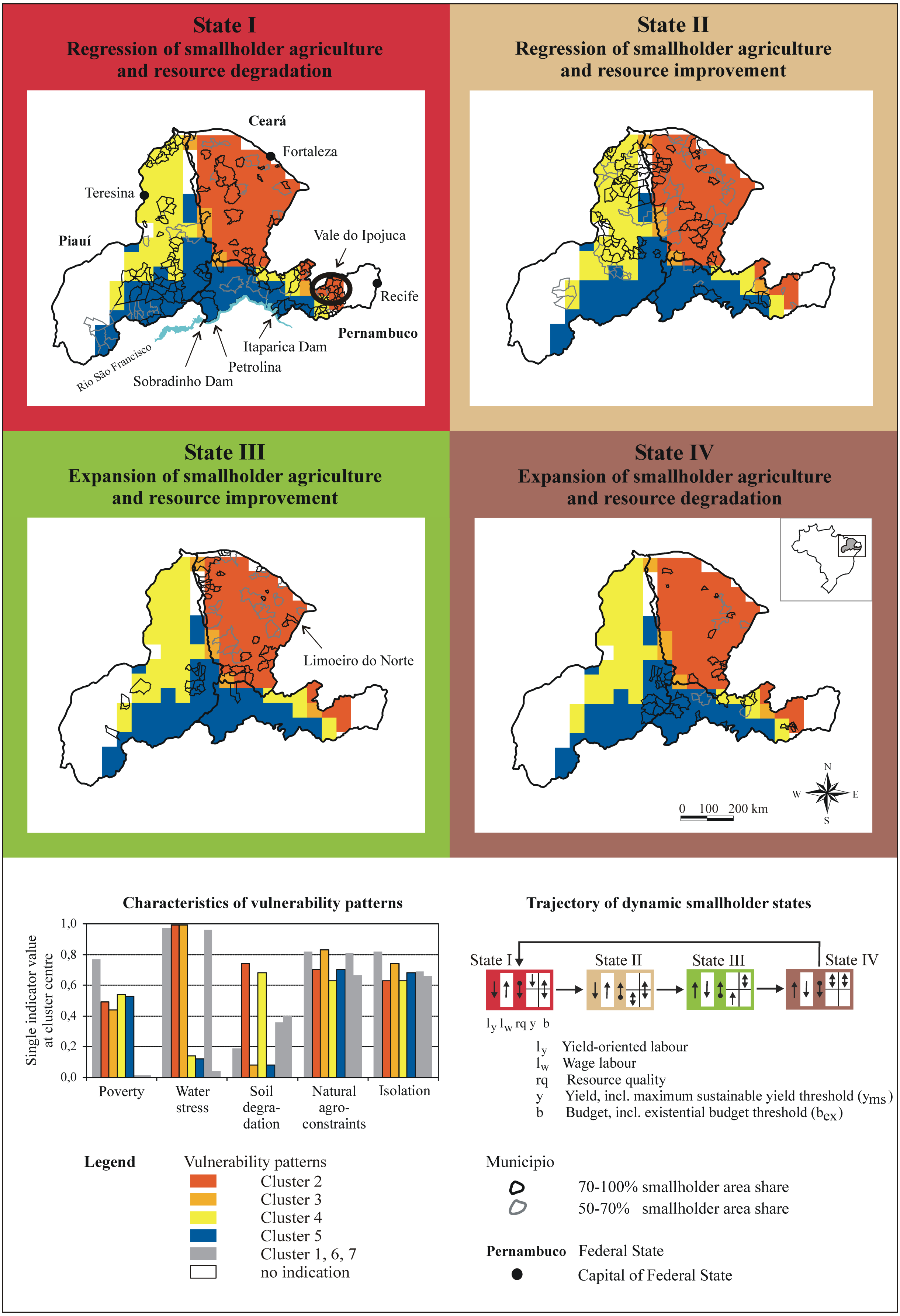

Figure 5.1 Smallholder development within the vulnerability patterns in the late 1990s in three federal states of Northeast Brazil based on the main results from Chapters 2 and 4.

Next, in order to evaluate changes in vulnerability, the clusters are further examined in respect of endogenous processes in the smallholder systems. The qualitative dynamic model outlined in Chapter 4 describes important mechanisms within the smallholder systems in Northeast Brazil. The model rests on generalised rules of labour allocation, yield extraction, constitution of budget and the dynamics of natural and technological resources. It results in a cyclic trajectory passing through four dynamic states as summarised in Figure 5.1 (lower right part). The modelled trajectory involves one most critical and one favourable state (States I and III, resp.). The most critical state describes a regression of smallholder agriculture in combination with resource degradation, whereas the expansion of smallholder systems in combination with resource improvement indicates favourable conditions. The remaining two states (II and IV) constitute transitions between these two opposing trend combinations. The relevant trend combinations were indicated in a spatially explicit way for the late 1990s (see Sect. 4.4.2) - a period covered by the clusters of vulnerability mentioned above.

Within the dynamic states, the trends of budget, labour allocation and quality of productive resources link directly to the mechanisms indicated by the vulnerability clusters. They thus allow the assessment of changes in the vulnerability-creating mechanisms. While the modelled trajectory describes the endogenous smallholder development independent of the exposure to particular stresses, data for crop productivity, livestock density as well as harvest and pasture area used to indicate the specific trend combinations reflect long-term effects of droughts, market forces and other stresses. Hence, the following discussion of changes in vulnerability considers the respective stress consequences.

The spatial distribution of trend combinations shows that States I and II prevailed in the study region in the late 1990s (37% and 35%, resp., Tab. 5.3). Overall, a higher share of smallholder land use relates to a more certain spatial indication. In average, State I dominates areas with a very high share of smallholder land use (70-100%), whereas State II is equally distributed among all smallholder dominated areas (50-100% smallholder share). The remainder of this section illustrates contrasting pathways of vulnerability resulting from both most critical and favourable trends in highly and less vulnerable smallholder systems.

Table 5.3 Cluster area share of modelled dynamic smallholder states in the late 1990 (For definition of the dynamic smallholder states see Fig. 5.1)

Vulnerability cluster	Area share (%)											
	70-100% smallholder area share per municipio				50-70% smallholder area share per municipio				Total			
	State I	State II	State III	State IV	State I	State II	State III	State IV	State I	State II	State III	State IV
Cluster 2	18	13	10	4	7	17	15	2	25	29	26	7
Cluster 3	23	20	10	0	9	33	3	0	32	53	13	0
Cluster 4	28	25	4	3	9	16	0	1	36	41	4	4
Cluster 5	33	11	4	13	23	6	0	2	56	17	4	15
Total	**25**	**17**	**7**	**5**	**12**	**18**	**5**	**1**	**37**	**35**	**12**	**7**

First, two cases will exemplify the aggravating effects of the most critical smallholder trends. The Valley of Ipojuca, located in eastern Pernambuco (Fig. 5.1, upper part), provides an example of a region in which State I prevailed in the late 1990s. There, overused water and soil resources mirror the critical natural resource conditions categorised as Cluster 2. In particular, river water flow is limited to a few months' water supply per year and highly sensitive to water uptake for agricultural production (CONDEPE 2001). During recurrent water shortages caused by droughts and overuse, some areas rely on trucks to supply their population with water from distant areas, e.g. the municipios of Pesqueira and Poção. Despite the limited water resources, livestock and cash-crop production were intensively developed to meet the needs of the relatively dense population in this Agreste region (IBGE 2000). This production increase contributed to the ongoing deforestation and degradation of the valley's soils (CONDEPE 2001, Lemos 2001). The overall declining importance of the agricultural sector in the late 1990s (CONDEPE 2001: 48) reflects the fact that the degradation of natural resources was not sufficiently compensated for by technological innovations. This subsequently encouraged the orientation towards more profitable off-farm activities. The observed combination of degrading resources, lack of investments and increasing off-farm activities describes the trends determining the most critical State I ($rq\downarrow$, $l_w\uparrow$) in a local context. These processes clearly point towards intensifying vulnerability which was already at a high level. The considerable poverty in the region (IBGE 2000) highlights the fact that the off-farm activities did not provide the desired opportunities for reaching an acceptable level of human well-being. Thus, State I further triggered the poverty-degradation nexus which had already developed in this region, indicated by Cluster 2. In particular, smallholders faced increasing difficulty in coping with or adapting to droughts, fluctuations in commodity prices and wages or immigration pressures when they generated income below the existential budget level (b_{ex}).

Some areas along the São Francisco River show the same critical trend of smallholder development, but within the conditions of relatively preserved natural resources classified as Cluster 5 (Fig. 5.1, upper part). Major interventions, among them the Sobradinho and Itaparica dams, have stabilised the river water flow since the late 1970s sustaining the water supply for agricultural, industrial and other purposes. Agriculture during the 1970s and 1980s was still practised at a low intensity, so that the profound and fertile soils (CONDEPE 1998) added to the favourable natural conditions indicated in this region. Pronounced agricultural intensification during the 1990s focused on expanding irrigation coverage for cash-crop production, including fruits and vegetables. However, this had adverse effects on the quality of soils. The resulting severe salinisation (CONDEPE 1998) illustrates an important aspect of resource degradation as indicated by State I ($rq\downarrow$). The subsequent decline in agricultural productivity (CONDEPE 1998) together with the high labour requirements of cash crops and a weak market position of smallholders caused a partial breakdown of smallholder farms. This was the case for example in the municipio of Petrolina (Fig. 5.1 upper part), one of the most important irrigation centres (BNB 2000). As a result, these smallholders needed to increase the portion of their off-farm activities to sustain their livelihoods - a typical trend captured in State I ($l_w\uparrow$). The remaining smallholders in the example of Petrolina continued cash-crop production, including acerola, banana and coconuts, stimulated by demand on the national market (BNB 2000). The market orientation encouraged persistent high-yield extraction above sustainable levels. This pointed towards implications comparable with those of intensive livestock production in the Valley of Ipojuca discussed above. If implemented without appropriate conservational management, intensive cash-crop production induces a further loss of quality in the soils as represented by

State I ($y > y_{ms}$, $rq\downarrow$). The exhaustion of once relatively favourable natural conditions describes aggravating vulnerability in the respective smallholder systems, though at a low initial level. Such a development undermines the smallholders' ability to deal with the recurrent droughts, market fluctuations and demographic stresses.

The second widespread trend combination given by State II indicates less critical conditions. In the areas with a higher largeholder share, this state prevailed in Clusters 2 to 4 (Tab. 5.3). Considerable investments were required to at least stabilise the overused resources in these clusters or even reverse their depletion and hence to foster a shift towards State II. Unlike the significantly asset-constrained smallholders, largeholders are well-positioned to make such capital-intensive investments. Thus, a higher share of largeholders may have contributed to improving resources as a transition away from their overuse. In contrast to this development, the most critical State I dominated Cluster 5 even in areas with a higher share of largeholder land use (Tab. 5.3). The still relatively high productivity of the better preserved natural resources in this cluster may explain the lack of investments such as mentioned above. In addition, the pronounced remoteness of the areas concerned in south Piauí and labour shortages resulting from a very sparse population in central Pernambuco (IBGE 2000) might have further curtailed incentives for largeholder investments.

In contrast to the critical States I and II, the favourable trends described by State III influenced only minor parts of the study region. Noteworthy areas are found particularly in Cluster 2 in Ceará (Fig. 5.1, upper part) which are relatively independent of the share of smallholder land use (Tab. 5.3). These favourable trends involve a recovery of natural resources and accumulation of technological assets, an expansion of smallholder agriculture and a budget sustained above the existential level. These processes all relate to the main objectives of the numerous development programmes implemented in Northeast Brazil to improve human well-being and the management of natural resources, e.g. PROTERRA, POLONORDESTE and Projeto Sertanejo. The minor importance of favourable trends mirrors the programmes' generally very limited achievements due to clientelism, patronage and the dominance of multi-national agricultural corporations, for example (e.g. Finan & Nelson 2001, Bezerra 2002, Carvalho & Egler 2003).

Although, by and large, the development programmes undoubtedly failed, they have induced at least partially positive effects, too. For example, intensive irrigation programmes in the formerly water-stressed municipio of Limoeiro do Norte improved water supply, initiated an extension of agricultural production systems and contributed towards preventing a rural exodus (Matias et al. 2004, Da Silva et al. 2004). These processes contributed to the advantageous development as indicated by State III in this municipio (Fig. 5.1, upper part).

Finally, the joint assessment of vulnerability patterns and endogenous processes reveals directions in which smallholder vulnerability developed in the late 1990s. Overall, 37% of the study region with intensifying vulnerability were accompanied by only 12% depicting increasingly strengthened smallholder systems, though at different levels of vulnerability (Tab. 5.3). The endogenous mechanisms demonstrate widening edges of the regional vulnerability gradient consisting of Clusters 2 to 5 as illustrated in Figure 5.2. In particular, 25% of the area located at the high vulnerability edge in Cluster 2 developed even more severe vulnerability. Improving socio-ecological systems were found in a similar share of these areas. However, only 4% of Cluster 5 regions moved towards reduced vulnerability, while vulnerability increased in more than half of these least vulnerable regions. The occurrence of droughts and drops in producer output prices imply transitions or leaps to the critical States I and II as discussed in Section 4.4.3. Thus, recurrent exposure to such stresses bears the potential to even deepen poverty, initiate or reinforce resource degradation and decrease the profitability of smallholder agriculture further.

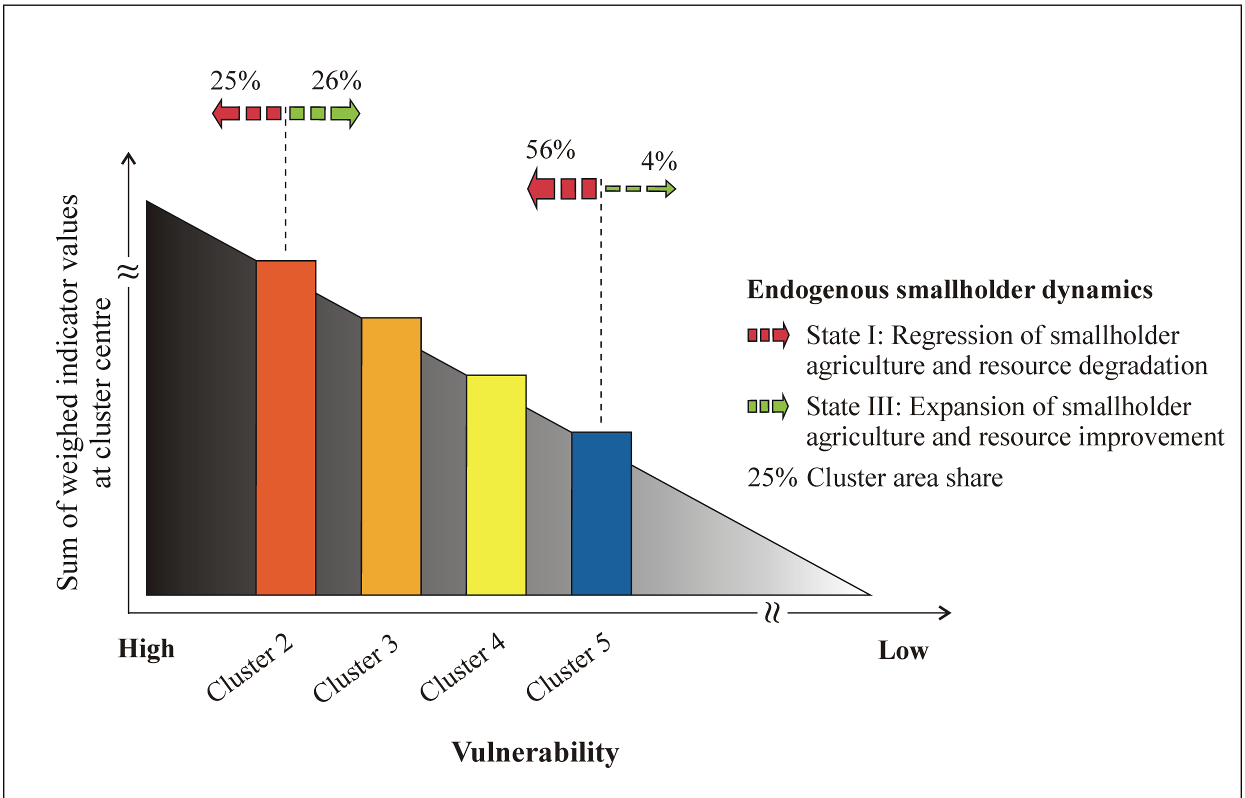

Figure 5.2 Endogenously driven changes at the edges of the regional vulnerability gradient in Northeast Brazil caused by both most critical and favourable smallholder development in the late 1990s (For quantitative cluster information see Fig. 2.2a)

5.2.2 Conclusions

This section investigated endogenously driven changes in vulnerability to environmental and socio-economic stresses in smallholder systems of Northeast Brazil. Firstly, four vulnerability patterns identified for the federal states of Pernambuco, Ceará and Piauí (see Chap. 2) indicated high to medium vulnerability compared to the global situation. These patterns were assessed with regard to endogenous processes in the smallholder systems as captured in a qualitative dynamic model (see Chap. 4). The spatial indication of the model results displays two critical development states prevailing throughout the smallholder-dominated areas in the late 1990s. Here, the indication of the smallholder development at the municipal level resolves further, in functional and spatial terms, the more aggregate vulnerability patterns identified in the global analysis.

A joint assessment of the endogenous processes and the four vulnerability patterns revealed specific changes in the mechanisms that generated vulnerability in the smallholder systems. About one third of the study region showed particularly aggravating vulnerability due to the further degradation of productive resources and consequently decreasing profitability of agricultural production. This endogenous development increased smallholders' vulnerability especially when reinforcing or initiating the poverty-degradation spiral. Results were most critical in those smallholder systems that had already been among the most vulnerable in the region. In response to the degradation of natural resources, these smallholders orientated their livelihoods increasingly towards off-farm activities. Though reducing their vulnerability to climate variability, these activities exposed them to other types of problematic stimuli, such as wage fluctuations. In addition, smallholders in another third of the study region also engaged more intensively in off-farm activities, but their productive resources improved due to less intensive use, technological investments and conservational measures. Similarly climate-exposed smallholders in Mexico, for example, attempted to gain employment in the textile industry (maquiladoras) and other sectors or migrated to generate off-farm income (Eakin 2005). However, most of them survived rather than accumulating resources in order to prepare for or cope with climate and economic stresses. Only some smallholders living in better integrated communities could improve their asset base through such activities in spite of crop damages caused by extreme weather events. However, they faced high competition for employment and low wages.

In contrast to these critical changes, a third trend towards enhanced living and environmental conditions occurred - but only in some areas. Here, smallholders secured their income above the existential budget threshold while improving their resource base and extending their agricultural activities. Notably, the regionally most vulnerable areas showed this favourable trend indicating some positive effects of intervention efforts. This development highlights that vulnerability is not an insoluble problem in Northeast Brazil and that smallholder livelihoods and natural resources can be improved.

The joint analysis implies changing regional hotspots of vulnerability and hence a changing demand for vulnerability reduction efforts. Urgent interventions are justified for the most vulnerable smallholders experiencing intensifying resource degradation and poverty. The cyclic trajectory of endogenous smallholder development however points to a constant need to create or ensure sustainable development conditions. Positively framed, this means that inappropriate decisions can still be corrected. Once a problematic state of the trajectory is entered, immediate interventions are required in order to accelerate a transition or leap into a more favourable state. To estimate the efforts needed for such a transition or leap, the distance to critical thresholds needs to be known.

Given the severe constraints in the smallholder systems, external assistance remains necessary to reduce their vulnerability. According to the modelled smallholder development, this would necessitate improvements in natural and technological resources as well as financial support to enable investments in resources. These findings corroborate important sub-components of the major national development programme “Avança Brasil”. It aims to strengthen smallholder agriculture in Northeast Brazil through improved access to land, water and credits as well as through capacity building (MPOG 2000). However, the findings point to strict requirements for the intended intensification of cash crops along the São Francisco River in order to avoid a further degradation of the natural resources. Furthermore, the changing hotspots of vulnerability that were revealed are suitable to inform the prioritisation of intervention options. They provide valuable insights in order to make local adjustments to the large-scale interventions outlined in the programme “Avança Brasil”.

Importantly, improvements in the smallholder’s resource base would stimulate positive feedbacks in an important area of adaptation to climate stress. Improved resources would serve to increase the currently very limited effectiveness of weather forecasts. For example, smallholders in Ceará are strongly constrained in their capacity to integrate forecast information into their decision-making (Finan & Nelson 2001, Lemos et al. 2002). Reducing the limitations in their resources would mean opening up the choice of crops and production technologies. This would enable smallholders to not only benefit from weather forecasts, but also become more independent of clientelistic structures that significantly constrain, among other things the effectiveness of drought forecasts.

Taken as a whole, the spatial analysis of changes in vulnerability in this section pointed to a significant regression of smallholder agriculture and a narrowing of already limited regional development perspectives in the agricultural sector due to the degradation of natural resources. Integrated quantitative modelling demonstrates that the already problematic conditions in water availability and agricultural production in Northeast Brazil would remain critical in the future or even become more severe and would persistently trigger migration under plausible scenarios of climate change, socio-economic development and policy interventions (Döll & Krol 2002, Krol & Bronstert 2007, Barbieri et al. 2010). Applied to the smallholder systems investigated in this section, these findings at meso- and macroscales imply a decrease in maximum sustainable yield. Such a decrease translates into the necessity to appropriately adjust agricultural land use in order to prevent intensified overuse of natural resources, impoverishment and emigration. Adaptive measures would include the development of further off-farm alternatives as viable supplements to agricultural production.

6 Summary and conclusions

This dissertation substantiated the application of a pattern recognition approach to analysing dryland vulnerability by an extensive discussion of existing pattern analyses in the areas of developmental dynamics and vulnerability. It demonstrated the suitability of pattern recognition in two studies that employed a cluster analysis to identify core patterns of dryland vulnerability at a global scale and in the Peruvian Altiplano. Based on these findings, the dissertation advanced pattern recognition along two lines. On the one hand, it defined conditions under which clustering the natural and socio-economic properties of dryland systems yields patterns that enhance our understanding of the vulnerability of these systems to climate, market and other stresses. On the other hand, by studying smallholder dynamics, it broadened the scope in evaluating endogenously driven changes in the vulnerability patterns identified in Northeast Brazil.

The study at the global scale yielded an overview of generic mechanisms that generate vulnerability to a set of environmental and socio-economic stresses in dryland systems (Chap. 2). This study presents the first vulnerability assessment covering global drylands at a sub-national resolution. It differentiated seven typical patterns of vulnerability given by seven clusters identified. Among them, one cluster indicates the highest vulnerability, primarily found in Africa. It displays the severest conditions in poverty, water stress, natural agro-constraints and isolation, but only a low level of soil degradation. The spatially explicit indication offers the opportunity for regional comparisons to identify hotspots of vulnerability, such as in north and east Africa. Based on the representative indicator combinations at the cluster centres, the study systematically derived and discussed entry points for vulnerability reduction. For example, poverty reduction efforts would need to be combined with improvements in water-use efficiency and regional integration into infrastructural and decision-making networks in large areas of north Africa. Overall, the results provide important insights for decision-making tailored to particular inner-country disparities. Taking Niger as an example, the aforementioned entry points apply to the north of the country, while improvements in the quality of soils in combination with poverty reduction would benefit the reduction of vulnerability in the southwest.

In particular, the global study used independent case study knowledge available for different regions to validate the cluster results. Moreover, it confirmed the hypothesis that a strategy that has reduced vulnerability in a given region is equally successful in another region with similar properties. For this, it drew upon the example of a traditional land rehabilitation strategy. This strategy improved the productivity of soils and consequently food production and rural well-being in various regions of west Africa for which the cluster analysis revealed similar vulnerability profiles. The global coverage of analysis enables the evaluation of regions for which empirical evidence or detailed case studies are not available. This is of particular interest in facilitating the transfer of successful intervention options.

At the local scale, the study in the Peruvian Altiplano investigated typical vulnerability patterns at the household level (Chap. 3). This study focused on the vulnerability of a particular social group to a specific type of stress with regard to an important livelihood aspect. It examined vulnerability of smallholders to weather extremes and its implications for food security. Here, clustering revealed four typical groups of households. Among these, resource-poor, educationally deprived smallholders with highest harvest failure risk and very limited non-agricultural income are the most sensitive and least able to respond to weather extremes.

Due to its focus on specific facets of vulnerability in a small area, the local study facilitated an outcome-oriented validation and ranking procedure using independent information on the purchase of food and fodder as a result of weather extremes. The vulnerability clusters clearly distinguish between households according to their purchase. This finding highlights their explanatory power in making statements about expected damage caused by weather extremes. In addition, independent information on weather-related causes of food insecurity served to validate the mechanisms implied by the clusters. This two-fold procedure presents a more elaborate validation compared to former vulnerability assessments that use either outcomes or underlying mechanisms to validate their results.

Taken together, the experience gained in applying the pattern recognition approach on the global and local scales served to elaborate the necessary conditions for identifying relevant and valid vulnerability patterns (Sect. 5.1). These conditions were summarised in five methodological steps. Prior to the cluster analysis, hypotheses about vulnerability-creating mechanisms were established drawing upon case studies as well as expert and stakeholder knowledge in the first step. The precise definition of the relevant mechanisms is a prerequisite for quantifying the underlying processes and moreover for interpreting, validating and ranking the identified clusters in a consistent way. In the second step, quantitative indicators were chosen to represent the relevant mechanisms. After applying the cluster analysis, in the third step, methodologically robust cluster partitions were selected for further analysis. The selection was based on the reproducibility of cluster results and took into account the degree of differentiation as well as the compactness and dissimilarity of the clusters. In the fourth step, the clusters were validated against independently reported causes and outcomes of vulnerability. Finally, in the fifth step the clusters were ranked according to the distribution of indicators or reported damage caused by stress exposure.

Relying on well-defined and formalised vulnerability-creating mechanisms, this procedure represents a deductive method of pattern recognition. By explicitly outlining each of the methodological steps, the essential elements are provided as a basis for applications of pattern recognition in future research on vulnerability. Such applications could refine specific underlying mechanisms and quantitative indication, such as those suggested in the global analysis to better reflect the dependence of people on natural resources or their degree of isolation.

Smallholder systems were further examined with regard to endogenously driven changes in vulnerability drawing upon the region of Northeast Brazil. A qualitative model simulated the endogenous development of the respective smallholder systems using generalised rules of labour allocation, yield extraction, budget constitution and the dynamics of natural and technological resources (Chap. 4). The resulting cyclic trajectory includes one most critical and one favourable state. While declining smallholder systems in combination with degrading resources specify the most critical state, expanding smallholder agriculture and regenerating resources demonstrate desirable conditions. The modelled states were linked to the patterns of vulnerability identified by the global study in Northeast Brazil (Chap. 2), thereby enabling the assessment of changes in the vulnerability-creating mechanisms. The link was established via the trends of budget, labour allocation and resource quality. Results indicate that conditions had deteriorated in nearly half of the study region in the late 1990s (Sect. 5.2). One important aspect was the overuse of both already degraded and still relatively preserved natural resources. This overuse has the potential to reinforce poverty, such as that illustrated in east Pernambuco and in irrigated areas along the São Francisco River.

The results underline the urgent need for interventions in two areas. First, the existing, though limited agricultural production potential would need to be maintained given the regionally high degree of dependence on the agricultural sector. At the same time, non-agricultural livelihood opportunities would have to be further developed in view of prevailing poverty. These findings generally support governmental development efforts that aim to improve smallholder livelihoods in Northeast Brazil. However, they point out that one of the major aims, namely the intensification of cash-crop production along the Rio São Francisco, requires rigorous deliberations. Appropriate considerations would need to go beyond purely economic aspects in order to halt the degradation of natural resources. Furthermore, the changing hotspots of vulnerability that were revealed may help to set priorities for related interventions. This is an important step towards the intended local adjustment of such large-scale programmes as “Avança Brasil”.

Altogether, the identified patterns of both vulnerability and changes in the underlying mechanisms yield mechanistic knowledge between an all-embracing perspective and the particularities of individual cases, that is to say at an intermediate functional scale. The patterns do not encompass all possible process combinations, but only a limited number of typical mechanisms that shape the vulnerability of dryland systems to particular stresses. Positive feedbacks as illustrated in the poverty-degradation spiral favour the development of such typical conditions. The obtained mechanistic knowledge contributes to an improved understanding of the causal structure of dryland vulnerability.

By considering a manageable number of representative categories indicated by the cluster centres, the pattern approach to vulnerability provides an efficient method of analysis. The meaningful generalisation highlights key constraints which can be influenced by policies to foster sustainable dryland development. Though the representative categories are theoretical constructs which may not exist exactly as such in reality, they function in the sense of archetypes to enhance overall comprehension of dryland vulnerability. Importantly, the selected pattern approach provides transparent clusters which display the constituting vulnerability indicators and their contribution to the cluster profiles. Besides depicting the overall vulnerability situation for a given spatial or functional unit, this transparency enables sectoral-oriented decision-makers to recognise their respective field of responsibility, for example in the agricultural, infrastructural or educational domain.

Overall, the findings of this dissertation may stimulate the discussion of dryland vulnerability and appropriate intervention options at more than one scale. One the one hand, the insights gained in the Peruvian Altiplano and Northeast Brazil differentiate and enrich the spatially and functionally coarse-grained results identified by the global study. On the other hand, the global analysis provides contextual information about adjacent regions which is useful when considering the design of specific intervention options. For example, in view of the very limited agricultural assets and productivity in the smallholder systems investigated in the Peruvian Altiplano, a potential strategy might be to extend agricultural land use into areas that have been either unused or used for less intensive purposes. This however is not a feasible option since the global analysis revealed that water and/or soil resources are already overused throughout the Altiplano. Furthermore, the broad global vulnerability patterns indicate that the integration into physical and decision-making networks is not only required in the Peruvian Altiplano, but at a larger regional scale. Improvements in the currently highly constrained education, healthcare, road and water infrastructures would create valuable opportunities for vulnerability reduction. In this sense, the findings at the various scales should be regarded as being complementary to each other, instead of considering any one scale as the most important. Efforts to reduce vulnerability will have a greater chance of success if they reflect multi-dimensional causes of vulnerability across scales and dynamics in the underlying mechanisms.

Finally, the investigation of typical patterns and dynamics of dryland vulnerability in this dissertation yields three realms for future research. First, building on the insights of relating the identified patterns to independently reported mechanisms and outcomes of vulnerability, a more rigorous validation is needed to increase the credibility of the results further. This applies for example to a cluster at the global level which represents medium poverty but relatively preserved natural resources, for which adequate empirical knowledge is particularly scarce. A sound validation requires methodological improvements in the collection of observational data to reflect spatial and temporal differences in relevant processes adequately. Moreover, improved observational data would enable the enhancement of the quantitative indication of underlying processes and damage caused by stress exposure. Such an advancement would allow researchers to review the substitutability of vulnerability dimensions, such as that implied by the damage-oriented ranking of the vulnerability patterns in the local study. A further important direction of future research relates to distinct constraints and opportunities in the socio-ecological systems. Here, the description of vulnerability-creating mechanisms will gain through refinements in differentiating social groups and evaluating their interactions, such as smallholders and largeholders in Northeast Brazil, and related livelihood options resulting from their degree of dependence on natural resources and integration in social networks. Thirdly, investigating the role of newly arising stresses would allow us to enhance the discussion of vulnerability causes and respective adaptation strategies. In this respect, it is important to realise that strategies employed in order to adapt to one type of stress may in turn trigger exposure to other stimuli. This applies for example to smallholder livelihoods which shift towards cash-crop production or off-farm activities. While a shift to off-farm activities may decrease the sensitivity of smallholder systems to climate stress, it is likely to expose them to previously less important wage fluctuations. The exposure to new stresses thus demands particular attention in strategies for enhancing overall adaptive capacity.

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Appendix A – Cluster analysis

The cluster analysis was performed using a sequence of a common hierarchical and partitioning cluster algorithm, i.e. hclust and k-means, based on sub-routines from the statistics package R (MacQueen 1967, RDCT 2009). There are a number of comparable approaches to estimating the optimal number of clusters (e.g. Mufti et al. 2005, Tibshirani & 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 & Harabasz 1974).

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. A.1). The pairwise comparison was repeated 200 times for each cluster number to identify the cluster number which maximises the consistency measure. The 2x200 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.

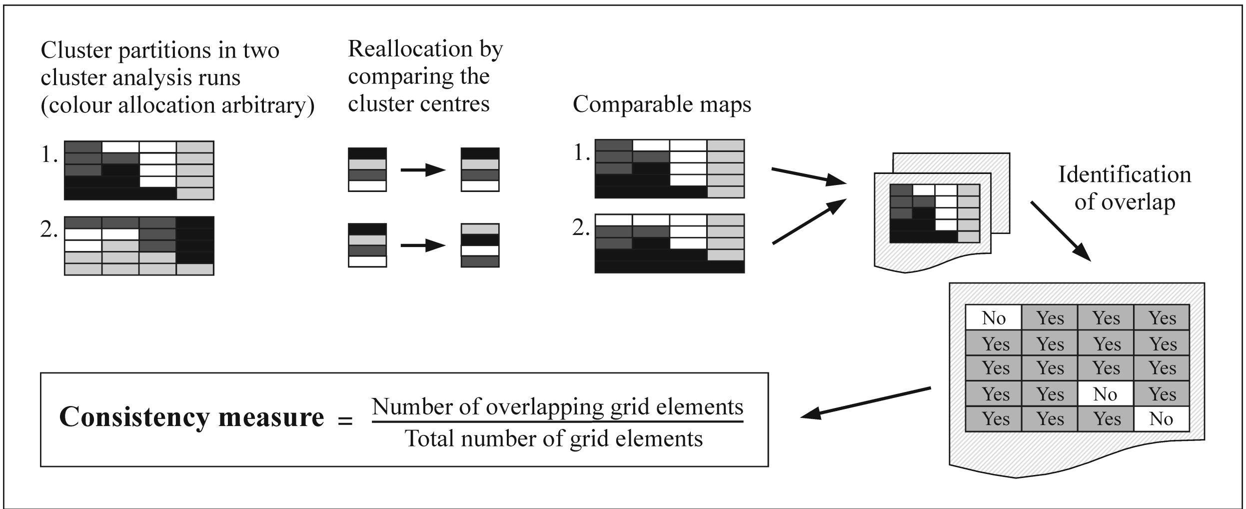

Figure A.1 Approach developed to calculating the consistency of cluster reproductions. An example is given for two cluster partitions showing four clusters.

Table A.1 gives the consistency measure for partitions with 2-10 clusters. 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, partitions with three, five and seven clusters show relative maxima for the consistency measure.

Table A.1 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 to say 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)

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 (Tab. A.1). 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.

Appendix B – Questionnaire for the household validation survey

Date of interview: **Interviewee:**	**Interviewer:** Location: District:

(1) Purchase of food and fodder

- Did you buy or exchange in kind agricultural products that you produced yourself in 2005/06?

 Yes What quantity of each crop did you buy or exchange in kind in 2005/06 as compared to a normal year?

Potatoes	……………..
Quinua	……………..
Broad beans	……………..
Barley	……………..
Oat	……………..

 No

(2) Key questions about the household's food and fodder purchase

(I) Changes in purchase

- Would you please explain why you bought or exchanged more (or less) of the food and fodder crops mentioned above as compared to a normal year?
- Did you sell livestock to buy food in 2005/06?
- Did you or someone in your family engage in a skilled activity outside agriculture to buy food in 2005/06?
- If you exchanged products in kind, what did you exchange them for?
- Did you receive any support by members of your family or your community to deal with food problems in 2005/06?
- Did the number of family members living in your household change in 2005/06?

(II) Prevention of loss in agricultural production

- How did the weather affect your crop production and livestock in 2005/06?
- What measures did you take in 2005/06 to prevent negative effects for crops and livestock?
- Did you cultivate an area as large as usual in 2005/06? If not, for which reasons?
- Did you cultivate land in plains, hillsides and hills in 2005/06? If not, for which reasons?

(III) Perspectives for improving the nutrition situation

- Which measure, do you believe, would be most important in order to improve the nutrition of your family?

Appendix C – Spatial indication of modelled smallholder dynamics

The trend combination of the two variables l_y and rq completely determines the qualitative state of the system. Thus, they were used to indicate the spatial distribution of the modelled states. The value of the variables l_y and rq for each year in the 5-year-period 1995-1999 was estimated using annual statistical data on the municipal level.

In mathematical terms, the indicator for the value of l_y in the year y for a municipio i, $l_{y\,y,i}$, is written as

$$l_{y\,y,i} = \sum_{j=1}^{4} l_y d_j * A^{(c)}_{y,ij} + \sum_{j=5}^{6} l_y d_j * N_{y,ij}$$

where j denotes the six classes of agricultural activities, $l_y d_j$ the relative specific labour demand and $A^{(c)}_{y,ij}$ and $N_{y,ij}$ are the harvested area and livestock quantity of class j in municipio i and year y, respectively. Table C.1 contains the relative specific labour demand, $l_y d_j$, of the different classes.

Table C.1 Relative specific labour demand of the six classes of agricultural activities. In the first three classes, the labour demand relates to the harvest area. (Source: based on Andreae 1977 and Torres 2003, Universidade Federal de Pernambuco, Recife, pers. comm.)

Activity	**Relative specific labour demand ($l_y d$)**	**Examples among major crops**
Cereal crops	1	Rice (beans, corn)
Roots and tubers	7	Manioc (cashew nuts, cotton)
Specialised crops	20	Tomatoes, melons, mangos
Pastures	0.3	
Cattle	2	
Goats	0.25	

The relative specific labour demand and the crop classification are based on Andreae (1977) and adjusted to the context of Northeast Brazil by expert communication (Torres 2003, Universidade Federal de Pernambuco, Recife, pers. comm.).

The indicator for the value of rq in the year y for a municipio i, $rq_{y,i}$, is constructed as follows:

$$rq_{y,i} = \frac{\sum_{j=1}^{63} \frac{m_{y,ij}}{f_{ij}}}{\sum_{j=1}^{63} A_{y,ij}}$$

where the $A_{y,ij}$, $j = 1,...,62$ are the harvest areas of the 62 crops for municipio i in year y, $A_{y,ij}$, $j = 63$ is the respective pasture area for cattle and goats, $m_{y,ij}$, $j = 1,...,62$ are the yields (tons) of the 62 crops for municipio i in year y and $m_{y,ij}$, $j = 63$ is the respective cattle and goat stock in livestock units for municipio i in year y (1 cow/ox = 1 livestock unit, 1 goat = 0.1 livestock units). The f_{ij}, $j = 1,...,63$ are empirically estimated for each municipio i using

$$f_{ij} = \frac{\overline{mij}}{\overline{Aij}}$$

where the lines above the symbols denote temporal means for the years 1995-1999. These conversion factors normalise the crop yields and livestock numbers by crop-specific yields per hectare and typical livestock densities, respectively, and, thus, allow a relative comparison between the different crops and livestock with respect to intensity trends (yields and livestock) in each municipio i. For each municipio i, a linear regression model was fitted to the l_y- and rq-values in the period 1995-1999, respectively. The value for the drought year 1998 was omitted in order to avoid an influence of this value on the trend. Thus, the respective linear models are effectively fitted on the basis of four data points. The signs of the slopes are then used to determine the qualitative state of the system which solely rests on the tuple of l_y- and rq-trend.

To check for the accuracy of the linear fits, the R^2-values have been recorded and translated into significance levels. Using an F-test to test against the null hypothesis ($R^2 = 0$), the significance level of $p = 0.05$ corresponds to $R^2 = 0.9025$. It turned out that 69% of the l_y-fits and 54% of the rq-fits have an R^2 which significantly differs from zero (significance level $p = 0.05$). For a qualitative state to be statistically significant, both l_y- and rq-fit have to be statistically significant which applies to 39% of the municipios. This rather small share of statistically significant qualitative states should be kept in mind interpreting the map of the spatial distribution of qualitative states.

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