Reg Environ Change (2006) 6: 132–146
DOI 10.1007/s10113-005-0010-9

ORIGINAL ARTICLE

D. Sietz · B. Untied · O. Walkenhorst
M. K. B. Lüdeke · G. Mertins · G. Petschel-Held
H. J. Schellnhuber

Smallholder agriculture in Northeast Brazil: assessing heterogeneous human-environmental dynamics

Received: 30 March 2004 / Accepted: 13 December 2005 / Published online: 14 April 2006

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 consists 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.

Keywords Rural poverty · Rural development · Semi-arid · Qualitative modelling · Syndromes

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 and 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 aggregated 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 geographically explicit (Lüdeke et al. 2004) or model their dynamics (Petschel-Held and 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 and 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 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

We regret to have to announce that since the writing of this article one of its authors, Gerhard Petschel-Held has died.

D. Sietz (✉) · O. Walkenhorst · M. K. B. Lüdeke
G. Petschel-Held · H. J. Schellnhuber
Potsdam Institute for Climate Impact Research,
Telegrafenberg, 14473 Potsdam, Germany
E-mail: sietz@pik-potsdam.de
Tel.: +49-331-2882554
Fax: +49-331-2882600

B. Untied · G. Mertins
Department of Geography, Deutschhausstraße 10,
35037 Marburg, Germany

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 paper 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.

Smallholder agriculture and major problems in Northeast Brazil

Northeast Brazil is traditionally subdivided into four natural units: the Zona da Mata, the Agreste, the Sertão and the Campos Cerrados (Fig. 1). To cover the major smallholder-related development, this study focuses on a transect across these four natural units

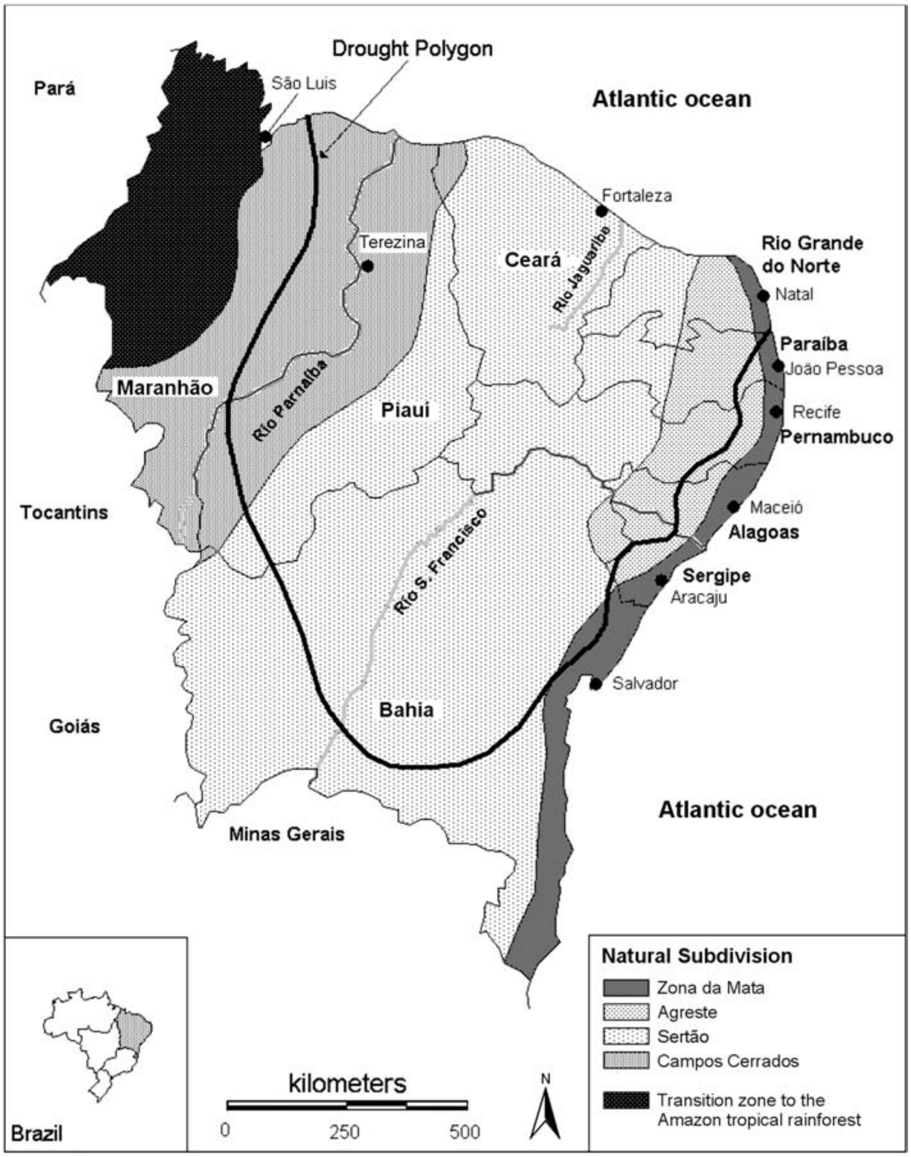

Fig. 1 Natural subdivision of Northeast Brazil. (Source Rönick 1986)

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 1999). A transition zone regarding natural as well as socio-economic conditions towards the Sertão forms the adjacent Agreste (Kohlhepp 1994). Small- 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; 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 to the global market (Andrade 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 100 ha, 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).

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 and 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 and 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 and 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.

Methodology

Conceptual framework

The phenomenon described previously 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, e.g. the actual yield. 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, considering, e.g. 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 aforementioned discussion, 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, Araujo 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 and Shiferaw 2004) heterogeneity is poorly represented. This is because of 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 an 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 first 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 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.

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 and 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 (ly) and off-farm labour (lw) as shown in Eq. 1 (subsequently). While for on-farm activities, the smallholder is the manager of his production resources, including soil, water and pasture, 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:

$$\mathrm{lt} = \mathrm{ly} + \mathrm{lw} \tag{1}$$

$$\mathrm{y} = \mathrm{f}(\mathrm{ly}, \mathrm{rq}) \tag{2}$$

with

$$\frac{\partial \mathrm{f}}{\partial \mathrm{ly}} > 0 \quad \frac{\partial \mathrm{f}}{\partial \mathrm{rq}} > 0 \quad \mathrm{f}(0, \mathrm{rq}) = \mathrm{f}(\mathrm{ly}, 0) = 0$$

$$\mathrm{b} = \mathrm{e_w} \times \mathrm{lw} + \mathrm{b_y} \tag{3}$$

with

$$\mathrm{b_y} = \mathrm{y} \times \mathrm{e_p}$$

$$\mathrm{b_w} = \mathrm{l_w} \times \mathrm{e_w},$$

where lt: total labour available, *y*: yield, ly: agricultural labour input, *b*: budget, lw: off-farm labour input, b_v: on-farm budget share, rq: resource quality, b_w: off-farm budget share, e_w: effective wage per hour, 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 (ly) and the actual resource quality (rq) according to Eq. 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_v) 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 obtained budget into the development of the resources. In line with evidence from Northeast Brazil (CONDEPE 2001, 47; Mertins 1997, 7), 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 for the development of on-farm labour. The effective price as well as 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.

$$\frac{\mathrm{dlw}}{\mathrm{dt}} = \mathrm{e_w} - \mathrm{e_p} \times \frac{\mathrm{y}}{\mathrm{ly}}. \qquad (4)$$

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, personal communication). Hence, decrease in resource quality resulting from yield extraction exceeding the threshold y_{ms} may be compensated. Figure 2 shows the assumed trends of resource quality depending on all possible combinations of yield and budget. Thus the investment decision is highly aggregated and does not explicitly cover other dimensions of decision making such as subjective priorities or knowledge.

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

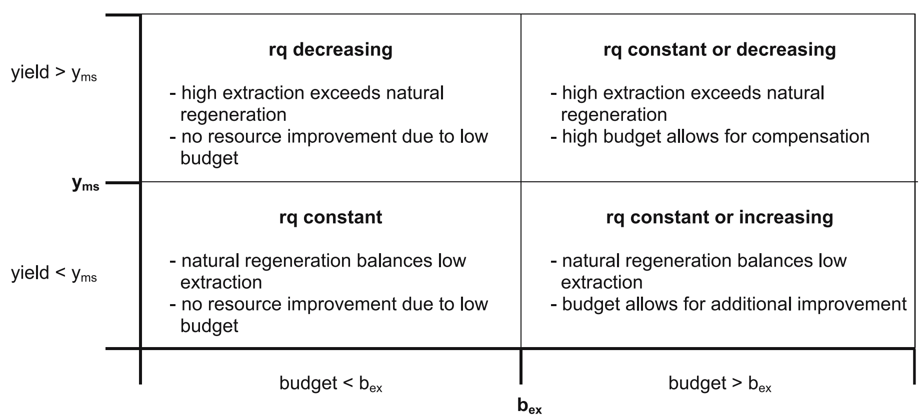

Fig. 2 Model assumptions on resource quality (rq) trends depending on budget (b) and yield (y)

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 Instituto Brasileiro de Geografia e Estatística (IGBE) and 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 only have 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 (ly) and resource quality (rq) (Fig. 3). While both trends show the same direction in state 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 and the natural processes of soil degradation and recovery (Pimentel et al. 1995; Brookfield and Stocking 1999). This subsection contains a basic description of data and analyses the techniques used. Details concerning the indicators as well as the assessment of their uncertainties are provided in the appendix.

The trends for rq and ly are estimated for the years 1995–1999 based on the data listed in Table 1. The indicator for the yield-oriented labour ly 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, pasture, cattle and goats—differ with respect to their relative specific labour demand according to Andreae (1977). The trend for ly 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 weighted 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.

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 Fig. 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, personal communication).

Results and discussion

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. 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, e.g. the oscillation of one variable while the other trends are stable. Such a behaviour is symbolised by double arrows in Fig. 3. In the following, these four summarised states are merely called states.

In view of smallholders' livelihoods, state I displays the most critical conditions. As socio-economic stress is

Table 1 Statistical data used

Datum	Units	Time resolution	Source
Harvest area for 62 crops	Ha	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 pasture and improved grassland	Ha	1985, 1995	CAP (IPEA)
Farm size distribution (15 size classes)	Ha/class	1995	CAP (IBGE)
Income distribution (16 income classes)	Capita/class	2000	CD (IBGE)
Share of rural population	%	1996	CD (IBGE)
People working in the primary sector	Number	1995	CAP (IBGE)

PAM Produção Agrícola Municipal, *PPM* Produção Pecuária Municipal, *CAP* Censo Agropecuária, *CD* Censo Demográfico, sources: *IBGE* Insituto Brasileiro de Geografia e Estatística, *IPEA* Instituto de Pesquisa Econômica Aplicada) reflected by an undetermined budget, that can drop below the existential threshold, the smallholders' investments into the 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 the 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 smallholder's on-farm activities are regressing (ly↓), 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 ly) 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 into the resources.

State III: Expansion of smallholder agriculture and resource improvement State III shows increasing on-farm labour (ly↑) 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

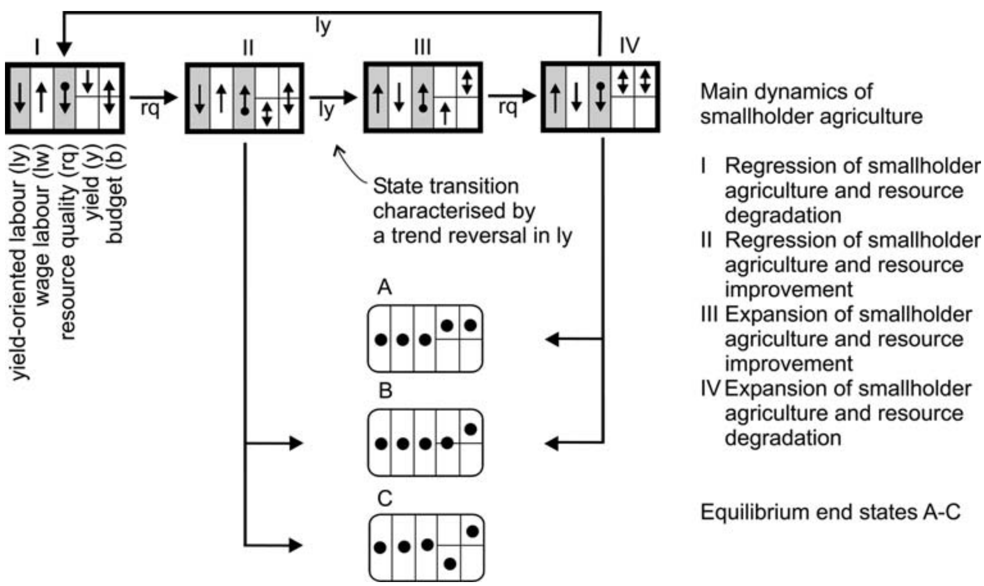

Fig. 3 Modelled qualitative dynamics of smallholder agriculture with the five relevant variables. The *boxes* represent cycle states (*I–IV*) showing time evolutions—trends and magnitudes—of the variables. Trends are symbolised by *arrows*. In the case of yield and budget, their position refers to landmarks indicating their magnitude. *Dots* indicate that the variable is constant over time. In addition, the trend combinations of ly and rq are shaded in *grey*. The model results include final equilibrium states (*A–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

exceeds the local production potentials (yield > y_{ms}). Thus, resource degradation can only be prevented if the smallholder invests part of his budget into resource conservation. A successful investment, however, presupposes knowledge on 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. 3).

The passage from state I to state 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 state 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↓) and a potential overuse of the soils (yield > y_{ms}). Therefore, the transition from state III to state IV is ultimately forced.

Changes in *labour allocation* indicate the transitions into the critical state I as well as into the desirable state III. The transition from state IV to state I shows that due to high yield extraction (yield > y_{ms}) and—without appropriate investment—degrading resources (rq↓), 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 state 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 into their own re-

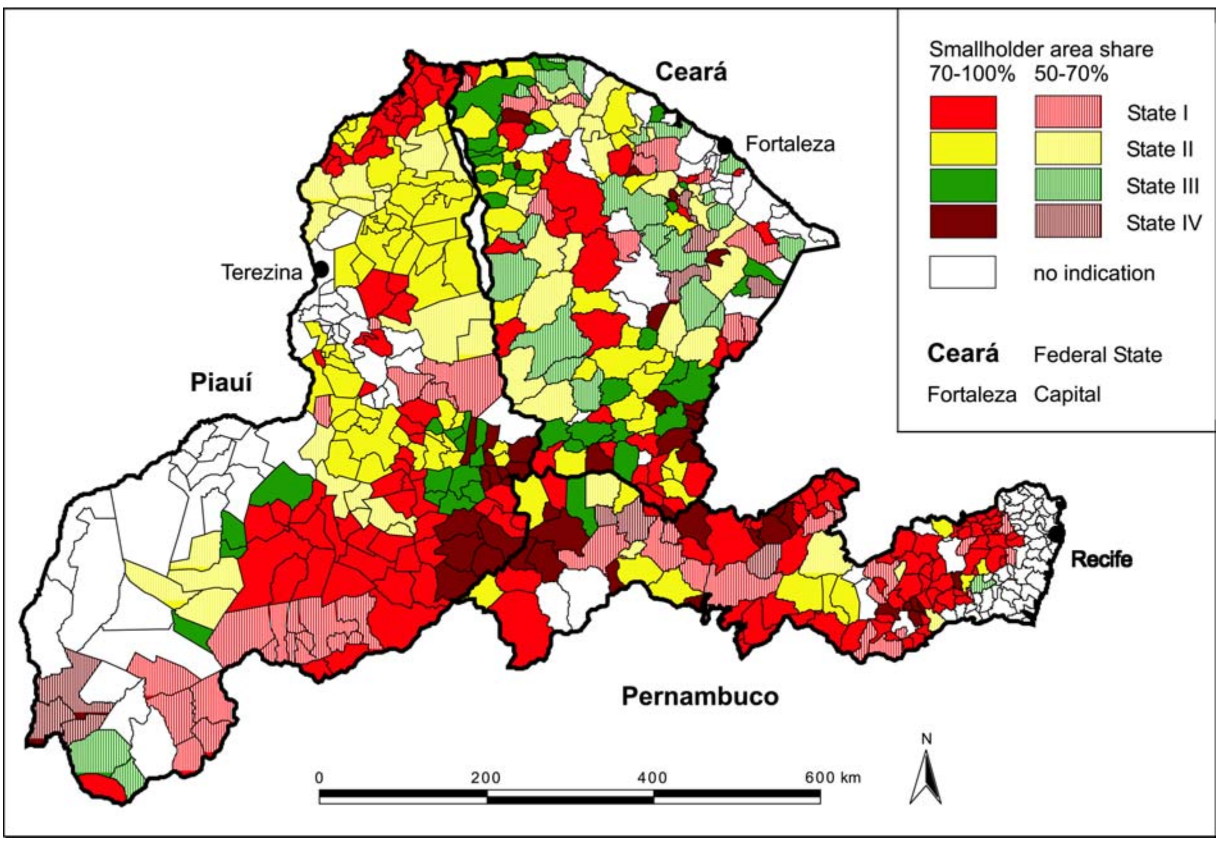

Fig. 4 Spatial distribution of the four qualitative states I–IV at the municipal level for the three federal states Pernambuco, Ceará and Piauí. Trends refer to the years 1995–1999. The *colours* reflect the criticality of local conditions. The *filled areas* are characterised by a very high area share 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

sources (state II). This results in an improving resource quality which bears a great potential that on-farm labour becomes more attractive and smallholders allocate more labour to agricultural production. Hence, the transition from state II to state 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 river São Francisco 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 (B. Untied, personal communication).

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 11 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 IGBE and IPEA appeared to be too noisy to extract significant trend changes of the variables. These data still allowed 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.

Spatial distribution of smallholder dynamics

The spatial distribution of the four qualitative states I–IV (cf. Fig. 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, increasing on-farm activities in combination with an undetermined trend in resource quality (states I and II, respectively) are widespread (Fig. 4). Their predominance confirms the critical development of rural poverty and out-migration in Northeast Brazil. The choice of colours for the states depicts the criticality of local conditions.

Clusters of 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 clusters of state IV occur predominantly in northwestern Pernambuco and in southern Ceará.

The uncertainty associated with the largeholder share is represented by the hatching in Fig. 4. The lower the smallholder area share, the more uncertain 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 beans production in Southwest Piauí are 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 is 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 clusters 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 into their resources, less pressure is put on soil and water. Hence, the resource 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 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 state III can be indicated with sufficient reliability and will therefore be discussed in the following. Figure 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.

As Fig. 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

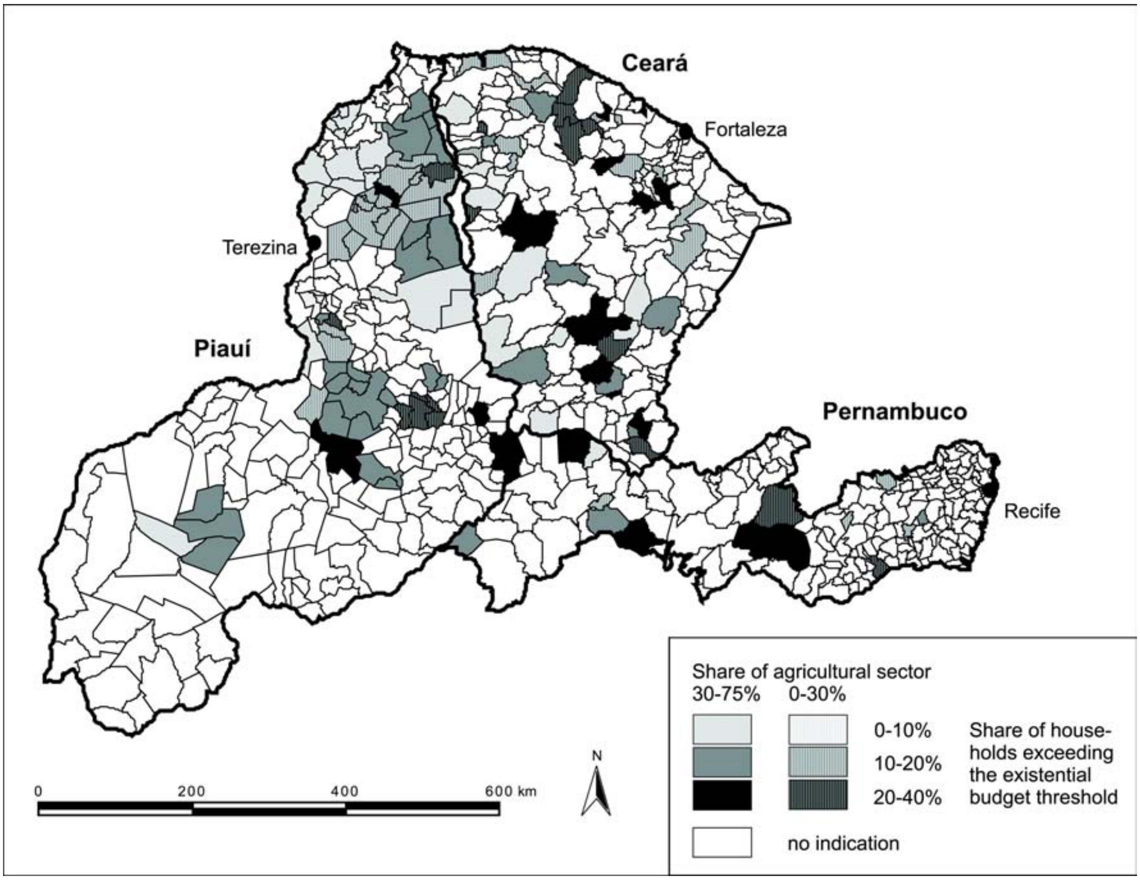

Fig. 5 Spatial distribution of the transition likelihood from state II to state III as indicated by the share of households in which the wage of the head of household exceeds the existential budget threshold. The indication of state II is based on trends of the years 1995–1999, budget data refer to the 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

II. The majority of the municipios depict a share of below 20%. Therefore, the internal transition likelihood from state II to state 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 river Jaguaribe 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 Fig. 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.

External shocks

The model presented only captures the internal dynamics of smallholder agriculture in Northeast Brazil. External shocks, e.g. climate extremes or 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 into 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, e.g. 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 into 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

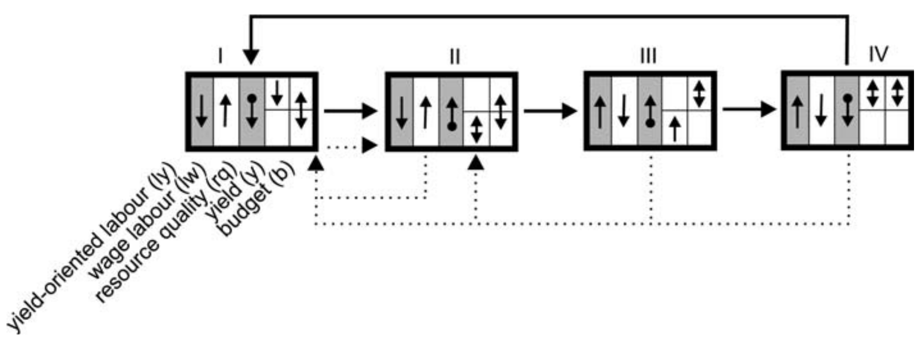

Fig. 6 Possible state transitions and leaps due to a massive drought (*dotted lines*)

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 effect 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. Vice versa, a trend of increasingly 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 Fig. 6 (see dotted lines).

According to Fig. 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 of producer output prices

Dropping 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 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 III to II is not possible from the endogenous model dynamics, the evolution from IV to I has its endogenous analogue. Thus this transition is accelerated by the price drop.

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 Fig. 4.

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, and the investment into 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 five 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 system. 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.

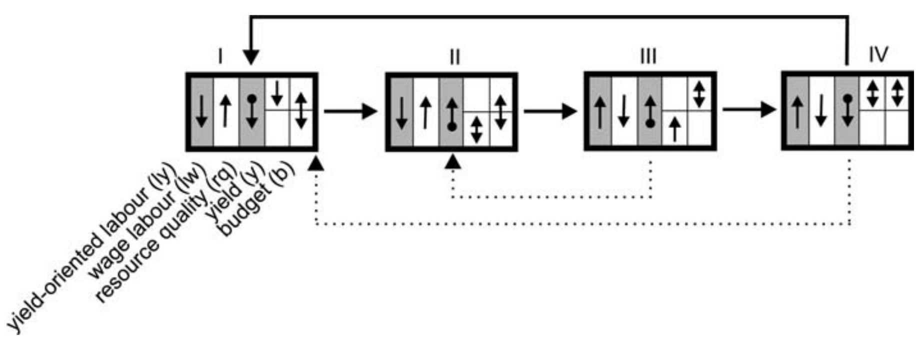

Fig. 7 Possible state transitions and leaps due to a drop in producer output prices (*dotted lines*)

We have shown in this paper 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 for 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 to join the syndromatic part of the trajectory. Figure 4 presents an example for 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). Thereby, 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 against which the system is sensitive.

Table 2 Relative specific labour demand of the six classes of agricultural activities

Activity	Relative-specific labour demand (lyd)	Examples among major crops
Cereal crops	1	Beans, corn, rice
Roots and tubers	7	Manioc, cashew nuts, cotton
Specialised crops	20	Tomatoes, melons, mangoes
Pastures	0.3	
Cattle	2	
Goats	0.25	

In the first three classes the labour demand relates to the harvest area

Appendix

Spatial indication of modelled states

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

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

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

where j denotes the six classes of agricultural activities, $\mathrm{ly}d_j$ the relative specific labour demands 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 2 contains the relative specific labour demands, lyd_j, of the different classes.

The relative specific labour demands 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, personal communication).

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

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

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

$$f_{ij} = \frac{\overline{m}_{ij}}{\overline{A}_{ij}},$$

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 ly- 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 ly- and rq-trend.

To check for the goodness 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 ly-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 ly- 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.

References

Andrade de Oliveira MC (1999) Atlas Escolar de Pernambuco. Espaco, Geo-Historico e Cultural, Recife

Andreae B (1977) Agrargeographie, Strukturzonen und Betriebsformen in der Weltwirtschaft. de Gruyter, Berlin New York

Araujo de JC, Döll P, Güntner A, Krol M, Beghini Rodrigues Abreu C, Hauschild M, Mendiondo EM (2004) Water scarcity under scenarios of global climate change and regional development in semiarid Northeastern Brazil. Water Int 29(2):209–220

Barbier EB (1990) The farm-level economics of soil conservation: the uplands of Java. Land Econ 66(2):199–211

Barret S (1991) Optimal soil conservation and the reform of agricultural pricing policies. J Devel Econ 36:167–187

Bezerra NF (2002) Água no semi-árido nordestino. Experiências e desafios. In: Hofmeister W (Hrsg.) Água e desenvolvimento sustentável no Semi-Árido. Fortaleza, pp 35–51

Blaikie P, Brookfield H (1987) Land degradation and society. Methuen, London

BNB (2000) Fruticultura Irrigada: Os casos das regiões de Petrolina-Juazeiro e Norte de Minas Gerais. Fortaleza

Brookfield H, Stocking M (1999) Agrodiversity: definition, description and design. Glob Environ Change 9:77–80

Carvalho O, y Egler CAG (2003) Alternativas de desenvolvimento para o Nordeste semi-árido. Fortaleza

CEPRO (2003) O Piauí hoje. Conjuntura econômica. Análise Geral da Economia Piauiense. Fundação Centro de pesquisa econômicas e sociais do Piauí, Teresina

Collins JL (1987) Labor scarcity and ecological change. In: Little PD, Horowitz MM, Nyerges AE (eds) Lands at risk in the third world: local-level perspectives. Westview Press, Boulder, pp 13–29

CONDEPE (2001) Monografia da Microrregiao do Vale do Ipojuca

Damiani O (1999) Beyond market failures: irrigation, the state and non-traditional agriculture in Northeast Brazil. Environ Manag 59:279–298

DFID (2000) Sustainable livelihoods guidance sheets. http://www.livelihoods.org

Eisenack K, Petschel-Held G (2002) Graph theoretical analysis of qualitative models in sustainability science. In: Working papers of 16th international workshop on qualitative reasoning, pp 53–60. http://www.upc.es/web/QR2002/Principal.htm

Elias D (2002) O Novo Espaço da Produção Globalizada. O Baixo Jaguaribe. Fortaleza

Eswaran H, Reich P, Beinroth F (1999) Global desertification Tension Zones. In: USDA (ed) Sustaining the global farm. Selected papers from the 10th international soil conservation organization meeting, pp 24–28

Gerstengarbe FW, Werner PC (2003) Climate analysis and scenarios for Northeast Brazil. In: Gaiser T, Krol M, Frischkorn H, Araujo JC de (eds) Global change and regional impacts. Water availability and vulnerability of ecosystems and society in the semiarid northeast of Brazil. Springer, Berlin Heidelberg New York, pp 137–151

Gomes GM (2001) Velhas Secas em Novos Sertoes. Brasilia

Grepperud S (1997) Poverty, land degradation and climatic uncertainty. Oxford Econ Pap 49:586–608

Häussler B (1996) Anspruch und Wirklichkeit der Basisbewegungen im Nordosten Brasiliens - Fallstudie der Cooperative COOMAP. Thesis, University of Hohenheim, Stuttgart

Heidemann D (1981) Arbeitsteilung und regionale Mobilität an der Peripherie des Weltmarktes. Zur Binnenwanderung in Nordostbrasilien. Brasilienkunde-Verlag, Mettingen

Holden S, Shiferaw B (2004) Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: a bio-economic model with market imperfections. Agr Econ 30(1):31–49

IBGE (1996) Banco de dados agregados. http://www.sidra.ibge.gov.br/bda/

Instituto Desert (2003) Programma de Combate a Desertificacao em Pernambuco. Informe Final. Terezina

Jones BD (1999) Bounded rationality. Annu Rev Polit Sci 2:297–312

Kohlhepp G (1994) Sozialräumliche Gliederung und Regionalstruktur. In: Briesemeister D, Kohlhepp G, Mertin RG, Sangmeister H, Schrader A (eds) Brasilien heute. Politik - Wirtschaft - Kultur. Bibliotheca Ibero-Americana 53, Frankfurt, pp 70–94

Kuipers B (1994) Qualitative reasoning. Modeling and simulation with incomplete knowledge. MIT Press, Cambridge

Lemos JS (2001) Niveis de degradacao no Nordeste Brasileiro. Rev Econ Nordeste 32(3):406–429

Lüdeke MKB, Petschel-Held G, Schellnhuber HJ (2004) Syndromes of global change. A first panoramic view. GAIA 13:42–49

Mertins G (1982) Determinanten, Umfang und Formen der Migration Nordostbrasiliens. Geogr Rdsch 34:352–358

Mertins G (1997) Agrarstrukturelle Probleme, staatliche Entwicklungsprogramme und Abwanderung im ländlichen Raum Nordostbrasiliens. Arbeitshefte des Lateinamerika-Zentrums 40, Münster

Mutter T (1991) Fehlt es nur an Wasser? Zur Agrarpolitik im Sertão, Nordost-Brasilien. Nord-Süd Aktuell 3:365–375

Olimpio JA (2000) A industria ceramica na regiao polarizada por Teresina-Piaui. Carta CEPRO 19(2):85–96

Petschel-Held G, Lüdeke MKB (2001) Integration of case studies on global change by means of qualitative differential equations. Integr Ass 2(3):123–138

Petschel-Held G, Block A, Cassel-Gintz M, Lüdeke MKB, Kropp J, Moldenhauer O, Reusswig F, Schellnhuber HJ (1999) Syndromes of global change: a qualitative modelling approach to assist global environmental management. Environ Model Assess 4:295–314

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117–1123

Rheker JR (1989) Untersuchungen zum Rückgang der kleinbäuerlichen Grundnahrungsmittelproduktion in ausgewählten Munizipien des nordostbrasilianischen Agreste. Erdkunde 43:119–132

Rönick, V. (1986) Regionale Entwicklungspolitik und Massenarmut im ländlichen Raum Nordost-Brasiliens. Ursachen des Elends und Hindernisse bei der Erfüllung der Grundbedürfnisse. Münstersche Geographische Arbeiten 25

Schellnhuber HJ, Block A, Cassel-Gintz M, Lammel J, Lass W, Lienenkamp R, Loose C, Lüdeke MKB, Moldenhauer O, Petschel-Held G, Plöchl M, Reusswig F (1997) Syndromes of global change. GAIA 6(1):19–34

Schellnhuber HJ, Lüdeke MKB, Petschel-Held G (2002) The syndromes approach to scaling-describing global change on an intermediate functional scale. Integr Ass 3(2–3):201–219

Schwalbach M (1993) Autokratismus und Wirtschaftspolitik in Brasilien (1964–1985) Zur politischen Ökonomie der wirtschaftlichen Entwicklung der Nordostregion. Frankfurt

da Silva JB (2002)Atlas Escolar de Ceara. Espaco, Geo-Historico e Cultural. Fortaleza

Stave KA (2002) Using systems dynamics to improve public participation in environmental decisions. Syst Dyn Rev 18(2):139–167

Thaler RH (2000) From homo economicus to homo sapiens. J Econ Perspect 14(1):133–141

Turner B II, Kasperson R, Meyer WB, Dow K, Golding D, Kasperson JX, Mitchell RC, Ratick SJ (1990) Two types of global environmental change: definitional and spatial scale issues in their human dimension. Glob Environ Change 1:14–22

Varian HR (1984) Microeconomic analysis, 2nd edn. WW Norton, New York

Voerkelius S, Külls C, Santiago MMF, Frischkorn H, Alves dos Santos Semrau L, Heinrichs, López Gil MM (2003) Investigation on water management and water quality in Picos/PI and Tauá/CE. In: Gaiser T, Krol M, Frischkorn H, de Araujo JC (eds) Global change and regional impacts. Water availability and vulnerability of ecosystems and society in the semiarid Northeast of Brazil. Springer, Berlin Heidelberg New York, pp 173–184

Voth A (2002) Innovative Entwicklungen in der Erzeugung und Vermarktung von Sonderkulturprodukten. Vechtaer Studien zur Angewandten Geographie und Regionalwissenschaft 24, Vechta

Wilbanks T, Kates K (1999) Global change in local places: how scale matters. Clim Change 43:601–628