Global Environmental Change 25 (2014) 173–185

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Regionalisation of global insights into dryland vulnerability: Better reflecting smallholders' vulnerability in Northeast Brazil☆

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ARTICLE INFO

Article history:
Received 15 August 2013
Received in revised form 15 December 2013
Accepted 22 January 2014
Available online 19 March 2014

Keywords:
Dryland agriculture
Perturbation
Adaptation
Scale
Typology
Qualitative dynamic modelling

ABSTRACT

Global analyses of vulnerability reveal generic insights into the relation between socio-ecological systems and the stress impacting upon them including climate and market variability. They thus provide a valuable basis for better understanding and comparing the evolution of socio-ecological systems from a broad perspective. However, even when reflecting sub-national differences, global assessments necessarily aggregate regional variations in the underlying conditions of vulnerability. Refinements are therefore necessary to better accommodate context-specific processes and hence facilitate vulnerability reduction. This study presents a novel methodology to refining global insights into vulnerability at a regional scale. It is based on a spatially explicit link between broad patterns of vulnerability and modelled regional smallholder development. Its application in order to better represent the drylands of Northeast Brazil reveals specific facets of smallholders' vulnerability at the *municipio* level, reflecting non-linear dynamics. The results show that smallholders' vulnerability was widely exacerbated in the most vulnerable areas. One key mechanism causing such a vulnerability increase involved intensifying resource degradation and the related potential for impoverishment as modelled at the regional scale. In addition, by subsequently re-orienting their livelihoods towards off-farm activities, smallholders became more sensitive to fluctuations and competition in the labour market. In contrast to these critical trends, living and environmental conditions improved in only some areas, thus indicating a decrease in vulnerability. Altogether, in differentiating the heterogeneity of resource management and smallholders' livelihoods, the regional refinement presented in this study indicates necessary adjustments to generic strategies for vulnerability reduction gained at the global scale.

1. Introduction

Global vulnerability analyses provide an overview of generic processes that determine the relation between socio-ecological systems and stress (UNDP, 2004; Brooks et al., 2005; Dilley et al., 2005; Sietz et al., 2011a; ADW, 2012). Typical factors such as the scarcity and overuse of natural resources, poverty and social exclusion help to frame the underlying conditions of vulnerability as multi-dimensional and interactive processes. The evaluation of such generic conditions of vulnerability is valuable in better understanding and comparing the evolution of socio-ecological systems in the face of perturbation. In particular, global vulnerability analyses that reveal similarities among socio-ecological systems may facilitate the transfer of successful intervention options (Sietz et al., 2011a), thus supporting vulnerability reduction efforts substantially. Moreover, a spatially explicit indication of underlying conditions (UNDP, 2004; Dilley et al., 2005; Sietz et al., 2011a) allows an assessment of regions for which empirical evidence is not available.

Due to their worldwide coverage, global assessments of vulnerability inevitably reflect regional conditions only to some extent. Thus, regional facets of specific processes such as the recovery of natural resources, labour allocation, market integration and migration (Eakin, 2005; Sietz et al., 2006; Sallu et al., 2010) are considered in a generalised form only. In addition, global vulnerability assessments are constrained by the availability of high-resolution data for the quantification of underlying processes. Often, available data either cover the systems under

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http://dx.doi.org/10.1016/j.gloenvcha.2014.01.010

investigation only partially (e.g., Lepers et al., 2005; Vörösmarty et al., 2010) or they are limited to larger grid elements (e.g., Alcamo et al., 2003) or even the national resolution (e.g., World Bank, 2008; UNDP, 2010).

A better reflection of regional heterogeneity within environmental and socio-economic conditions would, however, be important for designing policies that are well tailored to particular contexts (Campbell et al., 2006; Andersen et al., 2007; Vetter, 2013). This would help differentiate and enrich generic policies for vulnerability reduction with regard to particular social groups or exposure to specific stresses. Overall, working at an intermediate functional scale, that is to say between an all-embracing global and a purely local perspective, provides a suitable basis for a more successful analysis and more targeted strategies for reducing vulnerability (Cash et al., 2006).

Recognising the value of more differentiated insights, this study aims at improving our capacity to globally assess dryland vulnerability by better reflecting regional heterogeneity for the purpose of enhancing vulnerability reduction efforts. It demonstrates an innovative methodology for refining global insights into dryland vulnerability at a regional scale. Taking the drylands of Northeast Brazil as an example, the refinement considers regional processes that shape the vulnerability of smallholders, focusing on key inter-linkages between agricultural land use and environmental as well as socio-economic conditions. Vulnerability is employed as a concept for framing the relation between smallholder systems and recurrent stress. The concept of vulnerability as applied in this study encompasses exposure to climate, market-related and other stresses as well as the sensitivity of a socio-ecological system to these stresses and its capacity to cope and adapt (IPCC, 2007). This concept is suitable for capturing the multi-dimensional character of vulnerability.

For the purpose of regionalisation, this study links global insights into dryland vulnerability in a spatially explicit way with regional processes relevant to the smallholder systems of Northeast Brazil. It focuses particularly on vulnerability dynamics, that is to say the smallholders' changing ability to assimilate stresses or manage their outcomes. Overall, vulnerability insights are resolved for a significant social group and specific refinements are supported by empirical evidence. Here, the refinement of broad vulnerability patterns to the *municipio* level facilitates decision-making which takes such small administrative units into account. Reflecting the regional heterogeneity of natural resources, their management and the smallholders' livelihoods, the results provide insights that are supportive for locally-adjusted development interventions. Thus, this regional refinement helps to establish more targeted strategies for vulnerability reduction.

2. Background

2.1. Global insights into dryland vulnerability and their refinement

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). Drylands 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 view of the widespread prevalence of resource degradation, food insecurity and migration, 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.

Reflecting the importance of vulnerability reduction efforts, global assessments of drylands provide an overview of key issues pertaining to typical vulnerability mechanisms resulting from the multi-faceted interplay between marginal ecosystems, human societies and environmental as well as socio-economic stress (Dregne, 2002; Geist and Lambin, 2004; Safriel et al., 2005; Jäger et al., 2007; Reynolds et al., 2007; Safriel and Adeel, 2008; Sietz et al., 2011a). Vulnerability mechanisms relate to the scarce and unpredictable precipitation conditions, the degradation of the marginal natural resources, diversification of livelihoods, the importance of policies and institutions and social as well as technological ingenuity as an important stimulus for sustainable dryland development.

Focusing on the most important mechanisms derived from empirical evidence, Sietz et al. (2011a) present the first quantitative assessment of vulnerability in drylands worldwide, based on the best available observational and modelled data with complete coverage of global drylands and sub-national resolution. Data used for indication in the global assessment include measures of the degradation of water and soil resources, poverty, natural agro-constraints and isolation. Here, sub-national indicators express the specific values and distribution of dryland characteristics for countries whose territories include drylands and non-drylands such as Brazil and China. This assessment results in seven typical patterns of vulnerability. Among these, one pattern primarily found in Africa displays most severe vulnerability, indicating the poorest people in the most isolated dryland areas with highly overused water resources, though only a low level of soil degradation (Sietz et al., 2011a). In contrast, the least vulnerable patterns are found in industrialised regions with lowest poverty but with partially depleted water and soil resources. This pattern analysis presents a meaningful generalisation of heterogeneous vulnerability situations in global drylands, allowing their essence to be grasped beyond individual cases and, thus, at a spatially and functionally aggregate level.

The global study presented in Sietz et al. (2011a) allows an assessment of the global distribution and hotspots of dryland vulnerability, based on a limited number of key indicators. Using the representative indicator combinations at the cluster centres, the study systematically derived and discussed strategies for vulnerability reduction and the transferability of successful interventions. The implications for interventions aimed at vulnerability reduction are, however, necessarily broad, thus requiring local adjustments to address specific implementation needs. In this context, the development of approaches to refining global vulnerability insights to specific regional contexts (Birkmann, 2007; GRIP, 2013) arises as an important research field.

In contrast to global assessments, local to regional investigations deliver valuable knowledge on specific characteristics and outcomes of vulnerability, differentiating for example particular social groups or livelihoods (Sallu et al., 2010; Sietz et al., 2012). While stimulating valuable debate, the diverse approaches used to analyse vulnerability in specific dryland areas and elsewhere may complicate the comparison between different studies. In particular, the question arises: how relevant are the specific mechanisms identified in one location for locations elsewhere? This question is important since major decisions for reducing the vulnerability of larger socio-ecological systems are taken at a higher than local level (Adger et al., 2005). Thus, some degree of standardisation is desirable to compare regions. Here, the global perspective provides a suitable basis for developing a common conceptual framework and for standardising methodologies, data collection and knowledge management. To adequately capture the complexity in dryland vulnerability worldwide, however, a global perspective needs to maintain an appropriate level of regional differentiation.

The regionalisation of global insights into dryland vulnerability presented in this study depicts one important step towards integrating more differentiated insights into a global perspective while ensuring comparability at the global level. It is an attempt to bridge the gap between global and regional vulnerability analyses and to contribute to the debate on the usefulness of global approaches for better understanding and reducing vulnerability in drylands and elsewhere (Birkmann, 2007; Twyman et al., 2011). Focusing on vulnerability dynamics of smallholders as an important social group living in drylands, the refinement in this study uses data at *municipio* level, thus with relatively fine spatial resolution, to indicate underlying trends.

The refinement presented in this study takes global insights into vulnerability as reference conditions for the drylands of Northeast Brazil. These reference conditions are linked with the development of smallholder systems in Northeast Brazil as illustrated in Fig. 1. The evolution of smallholder systems at the regional scale is captured by a qualitative dynamic model. A key requirement of such a regional refinement is that the assessment at the higher level captures the main causal conditions important at the lower level in sufficient detail. The regionalisation in this study is feasible since the global assessment (Sietz et al., 2011a) comprises the main determinants of smallholder vulnerability in Northeast Brazil. The methodological approach is further detailed in Section 3. Resulting from the regional refinement, the generic conditions revealed by the global assessment are specified in the context of smallholder systems in Northeast Brazil regarding the use of resources, labour allocation and income generation. These regionalised insights add value to the global-scale assessment since they provide a more realistic perspective on dryland vulnerability in the context of Northeast Brazil. The regional refinement can thus contribute towards adjusting vulnerability reduction efforts based on more differentiated strategies.

2.2. Smallholder systems in Northeast Brazil

This study focuses on the drylands in the Brazilian federal states of Pernambuco, Ceará and Piauí, where smallholders constitute an important social group (IBGE, 2012). Smallholders in this region are involved in the production of subsistence and cash crops such as maize, beans and manioc as well as cashew, cotton, fruits and vegetables to supply the domestic and international markets (BNB, 2000; Voth, 2002; IBGE, 2012). The smallholders are markedly constrained in their access to productive land, water, infrastructure and markets as a result of an inequitable distribution of resources, clientelistic structures and systematic marginalisation (e.g., Mertins, 1982; Carvalho and Egler, 2003, p. 62; Nelson and Finan, 2009).

These conditions significantly limit the smallholders' agricultural production potential. Therefore, agricultural expansion into marginal areas is a widespread livelihood strategy to maintain living standards. Such an expansion, however, enforces pressure on natural resources, leading to further degradation and ultimately reducing agricultural yields (Gomes, 2001; Lemos, 2001). The transformation from tenant-oriented towards rather wage-labour-oriented smallholder systems throughout the region has detached many smallholders from their means of production (Carvalho and Egler, 2003, p. 25). Hence, off-farm activities provide an additional source of income, which is important to sustain the smallholders' livelihoods.

Overall, the Northeast of Brazil is among the poorest regions in the country, suffering from recurrent droughts, stagnation and rural out-migration (IBGE, 2011, 2012; EM-DAT, 2013). In view of the prevailing developmental problems, vast efforts have been made to reduce rural poverty and secure rural livelihoods. Various development programmes, including POLONORDESTE, Projeto Sertanejo and Avança Brasil, involved land distribution, irrigation schemes, infrastructure improvements, market integration and

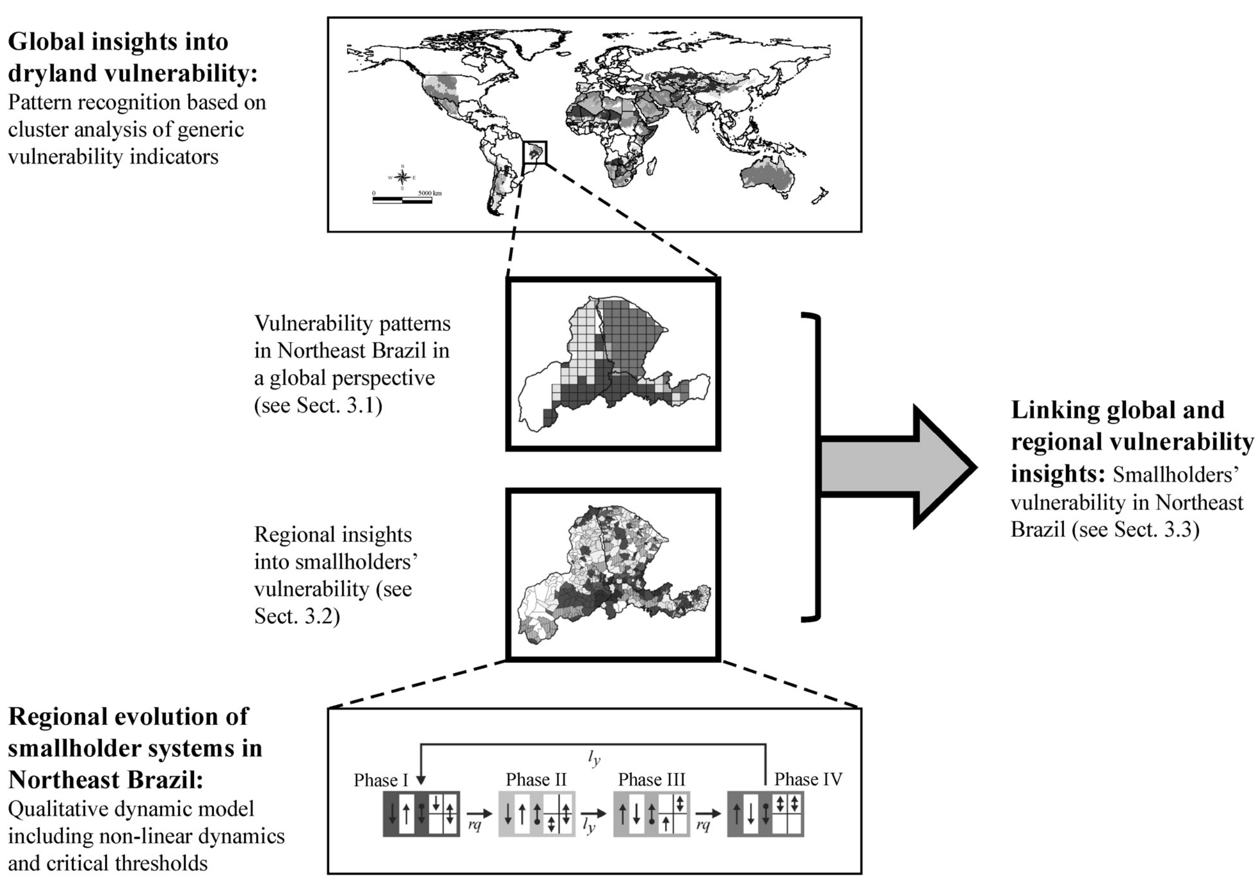

Fig. 1. Methodological approach used in this study to refining global vulnerability insights at a regional scale.

technical assistance as a means of reducing poverty and improving natural resources (Araújo Filho and De Vasconcelos, 1985; Mertins, 1997; MPOG, 2000).

These efforts were, however, neither effective nor efficient (Schwalbach, 1993; Mertins, 1997; Bezerra, 2002, p. 41; Carvalho and Egler, 2003, p. 19f.). Water resources continue to be overused threatening both agricultural and human water security (Vörösmarty et al., 2010). Moreover, the region is significantly affected by desertification (PAN, 2004). Potentially decreasing precipitation and related water scarcity in the future (Krol et al., 2001; Gerstengarbe and Werner, 2003; De Araújo et al., 2004; Krol and Bronstert, 2007) may further challenge sustainable development and, thus, persistently induce migration (Barbieri et al., 2010). Therefore, strategic interventions are still to be developed appropriately. In particular, a better understanding of smallholders' vulnerability to climate, market-related and other stresses may provide stimulus for advancing dryland development in Northeast Brazil.

2.3. Assessing smallholders' vulnerability in Northeast Brazil

Conceptual work in the field of global environmental change emphasises the importance of exposure-driven processes in shaping vulnerability (e.g. Adger and Kelly, 1999; Leichenko and O'Brien, 2002; Turner et al., 2003a; Kasperson et al., 2005; Luers, 2005; Füssel, 2007; IPCC, 2007; Ionescu et al., 2009). These processes include the transforming effects of exposure factors on sensitivity, coping strategies and adaptive capacity. For example, coping strategies may well vary during an on-going 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 differing economic opportunities and social relations.

The perspective of socio-ecological systems which are exposed to stress has provided valuable insights into dryland vulnerability in Northeast Brazil. Past research demonstrates how long-term trends in future climate change, natural resource use and socio-economic development may affect ecosystem services and therefore the people or sectors that rely on them (Krol et al., 2001; Döll and Krol, 2002; Gaiser et al., 2003; Krol and Bronstert, 2007). The results indicate a potential decrease in water availability in conjunction with population growth and an increase in irrigated area. Particularly, regional scenarios of climate exposure, demography, water and land use allow a differentiated discussion of possible future development.

However, exposure-driven processes depict just one aspect of vulnerability. Endogenously driven processes which unfold independently of the impacts of stress exposure play an equally important role in shaping vulnerability (Turner et al., 2003b; Kasperson et al., 2005; Luers, 2005). For example, the sensitivity and strategies to cope with a drought may fluctuate as a result of a re-orientation of livelihoods or the degradation of resources. Smallholders who engage increasingly in off-farm employment may become less sensitive to a drought when relying on more weather-independent activities. However, wage levels and the availability of employment influence their ability to deal with climate and other stresses as shown for smallholders in Mexico (Eakin, 2005). Such transforming processes reshape vulnerability depending on their local intensity. Endogenous processes without stress exposure remain to be assessed systematically in Northeast Brazil in order to identify critical feedbacks and emerging opportunities in smallholder systems.

3. Data and methods

The refinement presented in this study considers insights into vulnerability at a global and a regional scale (see Fig. 1). First, the global insights serve to depict generic vulnerability patterns in Northeast Brazil and to establish the reference conditions. Second, the regional insights into vulnerability are derived from a qualitative dynamic model characterising the endogenous evolution of smallholder systems. Both the global and regional insights into vulnerability reflect the sensitivity and adaptive capacity components of smallholders' vulnerability. After providing an overview of the two sets of input data, this section explains how the broad vulnerability patterns are linked with the regional smallholder development.

3.1. Vulnerability patterns in Northeast Brazil in a global perspective

As a first set of input data, a regional extract from a global study (Sietz et al., 2011a) is taken to characterise the generic conditions under which vulnerability develops in Northeast Brazil. Vulnerability refers here to socio-ecological systems in the face of environmental and socio-economic stress. The extract reveals distinct combinations of vulnerability indicators in Northeast Brazil in a global perspective. These indicator combinations, that is to say patterns, result from a cluster-based categorisation of relevant indicators including information on the degradation of water and soil resources, poverty, natural agro-constraints and isolation, as mentioned in Section 2.1. The indicators characterise vulnerability in drylands at 0.5° resolution, capturing the period of the late 1980s to 1990s. The indicators are outlined in the following paragraphs with regard to smallholder systems.

Regarding resource degradation, the ratio of water withdrawal to availability (Alcamo et al., 2003) is used to indicate the level of water stress. The model used to derive this ratio is based on the consideration that water in Northeast Brazil is mainly withdrawn for agricultural and domestic purposes. The modelled availability of water is determined by surface water. These underlying assumptions are well suited to characterise the agricultural sector in Northeast Brazil, which mainly relies on precipitation (FAO, 2000). In addition, the severity of human-induced soil degradation (Oldeman et al., 1991) provides information about the intensity of soil use. In Northeast Brazil, deforestation and the clearing of natural vegetation are indicated as the main cause of soil degradation. This indication thus relates directly to the effects of agricultural intensification in this region (IBGE, 2012).

Adding to the conditions of natural resources, the global assessment indicates poverty by infant mortality (CIESIN, 2005). This provides an integrated measure of efforts across nutritional, health and environmental dimensions to improve human well-being. Further, natural agro-constraints are given by combined climate, soil and terrain constraints (GAEZ, 2000). Smallholders in Northeast Brazil mainly rely on rain-fed agriculture with irrigation coverage being largely limited to the few perennial rivers such as the São Francisco River (FAO, 2000). Thus, this indicator suitably reflects the smallholders' production constraints.

Finally, the isolation dimension captures the potentials of service supply, income generation and participation in decision-making, indicated by the road density (ESRI, 2002). It characterises the remoteness and the institutional context in which smallholders operate in Northeast Brazil. In particular, better access to service supply and markets (Fay et al., 2005; Macours and Swinnen, 2008) may increase smallholders' capacity to diversify their livelihoods as a strategy for vulnerability reduction. For example, the proximity to urban areas may benefit the non-agricultural sector in rural areas as an important income source (Ferreira and Lanjouw, 2001), particularly in areas with limited agricultural productivity. Thus, a better integration of smallholders and regions in infrastructural and decision-making networks may help reduce regional disparities. Furthermore, to combat poverty and other socio-economic inequalities, functional institutions are

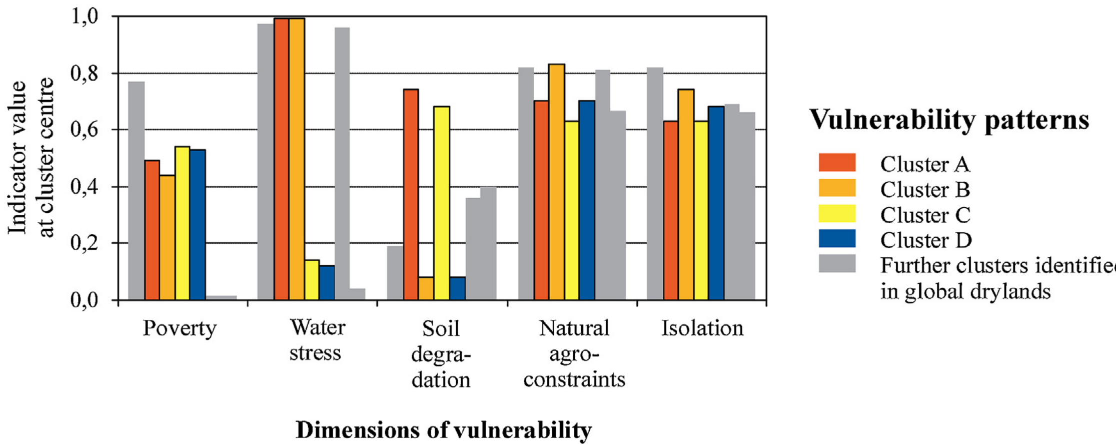

Fig. 2. Characteristics of vulnerability patterns in Northeast Brazil, as compared to the situation in global drylands. Patterns are ranked according to the severity of vulnerability.
Source: Adapted from Sietz et al. (2011a, Fig. 2).

required that address relevant sectors' and stakeholders' concerns and employ a variety of rules for taking decisions (Dietz et al., 2003). In capturing these socio-economic aspects of vulnerability, the isolation dimension merges the following two key features of dryland development: 'remoteness' and 'distant voice' (Reynolds et al., 2007).

Taken together, the global assessment (Sietz et al., 2011a) determines dryland vulnerability as a function of important environmental and socio-economic factors. Consideration of further social dimensions of vulnerability related to the importance, for example, of institutions, power relations and cultural factors (Adger and Kelly, 1999; Crane, 2010; Twyman et al., 2011), would allow an even more differentiated perspective on the underlying conditions. The depth of the global assessment is, however, largely determined by available quantitative information required for capturing sub-national variations in these dimensions.

Based on the indicators outlined above, a cluster analysis revealed seven patterns of vulnerability in drylands worldwide (Sietz et al., 2011a). The patterns or clusters represent recurrent combinations of these indicators. The seven vulnerability patterns are ranked according to the sum of indicator values at a given cluster centre. The ranking procedure reflects the fact that high indicator values represent conditions that contribute to high vulnerability (Sietz et al., 2011a). Thus, this ranking builds a bridge to vulnerability metrics based on index construction. The distribution of indicator combinations highlights the intrinsically non-linear characteristics of dryland vulnerability. For example, vulnerability does not linearly increase with the degradation of water and soil resources.

Out of the seven vulnerability patterns, four clusters are identified in the three federal states of Pernambuco, Ceará and Piauí. The four clusters cover major parts of these federal states. The intersection between the clusters and the federal states is referred to as the "study region" in the following. The respective vulnerability profiles identified for the study region depict high to medium vulnerability in the global comparison (Sietz et al., 2011a). They differ significantly in the severity of water stress and soil degradation, but concur approximately in their levels of poverty, natural agro-constraints and isolation (Fig. 2).

The profiles indicate that the highest vulnerability in Northeast Brazil results from severe water stress and soil degradation described by Cluster A (Fig. 2, dark orange colour). These regionally most vulnerable areas account for about one third of the study region and prevail in Ceará and Pernambuco (Table 1). In contrast, areas with relatively well-preserved natural resources are classified as Cluster D (Fig. 2, blue colour). They characterise the lowest vulnerability and comprise another third of the study region (Table 1). 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 C (Fig. 2, yellow colour) dominate the federal state of Piauí and occur in parts of Pernambuco. They add up to about one quarter of the study region (Table 1). The remaining dispersed areas of Cluster B (Fig. 2, light orange colour) show heavily overused water resources mainly in Ceará and Pernambuco (Table 1).

3.2. Regional insights into smallholders' vulnerability

Regional insights into smallholders' vulnerability in Northeast Brazil are characterised by a qualitative dynamic model (Sietz et al., 2006), serving as a second set of input data. This model reflects important non-linear dynamics in the endogenous evolution of smallholder systems. Quantitative modelling of underlying conditions of vulnerability is not feasible in this study

Table 1
Distribution of vulnerability patterns in the study region according to the analysis of global drylands.

Vulnerability pattern	Federal state			Total area (km^2)	Area share (%)
	Pernambuco (km^2)	Ceará (km^2)	Piauí (km^2)		
Cluster A	11,390	104,730	370	116,490	37
Cluster B	3120	6720	2380	12,220	4
Cluster C	11,550	510	74,740	86,800	27
Cluster D	39,460	980	61,370	101,810	32
Total	65,520	112,940	138,860	317,320	100

due to the limited availability and resolution of data representing smallholder systems. Therefore, qualitative dynamic modelling serves to indicate relevant trends in the evolution of smallholder systems, hence adding mechanistic knowledge to the sparse observational data.

The model assumptions encompass generalised rules of labour allocation, the dynamics of natural and technological resources, yield extraction and the constitution of budget. These rules constitute a qualitative dynamic model which is solved using the QSIM algorithm (Kuipers, 1994; Eisenack and Petschel-Held, 2002). The algorithm computes the entire set of qualitative trajectories that are consistent with the model assumptions.

In particular, the rules upon which the qualitative dynamic model (Sietz et al., 2006) rests include the allocation of yield-oriented and wage labour as well as the quality of resources as crucial determinants of agricultural production. Resources include both natural and technological resources relating to soil fertility, water availability, the possession of technical equipment and access to irrigation. The yield-oriented labour and the quality of resources determine the yield extraction. Moreover, the on-farm share of the budget is constituted by the yield and price of agricultural produce, while the off-farm budget results from wage and wage labour. Finally, the smallholders' total budget is the sum of on-farm and off-farm budgets.

In addition to these basic rules, smallholders' decisions to invest in resources are modelled by relating the budget and yield to the resource quality in the following way (Sietz et al., 2006). First, an existential budget threshold (b_{ex}) is defined beyond which basic livelihood needs are fulfilled and investments in resource regeneration can take place. In addition, the yield includes a threshold (y_{ms}) which describes the maximum level of yield extraction that is sustainable without additional external inputs. Beyond this threshold, natural regeneration cannot balance the loss induced by yield extraction, meaning that the resources will degrade without compensatory measures. Altogether, when yield extraction exceeds y_{ms}, resource degradation can only be compensated for if the budget is higher than b_{ex}. Moreover, a yield $< y_{ms}$ and a budget $> b_{ex}$ allow the resource quality to improve.

Based on these rules, the qualitative dynamic model captures essential non-linear processes of smallholder development. Smallholders' decisions are modelled in an aggregate way and do not explicitly cover other dimensions of decision-making such as subjective priorities or knowledge. For the refinement of vulnerability in this study, it is necessary to know the existence of these thresholds and the behaviour of variables in relation to these thresholds, while actual values depend on locally specific conditions. This qualitative approach enables the comparison of smallholder systems across the study region in a generalised way. Overall, the regional model focuses on the inter-linkages between livelihood options and environmental as well as socio-economic conditions. Specific social dimensions shaping smallholders' vulnerability in Northeast Brazil such as entitlements, power relations, governance mechanisms or the impacts of social transfer programmes (Lemos and De Oliveira, 2004; Nelson and Finan, 2009) remain beyond the scope of the regional model due to model constraints.

The model results in a cyclic trajectory passing through four main phases of smallholder development as summarised in Fig. 3. Each of the modelled phases can be completely described by the trend combination of yield-oriented labour (l_y) and resource quality (rq) (Fig. 3, shaded in the colour of the respective phase). While both trends show the same direction in Phases I and III, they are antipodal in Phases II and IV. Moreover, changes in resource quality and labour allocation characterise the passage between the phases. Passing from Phase I to II, the resource quality improves as a result of decreasing yield extraction below the maximum sustainable yield threshold (y_{ms}). The reverse applies to the transition from Phase III to IV. Finally, changes in labour allocation indicate the transitions into Phase I as well as into Phase III.

With regard to vulnerability, the modelled trajectory involves one most critical and one favourable phase (Phase I and III, resp.). The most critical Phase I describes a regression of smallholder agriculture in combination with resource degradation (Fig. 3, red colour). These trends increase the smallholders' sensitivity to stress and decrease their adaptive capacity. In the model perspective, degrading resources limit agricultural productivity and therefore decrease the profitability of on-farm activities. On the one hand, relying on degraded resources makes smallholders more susceptible to completely losing the harvest when exposed to climate stress. In addition, their ability to produce sufficient amounts and accumulate food reserves for the coming year is limited. On the other hand, when shifting to off-farm activities, smallholders become more sensitive to wage fluctuations and competition for employment. This shift is particularly critical when smallholders are restricted to unskilled work in insecure arrangements. A detailed assessment of smallholders' sensitivity to such stress and their related adaptive capacity goes beyond the regional smallholder model, however, which focuses mainly on their on-farm activities. In contrast to these critical conditions, Phase III describes the expansion of smallholder systems in combination with resource improvement. These trends indicate favourable conditions leading to a reduction in vulnerability (Fig. 3, green colour). The remaining phases, Phases II and IV, constitute transitions between these two opposing trend combinations.

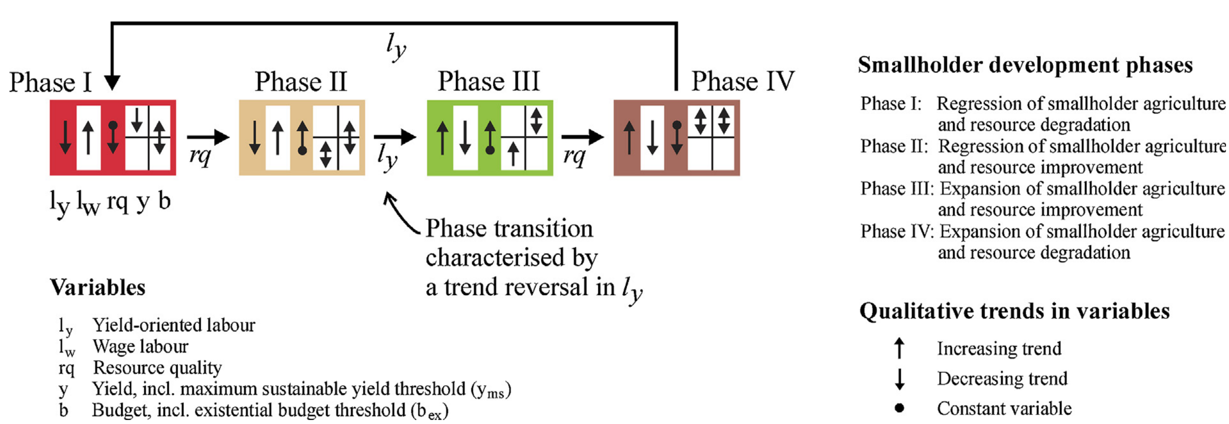

Fig. 3. Modelled phases of smallholder development in Northeast Brazil.
Source: Adapted from Sietz et al. (2006, Fig. 3).

The modelled phases of smallholder evolution were indicated at *municipio* level using crop, pasture and livestock data (IBGE, 2012; Produção Agrícola Municipal; Produção Pecuária Municipal; Censo Agropecuário; for the mathematical details see Sietz et al., 2006). This spatial indication considers the highest resolution at which the relevant statistical data are available. The indication integrates data for all 62 crops registered in the data base of agricultural production as well as cattle and goat keeping.

First, the indication of yield-oriented labour reflects the annual labour requirements for cropping and livestock activities. It is the sum of relative specific labour demands per harvested area and per livestock quantities per *municipio*. In this calculation, agricultural activities were categorised according to six classes (cereal crops, roots and tubers, specialised crops such as tomatoes and mangoes, pastures, cattle and goats). Relative specific labour requirements of these activity classes were determined in relation to the category of 'cereal crops' (conversion factors = 1, 7, 20, 0.3, 2 and 0.25, resp.; based on Andreae (1977) and Torres (2003), Universidade Federal de Pernambuco, Recife, personal communication).

Second, the resource quality captures *municipio* trends of agricultural productivity. These trends are given by the weighted average of the yield per hectare harvested (all 62 crops) and the livestock densities (cattle and goats). Here, livestock units were converted using the following factors: 1 and 0.1 for cattle and goats, respectively. Moreover based on empirical estimates (i.e., observed mean values of yield/livestock units per harvest/pasture area per *municipio*), crop yields and livestock numbers are normalised by crop-specific yields per hectare and typical livestock densities, respectively. This allows a relative comparison between yields and livestock with regard to intensity trends in each municipio.

The spatial indication of both yield-oriented labour and resource quality refer to smallholder-dominated *municipios* (50–100% smallholder area share; IBGE, 2012; Censo Agropecuário) during the years 1995–1999. Choosing this period ensures a consistent methodology since indications at both regional and global scales refer to concurrent time periods. Thus, indication of modelled development trends temporally matches the globally determined vulnerability patterns (Sietz et al., 2011a).

Above all, the indication of yield-oriented labour and resource quality takes into account shorter-term trends relating to the time horizon of smallholder decision-making regarding their labour allocation, investments in resources and agricultural practices. Smallholders take decisions based on, for example, the profitability of agricultural labour or fertilizer prices in relation to yields, which may change rapidly over a few months or years (Brookfield and Stocking, 1999). As conceptualised in the regional model outlined above, the indication of resource quality captures the combined impacts of natural production factors and agronomic inputs such as water availability, fertiliser use and irrigation. In the model perspective, a clear distinction is made between minor modifications which do affect a smallholder system, though without implying a change in a qualitative trend of relevant variables, and major or drastic short-term modifications which do change qualitative trends. An example of the former is minor reduction of water availability (e.g., caused by precipitation variability), conceptualised as one key component of resource quality, which does not make off-farm labour more profitable than yield-oriented labour. In contrast, major drought stress perturbing the smallholder systems illustrates the latter and will be discussed in Section 4.5 in more detail. Finally, longer-term dynamics in labour allocation and resource quality, for example as a result of soil forming factors, go beyond the scope of spatial indication of modelled trends, however. Therefore, the mapping of modelled trends should be considered to be indicative for shorter time scales only.

3.3. Linking global and regional vulnerability insights

The broad vulnerability patterns are coupled with smallholder development in Northeast Brazil in a spatially explicit way to enable a regional refinement. Insights into vulnerability at both scales can be linked since the broad vulnerability patterns tie in, functionally and temporally, with the underlying processes of smallholder evolution modelled at the regional scale.

In particular, the dimensions of water and soil degradation encompassed in the broad vulnerability patterns relate directly to the resource quality in the smallholder model. While the vulnerability patterns capture the conditions of water and soil resources directly, the modelled trends of resource quality additionally take into account the climatic situation, land use practices and related technological resources. Thus, the regional indication of resource quality provides more integrated insights into changes of agricultural productivity. Regarding the regional refinement, if a region with degraded water and soil resources (Cluster A, see Fig. 2) experiences a further decline in resource quality (Phases I and IV, see Fig. 3), the smallholders' capability of sustaining food production and agricultural income will decrease. This means that due to the further loss of productivity their vulnerability will increase.

Given a decline in resource quality, the profitability of yield-oriented labour may decrease to such an extent that wage labour becomes more rewarding (Phase I, see Fig. 3). A consequent relocation of labour towards off-farm activities may ultimately reduce pressure on resources and thus support the improvement of resources (Phase II, see Fig. 3). This mechanism exemplifies a situation in which the smallholders' sensitivity to climate stress decreases. However, due to the rising dependence on wage income, smallholders become additionally more sensitive to stress on the labour market. If economic conditions are advantageous and stress remains limited, poverty may nevertheless decrease and the smallholders' income may exceed the existential budget threshold. This implies that investments are possible to improve the resource quality – a trend described by Phase III (see Fig. 3). Thus, the smallholders' adaptive capacity would increase.

For the regional refinement, the modelled phases of smallholder development and their indication at *municipio* level are overlaid with the broad vulnerability patterns. Based on intersection geo-processing, the features and attributes of the two layers are combined allowing the area share of modelled development phases to be calculated for each of the vulnerability patterns. Thus, the broad vulnerability patterns are resolved at *municipio* level with regard to smallholder development. If a *municipio* falls across two vulnerability patterns, it is split into two separate polygons each containing the portion of the vulnerability pattern falling in each zone. The same applies for vulnerability patterns falling across several *municipios*. Specific regional refinements are discussed in the following section and supported by empirical evidence.

4. Results and discussion

4.1. Regional differentiation of vulnerability

The coupling of broad vulnerability patterns and regional smallholder development results in a differentiation of vulnerability with regard to modelled dynamics in the underlying conditions. Indicated by the prevalence of Phases I and II (Table 2), the study region shows a widespread increase of

Table 2
Cluster area share of smallholder development phases in the late 1990s. (For a characterisation of vulnerability patterns and development phases see Figs. 2 and 3, resp.).

Vulnerability pattern	Area share (%)				
	Phase I	Phase II	Phase III	Phase IV	Total
Cluster A	25	29	26	7	87
Cluster B	32	53	13	0	98
Cluster C	36	41	4	4	85
Cluster D	56	17	4	15	93
Total	37	35	12	7	91

smallholders' vulnerability during the late 1990s. Particularly, 25% of the regionally most vulnerable area (Cluster A) developed even more severe vulnerability (Phase I). Moreover, vulnerability increased in more than half of the least vulnerable regions (Cluster D). In contrast, a decrease in vulnerability occurred in only 12% of the study region (Phase III). The spatial distribution of refined vulnerability patterns is displayed in Fig. 4. Here, the intersection of vulnerability patterns and modelled smallholder development is given according to each of the four development phases. The remainder of this section discusses the regional differentiation with regard to smallholders' vulnerability focusing on both critical and favourable trends in the endogenous evolution of smallholder systems.

4.2. Critical trends in most vulnerable areas

Ceará and east Pernambuco are regions in which the most critical development trends are indicated to exacerbate smallholders' vulnerability in already degraded areas (Fig. 4, upper left part). Overused resources in these regions are shown by a combination of water withdrawal significantly exceeding availability and severely degraded soils (Cluster A). According to the smallholder model, resources continue to degrade ($rq\downarrow$) resulting in less profitable on-farm activities ($l_y\downarrow$) and consequently an orientation towards more profitable off-farm activities (Phase I).

The Valley of Ipojuca, located in eastern Pernambuco (Fig. 4, upper left part), provides an example to illustrate these critical vulnerability trends. In this regional context, river water flow is limited to a few months' water supply per year and is thus highly sensitive to water uptake for agricultural production (FAO, 2000; CONDEPE, 2001). During recurrent water shortages, some areas rely on trucks to supply their population with water from distant areas, e.g., the *municipios* of Pesqueira and Poção. However, despite the limited water resources, livestock and cash-crop production were intensively developed to meet the needs of the relatively dense population in this region (IBGE, 2012). This production increase contributed to the on-going degradation of the valley's soils (CONDEPE, 2001; Lemos, 2001). The resulting decrease in agricultural profitability contributed to the declining importance of the agricultural sector in the late 1990s (CONDEPE, 2001, p. 48). These observations illustrate one possible, endogenous key mechanism leading to a decrease in yield-oriented labour (ly↓), as indicated in the regional model. Besides the overuse of water and soil resources, the effects which droughts (such as the one that occurred in 1998) have on reducing the profitability of yield-oriented labour are discussed in more detail in Section 4.5.

The resource trends in combination with considerable poverty (IBGE, 2012) translate into difficulties in coping with stress. Under these conditions, smallholders are particularly limited in their ability to accumulate food or income reserves that would enable them to cope with droughts or wage fluctuations. When affected by such adversities, smallholders will need to use resources that were earmarked for health, educational and other purposes to compensate for production failure or income reduction, thus constraining their future coping capacity even further.

Similarly, smallholders in other dryland regions attempt to secure their livelihoods through off-farm activities, market integration and migration (e.g., Eakin, 2005; Eriksen and Silva, 2009; Sietz et al., 2012). Nevertheless, employment in the maquiladora textile industry in Mexico, for example, enabled most of the smallholders affected to survive rather than accumulate resources in order to prepare for or cope with climate and economic stresses (Eakin, 2005). Only a few other smallholders living in more closely integrated communities could improve their asset base through the activities mentioned in spite of crop damage caused by extreme weather events. However, they faced low wages and high competition for employment. Overall high rates of out-migration from Northeast Brazil (IBGE, 2011) demonstrate that besides adverse environmental conditions the labour market is significantly constrained, thus limiting the options of securing a livelihood.

4.3. Critical trends in least vulnerable areas

The same critical trend of smallholder development (Phase I) described in the previous subsection is further identified for areas with relatively well-preserved natural resources (Cluster D). These areas are mainly located in Pernambuco and south Piauí (Fig. 4, upper left part). Areas along the São Francisco River serve to discuss these vulnerability trends in more detail.

Critical trends in least vulnerable areas occurred, for example, in the *municipio* of Petrolina (Fig. 4, upper left part), one of the regionally most important irrigation centres (BNB, 2000). Major interventions focusing on the São Francisco River, among them the Sobradinho and Itaparica Dams, have stabilised the river water flow since the late 1970s sustaining the water supply for agricultural and other purposes. Agriculture during the 1970s and 1980s was still practised at a low intensity, so that the deep and fertile soils added to the favourable natural resources prevailing in this region (CONDEPE, 1998). However, agricultural intensification during the 1990s focused on expanding irrigation coverage for cash-crop production, including fruits and vegetables (IBGE, 2012) leading to adverse effects on the quality of soils. The severe salinisation which occurred as a result (CONDEPE, 1998) illustrates one important aspect of resource degradation as indicated by Phase I ($rq\downarrow$).

Stimulated by the demand on the national market, cash-crop production continued to encourage high-yield extraction above sustainable levels (BNB, 2000), triggering on-going degradation. The subsequent decline in agricultural productivity (CONDEPE, 1998), together with the high labour requirements of cash crops and the weak market position of smallholders, caused a partial breakdown of smallholder farms. This observed mechanism depicts a potential endogenous cause of decreasing yield-oriented labour as captured in Phase I ($l_y\downarrow$). Regarding other possible causes, Section 4.5 discusses in more detail the effects which droughts have on reducing the profitability of yield-oriented labour.

Again, this decline should be seen in connection with the availability of alternative livelihoods. For example, in contrast to many other regions in Northeast Brazil, employment and wage conditions are favourable in the region of Petrolina-Juazeiro (Damiani, 1999), such that orientation to off-farm activities may present a valuable alternative to agriculture. Its effects on vulnerability will depend, however, on smallholders' ability to deal with newly arising stresses such as wage fluctuations and competition for employment. Due to the focus on agricultural activities in the smallholder model used for this study, further analysis would be required to evaluate the consequences for smallholders' sensitivity and adaptive capacity in more detail.

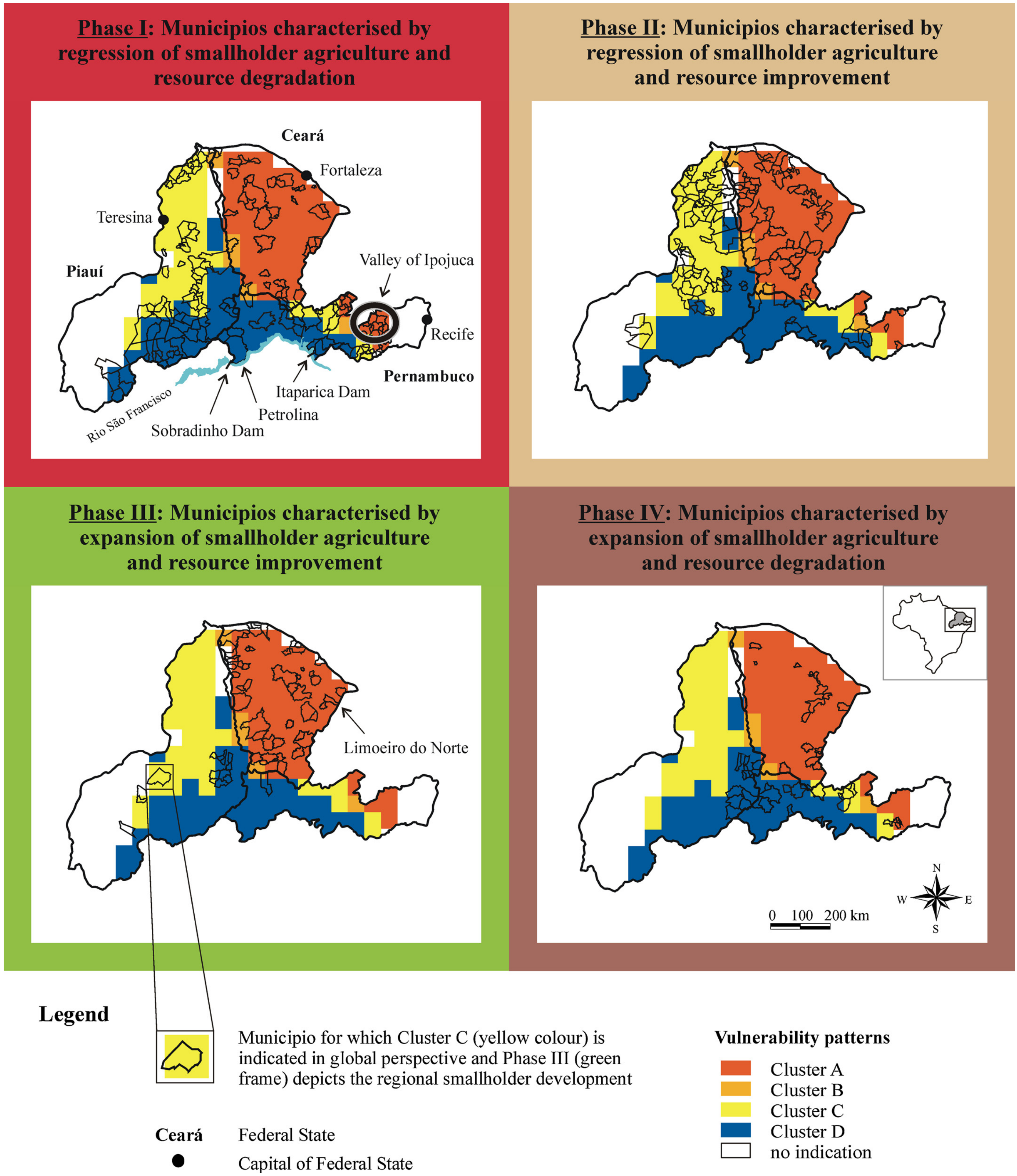

Fig. 4. Refined vulnerability patterns (Clusters A–D) in Northeast Brazil based on four main phases of smallholder development indicated at *municipio* level for the late 1990s (Phases I–IV). (For a characterisation of vulnerability patterns and development phases see Figs. 2 and 3, resp.)

4.4. Favourable trends in most vulnerable areas

In contrast to the critical Phase I, the favourable trends described by Phase III are indicated only for minor parts of the study region. According to the model, these favourable trends involve a recovery of resources, an expansion of smallholder agriculture and a budget sustained above the existential level. Noteworthy areas are found particularly in Cluster A in Ceará (Fig. 4, lower left part).

For example, in Limoeiro do Norte (Fig. 4, lower left part), a formerly water-stressed *municipio*, water supply was improved in the late 1990s leading to an increase in profitability of yield-oriented labour (Da Silva et al., 2004; Matias et al., 2004). In this region, on-farm activities expanded and contributed towards preventing a rural exodus. These processes imply a decrease in smallholders' sensitivity and improvement of their adaptive capacity. However, the recurrent exposure to droughts and other stresses bears the potential to interrupt the favourable trends, consequently deepening poverty, initiating or reinforcing resource degradation and decreasing the profitability of smallholder agriculture. Specific effects of stress exposure are discussed in the following sub-section.

4.5. Exposure to stress

The refinement of vulnerability insights captures core endogenous dynamics of smallholders' sensitivity and adaptive capacity. Due to the inter-linkages of endogenous and exogenous processes, the effects of stresses such as recurrent droughts and price or wage fluctuations are reflected in the observational data used for indication. Exemplarily, the exposure to droughts will be discussed as an exogenous perturbation to the regional model causing changes in the trend of a qualitative variable and in the real-world values of a qualitative threshold.

A drought directly affects smallholder systems in two ways: first, it reduces yields and second, it may decrease the real-world value of maximum sustainable yield (Sietz et al., 2006). A yield loss resulting from a major lack of precipitation such as during the severe drought of 1998 causes yield-oriented labour to become less profitable than before. Hence, a previously increasing trend might switch around, while a decrease will continue. Moreover, a drought may lead to a decrease in the maximum sustainable yield threshold due to an increasing susceptibility of overusing the limited water resources. As a result, the yield is undetermined in its relation to this threshold. These effects of a drought induce transitions and leaps to the Phases I or II of modelled development phases (see. Fig. 3). Here, the relative reduction both in yields and the maximum sustainable yield threshold determine which new phase is reached. If yields decrease to below this threshold, a switch to Phase II is induced. Even if the yield trend remains unchanged, the distance from the maximum sustainable yield threshold may change. This may apply to smallholder systems remaining in the Phases I or II.

This model-based discussion reveals that the recurrent droughts in Northeast Brazil favour the critical phases of smallholder development (Phases I or II), thus contributing to their regional prevalence during the late 1990s (see Table 2). In addition, water availability and agricultural production are likely to remain critical under future climate change (e.g., Döll and Krol, 2002; Krol and Bronstert, 2007). Applied to the smallholder systems investigated in this study, these findings translate into a potential decrease in maximum sustainable yield. Hence, the conditions for impeding transitions from Phases II and III to the more critical Phases I and IV, and thus for preventing an increase in vulnerability, would become even more difficult to meet.

5. Refined implications for development interventions

The global vulnerability analysis revealed generic strategies for vulnerability reduction in Northeast Brazil that were deduced from the indicator values at the cluster centres (Sietz et al., 2011a). These strategies differentiate thematic and spatial priorities in Northeast Brazil mainly related to the improvement of natural resources and poverty reduction. For example, land use intensity would need to be better adjusted to specific conditions of both water and soil resources in Cluster A to reduce resource overuse, while mainly the soil resources are of concern in Cluster B. In contrast, interventions in areas with relatively well-preserved natural resources in the global perspective (Cluster D) would need to focus on maintaining the favourable conditions. In addition, poverty, natural agro-constraints and isolation dimensions would require attention in all three clusters identified in Northeast Brazil. Besides their general applicability, the implementation of specific strategies goes beyond the functional resolution of an analysis with global coverage. Therefore, refinements are needed for designing interventions better tailored to particular local conditions. This study presents one step in this direction.

Based on the regionalisation of vulnerability insights in the previous section, these generic strategies can now be refined with regard to dynamics in the smallholder systems. The spatially explicit indication of trends for the entirety of smallholder-dominated *municipios* enable us to evaluate 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. In addition, the regionalisation highlights areas that display particularly deteriorating trends, thus allowing decision-makers to adapt efforts to reduce vulnerability accordingly. In particular, the critical thresholds implemented in the regional model provide valuable information for decision-making (Safriel and Adeel, 2008; Briske et al., 2010).

High priority for intervention is required in the extended areas encompassing the most vulnerable smallholder systems (Cluster A) that experience intensifying resource degradation and poverty (Phase I), such as in Ceará and parts of east Pernambuco (see Fig. 4). In these areas a transition from Phase I to Phase II would be crucial to reduce smallholders' sensitivity and increase their adaptive capacity. From the model perspective, transitions only proceed under specific conditions related to the magnitude and trends of particular variables. In the areas mentioned above, efforts would be necessary to adjust yield extraction to local thresholds of maximum sustainable yield ($y < y_{ms}$) in order to combat resource degradation. Resulting resource improvements would foster a transition to the less critical Phase II (see Fig. 3). On-going resource improvements would ultimately lead to increasingly profitable yield-oriented labour. This triggers the transition from the still critical Phase II to the favourable Phase III resulting in an even more pronounced decrease in vulnerability.

The refined insights into vulnerability further imply that least vulnerable areas with relatively well-preserved natural resources (Cluster D) are not entirely well-off as far as the quality of natural resources is concerned. Instead, a substantial part of these areas have experienced the same critical trend of increasing vulnerability (Phase I). They would therefore also deserve attention to adjust production to sustainable yield levels in order to halt any incipient degradation of resources and maintain agricultural production potential. This concerns above all areas with subsistence and cash-crop production in west Pernambuco as well as south and east Piauí.

In contrast to these increases in vulnerability, the favourable development Phase III in parts of the most vulnerable areas (Cluster A) in Ceará may provide promising insights into vulnerability reduction. Though these examples are few, they do provide important instances of decreasing vulnerability from a high level of severity. They should be evaluated in detail specifically with regard to the transition from Phase II to Phase III. This transition involves a successive increase in the profitability of yield-oriented labour due to sustainable yield extraction and investments in resources provided that the budget exceeds the existential level ($b > b_{ex}$). Irrigation measures are commonly implemented as a means of increasing agricultural profitability. However, they require careful consideration since inappropriate irrigation may foster a decline in the quality of natural resources. Such a development would ultimately force the transition out of the favourable Phase III into the more critical Phase IV.

Differences in the velocity of underlying processes are crucial for understanding and managing the dynamics of socio-ecological systems (e.g., Carpenter et al., 2001; Gunderson and Pritchard, 2002; Luers, 2005; Folke, 2006). Above all, slowly changing conditions that induce shifts to more critical phases are of importance. The underlying processes of changing vulnerability considered in this study relate mainly to fast changing conditions. However, the variable of resource quality captures the properties of soils as a slowly changing condition (Freibauer et al., 2004). Soil salinity serves here as an example to depict the importance of a slowly changing condition. High levels of soil salinity can be the result of inappropriate irrigation such as that exemplified in the *municipio* of Petrolina. When soils are insufficiently drained over a long time, the salts accumulate in the root zone leading to a decline in agricultural production. Hence, adjustments in irrigation procedures to local soil properties would be necessary to stabilise or improve the soil quality. To enable an adequate response, slowly changing properties need to be monitored with care to identify critical shifts in the long run. In this study, the spatial indication of smallholder dynamics used to apply the new regionalisation approach depicts above all shorter-term trends. In future applications, a more rigorous investigation of slowly changing conditions would require an indication based on longer time series.

Considering the continuing challenge of vulnerability reduction in Northeast Brazil, the insights gained in this study are suitable for locally adjusting large-scale efforts of major national development programmes such as "Avança Brasil" (MPOG, 2000) and informing the prioritisation of related interventions. For example, they affirm that one of the major aims, namely the intensification of cash-crop production along the São Francisco River, requires rigorous deliberations. Some of the areas along the São Francisco River displayed in the past relatively well-preserved natural resources (Cluster D), but have experienced a decline in resource quality, such as the *municipio* of Petrolina (see Fig. 4). Development initiatives would therefore particularly need to address the issue of maintaining and improving the quality of resources.

Resource improvements, among others, would stimulate positive feedbacks in the currently very limited effectiveness of weather forecasts as an important area of adaptation to climate stress. For example, smallholders in Ceará are strongly limited in their capacity to integrate forecast information into their decision-making (Finan and Nelson, 2001; Lemos et al., 2002). Improving the quality and quantity of their resources would lead to an increased choice of crops and production technologies. In addition, it would enable smallholders to become more independent of clientelistic structures which significantly constrain the effectiveness of drought forecasts, among other things (Finan and Nelson, 2001; Lemos et al., 2002).

In the climate change community, it has often been argued that strategies for reducing vulnerability need to be integrated into the wider development planning in order to be successful (e.g., Huq and Reid, 2004; Agrawala, 2005; Kok and De Coninck, 2007). This integration, also called mainstreaming, is not only determined by available resources and 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 (e.g., Lasco et al., 2009; Sietz et al., 2011b). Thus, in addition to technical approaches, the operationalisation of refined strategies for vulnerability reduction revealed in this study needs to consider the specific institutional context of Northeast Brazil.

Institutional requirements necessary for successful vulnerability reduction would include truly transparent and participatory decision-making as well as overcoming government patronage as an institution that reinforces the lack of adaptive capacity (Nelson and Finan, 2009; Lemos et al., 2013). The reform in the Brazilian water sector provides an example of the ways in which more transparent water governance may contribute to improvements in adaptive capacity (Lemos and De Oliveira, 2004; Engle and Lemos, 2010). Among the key changes in reforming the water sector, environmental and socio-economic concerns have been better integrated, water management has become focused on river basins as a unit of decision-making and stakeholder councils have been created. A detailed assessment of specific governance and institutional mechanisms relating to power distribution among stakeholders, knowledge access and freedom of expressing interests and concerns would provide valuable knowledge to further refining the insights gained in this study.

6. Summary and conclusions

Reflecting the importance of fine-scale processes in shaping vulnerability, this study outlined a novel methodology to refining global insights into vulnerability to environmental and socio-economic stresses at a regional scale. The refinement was applied to better capture regional aspects of smallholders' vulnerability in the drylands of Northeast Brazil. It was based on a spatially explicit link of broad vulnerability patterns determined at a global scale with modelled trends of smallholder development at a regional scale. This approach presents one way of extending the capabilities of a global assessment of dryland vulnerability in a way that allows regional heterogeneity to be reflected more appropriately.

The combination of both clustering and qualitative dynamic modelling used in this study is well suited to the task of revealing the non-linear dynamics of vulnerability. The refined insights enable an improved understanding of dryland vulnerability and a differentiation of generic strategies for vulnerability reduction derived at the global level. Spatial indication of refined insights captures the period of late 1990s, such that modifications in vulnerability resulting from changes in the underlying environmental and socio-economic conditions since the turn of the millennium remain to be assessed in the future.

The refinement indicates that vulnerability increased in the late 1990s in areas with already degraded as well as still relatively well-preserved natural resources, due to persistent or incipient resource overuse as shown by the regional model. This resource overuse may reinforce poverty, such as that illustrated in east Pernambuco and in irrigated areas along the São Francisco River. In contrast to these critical changes, another trend towards enhanced living and environmental conditions, thus decreasing vulnerability, occurred in the study region – but only in some areas. Here, smallholders secured their income above the existential budget while improving their resource base and extending their agricultural activities. Notably, the regionally most vulnerable areas showed this favourable trend.

This study establishes an efficient approach to refining broad vulnerability insights and related intervention options based on the evaluation of a limited number of typical patterns in underlying conditions. The resulting mechanistic knowledge underlines key aspects of smallholders' vulnerability in Northeast Brazil which are suited to adjusting development interventions accordingly. The complete coverage of smallholder-dominated areas enables an evaluation of smallholder systems in their wider context, even in poorly-documented areas. In addition, the similarities revealed in the regional refinement provide useful insights for a potential transfer of successful adaptation strategies.

The cyclic trajectory of endogenous smallholder development points to a persistent need to create or ensure sustainable development conditions. This means that inappropriate decisions can still be corrected. Once a problematic development phase is entered, immediate interventions are required in order to accelerate a transition into a more favourable phase. To estimate the efforts needed for such a transition, the velocity of the relevant processes and the distance from critical thresholds in budget and yields would need to be assessed in more detail. In addition, the development of off-farm alternatives as viable supplements to agricultural production is another area in need of future research. Investigations of newly arising stresses related to such shifting livelihoods would allow us to enhance the discussion of vulnerability dynamics and suitable adaptation strategies.

By taking into account the heterogeneity of regional smallholder conditions, this study provides new impetus for assessing vulnerability between an all-embracing global perspective and regional particularities of socio-ecological systems. The global assessments used in this study well reflects the diversity of drylands, thus allowing a direct link to a variety of relevant regional conditions. The use of global vulnerability insights as reference conditions for the regionalisation facilitates the generalisation and comparison of refinements carried out in various dryland regions. Moreover, the refinements revealed in this study enable a more differentiated understanding of dryland vulnerability and thus allow for more efficient approaches to reducing vulnerability at larger scales. Future applications of the approach outlined in this study should consider the integration of additional social dimensions of vulnerability, including institutions and power relations shaping the smallholders' adaptive capacity. The methodology outlined here enables such an integration in cases where relevant information exists at regional to global scales or, alternatively, the underlying processes tie in with the processes captured at higher scales.

Feeding back to case study research, regionalised mechanisms such as those identified in this study may stimulate investigations in order to further elaborate our knowledge. Taken together, the findings at various scales should be regarded as being complementary to each other, instead of any one scale being considered the most important. Efforts to reduce vulnerability will have a greater chance of success if they reflect multi-dimensional conditions of vulnerability across scales and dynamics in the underlying mechanisms.

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