Environmental and socio-economic dynamics of smallholder agriculture: a systematic generalisation of case studies resulting in a formal qualitative model as a basis for policy assessment

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1. Introduction

The integration and generalisation of the large number of existing regional case studies on different aspects of the man-environment interaction is a major challenge in Global Change Research. As formulated, .for example, in the LUCC science plan for the land use change problematique, "the general idea is to compare geographically different but analytically similar land use situations" and "...to identify and analyse a series of regional situations that represent the major clusters of land-use and land-cover change dynamics." (Turner et al., 1995). Section 3 of this paper presents a novel methodology to integrate qualitative knowledge from different case studies on Global Change related issues into a single framework.

As an example for this methodology the field of the closely related environmental, economical, social and political aspects of smallholder farming in developing countries is investigated in section 2 - a field where anthropogenic environmental change often feeds back rather rapidly on the socio-economic situation of the actors - and where the latter are confronted with strong constraints like social and economic marginalisation, population pressure and fragile natural production conditions (Lüdeke et al., 1999).

In section 4 the qualitative trajectories consistent with the smallholder model are discussed and evaluated with respect to their sustainability. In section 5 some selected trajectories are investigated in more detail and the possibility to evaluate different policy options on the basis of the introduced concept is exemplifyed. In section 6 problems related to prediction and validation are discussed with respect to the solutions given by the proposed method.

This study contributes to the Syndrome-Project (Schellnhuber et al., 1997; Petschel-Held et al., 1999) which aims to identify a small number of qualitative functional models (including some inter-model interactions) which are able to describe the most important problematic trends of Global Change.

2. A mental map of smallholder agriculture

From several studies on the semantic aspects mentioned in section 1 a formal model is teased out which describes the qualitative functional relationships between labour allocation into off-farm labour, resource conservation measures and short-term yield maximizing activities with natural degradation, income and poverty, market prices, access to resources, population growth and some further relevant variables.
Figure 1 shows an aggregated synopsis of relations as for example stated by Leonard (1989), Kates and Haarmann (1992), Kasperson et al. (1995) and others dealing with the environment – poverty problem. This scheme is supposed to constitute a "Mental Map" of the most important mechanisms underlying the dynamics of smallholder agriculture in an intermediate functional resolution. The green ellipses describe the agricultural activities, the yellow ones the off-farm activities while the whole system is embedded in an environment of demographic, economic and political trends.

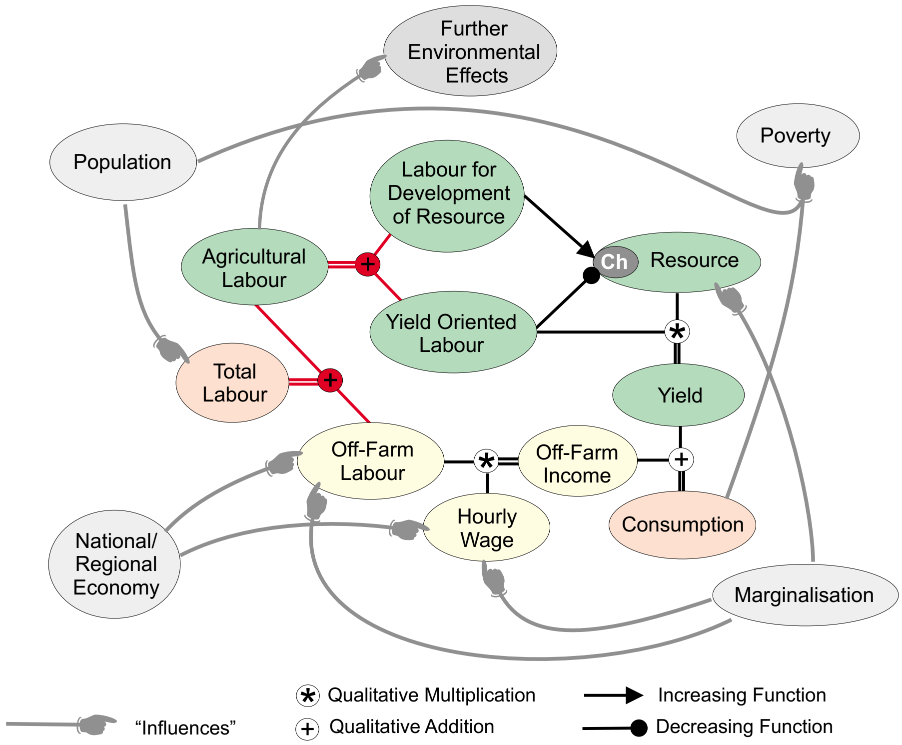

Figure 1: Mental map of smallholder agriculture

In the agricultural subsystem yield depends on the state of the resource and the directly yield oriented labour investment – it increases with both factors and vanishes if one factor becomes 0: a relation we subsequently call "qualitative multiplication" (Kuipers 1994).
Under "yield oriented labour" we subsume frequent tillage and weeding, the shortening of fallow periods, intensive irrigation etc. All these measures can increase the annual yield in the short term but put pressure on the resource, leading to resource degradation by erosion, soil fertility losses, salinisation etc. On the other hand we have agricultural activities which counteract these degradation trends as terracing, drainage ditches, hedge plantings, mulching etc. We include here not only

activities for resource conservation but also endogenous technological progress which increases the efficiency of the resource and obviously needs some engagement by the farmer. A process which – in our qualitative framework - can be represented by developing the resource (in that way we map Boserupian aspects of the dynamics).

These two kinds of activities constitute the pool of agricultural labour – and decreasing one of them means increasing the other (under constant total agricultural labour). This simple relation is called “qualitative addition” (Kuipers, 1994).

The second realm of smallholder activities is the off-farm labour: here an off-farm income is generated via the hourly wage. This income, measured in units of agricultural produce, together with the obtained yield adds up to the total consumption. The total available labour is divided into the labour on the own farm (as land manager) and off-farm labour.

Furthermore the qualitative model in Figure 1 considers population which, on the one hand, generates the total available labour and, on the other hand, divides the total consumption into per capita consumption, sometimes resulting in poverty. Marginalisation of smallholders influences their access to resources as well as to wage labour (e.g. via ethnic discrimination). The total availability of wage labour and the hourly wage depend on trends in the national economy.

How can such a mental map be used for any (weak) kind of prediction, which is the basis for any assessment of policy options? One way would be to quantify the variables and relations and to introduce an utility optimisation hypothesis for the two decision problems considered in the qualitative model: the allocation of labour between on farm vs. off-farm and between short term yield and resource development (red symbols in Figure 1). This kind of approach was chosen by many modellers (e.g. Barbier, 1990; Barret, 1991; Grepperud, 1997) – but both, the optimization hypothesis and the possibility of adequate quantification are questionable. In particular under the rapid change of the conditions of smallholder agriculture in developing countries the argument that an optimisation approach would model the result of a long lasting evolution process leading to an optimal adaptation of the actor’s strategy seems implausible.

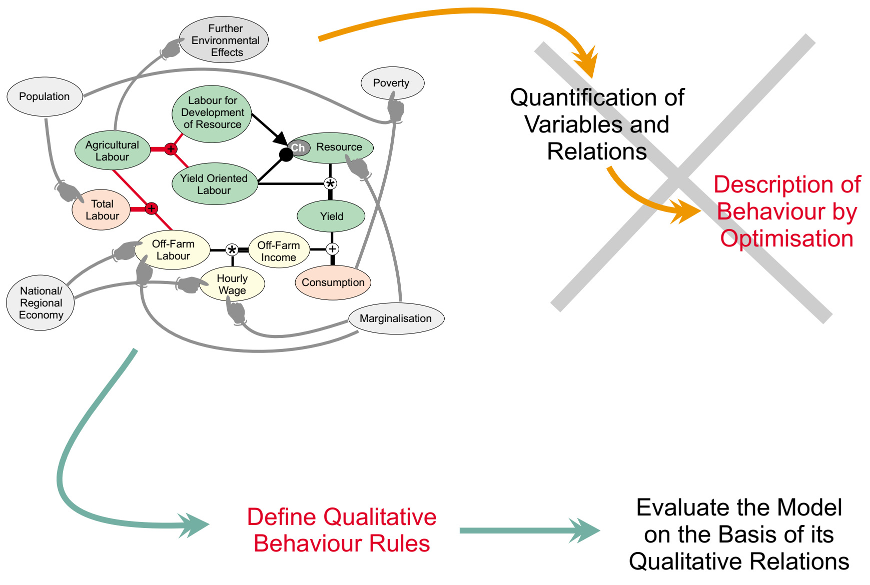

Figure 2: Framework for the description of behaviour

In contrast to these attempts we define qualitative behaviour rules which are far less sophisticated and evaluate the dynamics solely on the basis of the assumptions made in the mental model as given in Figure 1 - the two alternative frameworks are summarized in Figure 2.
The following plausible qualitative rules for the smallholder behaviour are shown in Figure 3:

- the reallocation between on- and off-farm labour is performed according to the difference between present labour productivity of the agricultural and the off-farm activity (red lines)
- the reallocation between yield oriented labour and labour for the development/conservation of the resource is governed by the relation of present per capita consumption and a critical level of consumption, c_k, below which conservational labour is reduced (blue lines)

With this definitions the formulation of the qualitative model is almost finished, only two additional assumptions concerning the ability of natural regeneration of the resource and the monotonicity properties of agricultural production were made, summarized in Figure 4.
In the following section an algorithm is discussed which allows to deduce dynamic behaviours which are in accordance with the qualitative model.

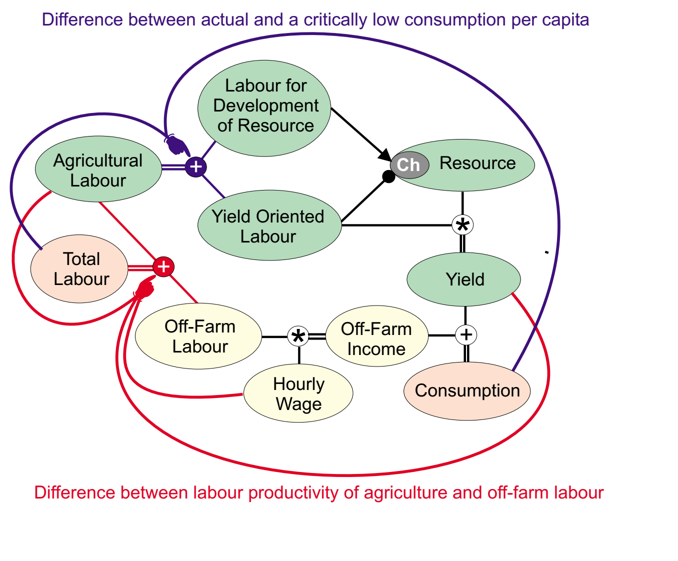

Figure 3: Hypothesis for the description of behaviour in the case of smallholder agriculture

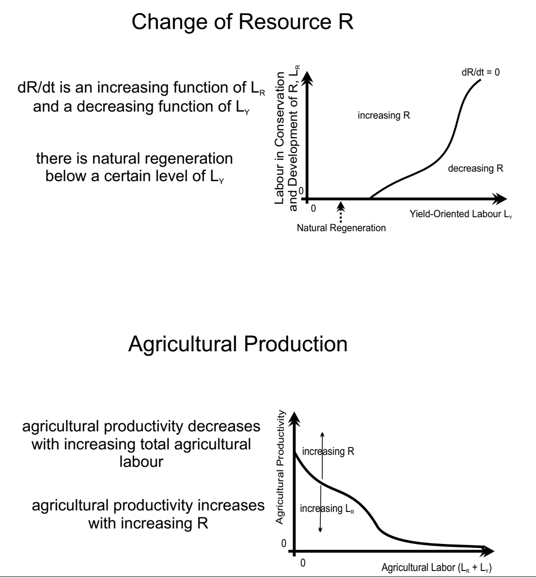

Figure 4: Two further plausible assumptions added to the qualitative smallholder model

3. Qualitative Differential Equations (QDEs)

The study is formally based on the concept of qualitative differential equations (QDEs) which represents a mathematically well-defined approach to investigate whole classes of ordinary differential equations (ODEs) used in conventional modelling exercises. These classes are defined by common qualitative features, for example monotonicity, signs, etc. Using the QSIM-Algorithm (Kuipers 1994) it is

possible to derive the set of possible solutions of all ODEs in the class in qualitative terms, which can then be used for prediction and validation of a hypothesized common, qualitatively specified cause-effect scheme.
The characterisation of a qualitative state and the rules for time development (a time series of different qualitative states constitutes a qualitative trajectory) are illustrated in Figure 5 for the smallholder model. It should be stressed that due to the weak determination of the relations (compared with a quantitative model) one (initial) qualitative state may have more than one successor. Therefore the proposed method generates instead of one determined future a set of possible scenarios – strictly based on the assumptions made in the qualitative model.

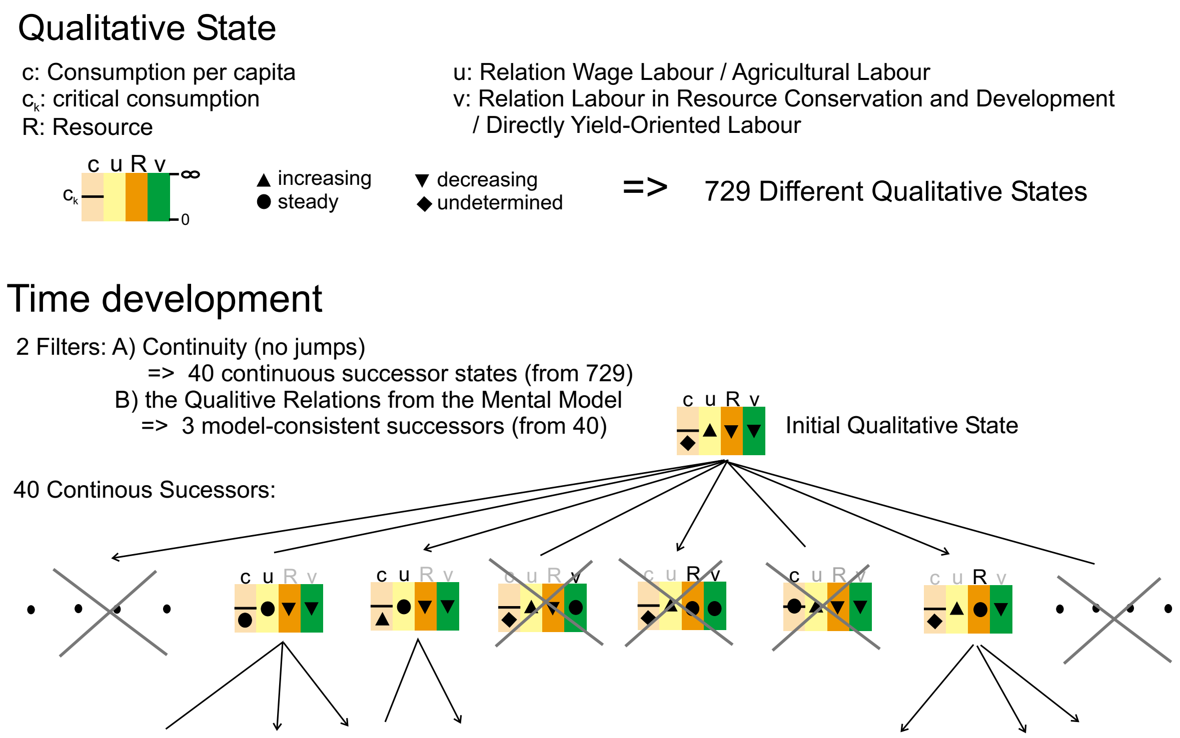

Figure 5: General concepts of qualitative differential equation (here related to the qualitative smallholder model)

4. General Evaluation of the qualitative smallholder model

In this section the algorithm described above is applied to the qualitative smallholder model under the following conditions:

- permanent population growth
- critical consumption is greater than the hourly wage implying that agriculture is necessary to escape poverty

As initial qualitative state the following situation is assumed:

1. poverty (c less c_k)
2. increasing share of wage labour (agricultural productivity less than hourly wage)
3. decreasing resource quality (due to the balance of L_Y and L_R)
4. decreasing share of conservation oriented labour (due to 1.)

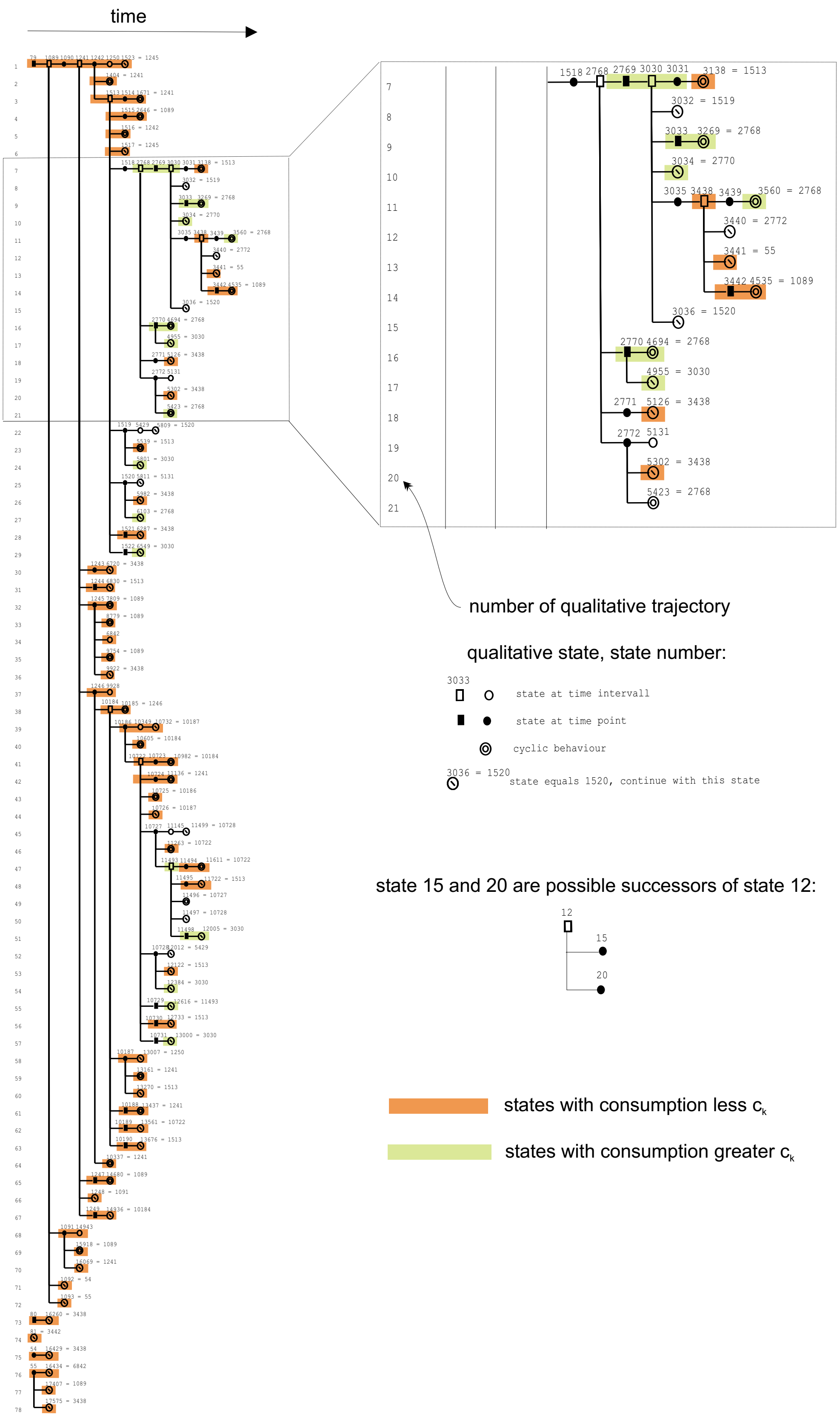

Figure 6: All qualitative behaviours consistent with the smallholder model (for closer inspection enlarge with the zoom function)

One obvious question is now:
Is there a qualitative trajectory (a sequence of qualitative states) starting with the above characterized initial state which leads out of poverty (c becomes greater c_k) and is consistent with the qualitative model of smallholder agriculture (Figures 1, 3 and 4) under population growth and the necessity of agricultural activities to supplement consumption ?
To answer this question the QSIM algorithm was used to calculate the complete behaviour tree for this problem (Figure 6). Here all achieved states (as defined in Figure 5) together with their possible successors are displayed – resulting in 74 different trajectories (or more exactly: sub- trajectories as they usually continue at a specified state in the tree).
To read this behaviour tree one has to start with the initial state (No. 73 in the first line) which has the unambiguous successor state No. 1089. But from now on there are four possible next states: 1090, 1091, 1092 and 1093. This means that due to the particular form of the relations in the model one of these four possible qualitative futures will be realized. Each of these four states has again one or more successors, and so on.
In a next step all states where consumption is greater c_k are marked green while the states with c less than c_k (poverty) are marked red. Closer inspection shows that despite the dominating red marks there are some trajectories which describe sustainable ways out of the initial poverty, for example trajectory No. 9, ending in a cyclic behaviour including only states with c greater than c_k.
So we can conclude as a first result, that for the smallholder system (assumed to be describable by the mental map of Figures 1, 3, and 4) there is the chance (under certain advantageous conditions, which we cannot specify at this point) to escape poverty according to its endogenous development – even under the difficult conditions of permanent population growth and hourly wages insufficient to fulfil the consumption needs. It is obvious that a result of this kind is hardly attainable by heuristic discussion of the web of interrelations which is simply to complex due to the complicated feedback structures.
More insight in the detailed dynamics will be given in the next section, where some trajectories are discussed in more detail and first policy options are deduced.

5. Sustainable trajectories and policy options

In Figure 7 we discuss a part of the behaviour tree (Figure 6) more explicitly. Starting with the initial state at t_0 we follow trajectory 3 which ends up in a cyclic behaviour (from t_3 back to (t_1, t_2), symbolized by the red arrow). This trajectory is characterized by a consumption less than c_k all the time, thus being an unacceptable development path. The particular problem in this case is that no sufficient development of the agricultural option occurs (the relation of wage labour and agricultural labour oscillates: relatively stronger engagement in agriculture leads to a decrease in labour productivity which then reverts the reallocation).
Investigation of the bifurcation between the unsustainable trajectory 3 and the sustainable trajectory 9 (see preceding section) occurs at time (t_2, t_3): only if by increasing relative engagement in agriculture (i.e. u decreasing) the consumption reaches c_k before agricultural productivity drops to wage labour productivity, the system may switch to trajectory 9.

The latter ends up in a cyclic behaviour (from t_5 back to (t_3, t_4), green arrow) which is characterized by sufficient consumption (c greater than c_k), a constant decrease of the relation between wage labour and agricultural labour (u decreasing: this means relative development of agriculture), a constant increase of labour in resource development relative to direct yield oriented labour and a moderate resource use leading to an oscillating resource quality.

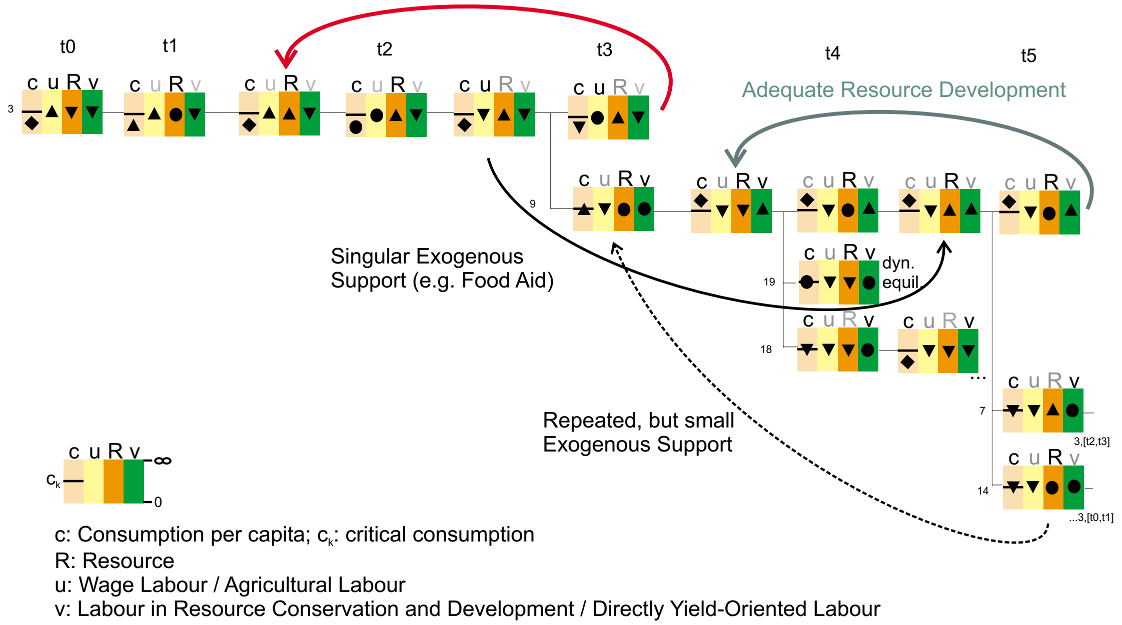

Figure 7: One way out of the crises if hourly wage is less than c_k and population (L_T) is permanently growing.

Let us assume that the system is caught in the non-sustainable trajectory 3 by its endogenous dynamics. Let us further assume that we are in the state at (t_2, t_3) and that a singular exogenous support to increase consumption above c_k (e.g. food aid) is given. Such a support would modify the qualitative state of the system: during the intervention c is greater than c_k - and as a direct consequence of the allocation rules, v will increase. But this is exactly the qualitative state at (t_4, t_5) of trajectory 9! Therefore the exogenous intervention (policy option) can be interpreted as a "jump" in the behaviour tree and further analysed (symbolized by the black arrow). In the best case the system stays in the sustainable cyclic behaviour of trajectory 9 and the measure was successful. Now, this is possible but not guaranteed as there are several bifurcations which may deviate the trajectory from the sustainable one. So, for example, the state at t_5 of trajectory 14 may follow the "jump". But this trajectory joins trajectory 3 (at t_0) and the system is again caught in the non-sustainable cycle. To avoid this a small exogenous support at t_5 of trajectory 14 is sufficient to just change the direction of change in the consumption which brings the system back to trajectory 9 (dotted arrow). But in this case, the singular intervention has to be performed repeatedly as the system will deviate from trajectory 9 at t_5 caused by its endogenous dynamics.
These examples illustrate how policy options can be mapped on the full picture of possible qualitative trajectories with the aim to investigate conditions of success of particular measures.

Another situation which is characterized by continuous poverty and resource degradation (stagnation) is discussed in Figure 8. The red lines indicate such non-sustainable trajectories (No. 69, 68, 34). While 69 describes a cyclic behaviour where the resource declines via saddle points, 68 and 34 end in an asymptotic dynamical state.

Examination of the cyclic non-sustainable behaviour indicates that the only way out is via a "policy basket". At t_0 the exogenous introduction of an improved agricultural technology can increase the productivity of agricultural labour so far that the direction of u changes (decreasing relative engagement in wage labour), but such an increase in productivity must not necessarily result in a sufficient increase in consumption required to exceed c_k. But the latter is necessary to reach the sustainable trajectory No. 9. Therefore only an intervention which combines the introduction of an improved agricultural technology and a singular consumption support will be successful.

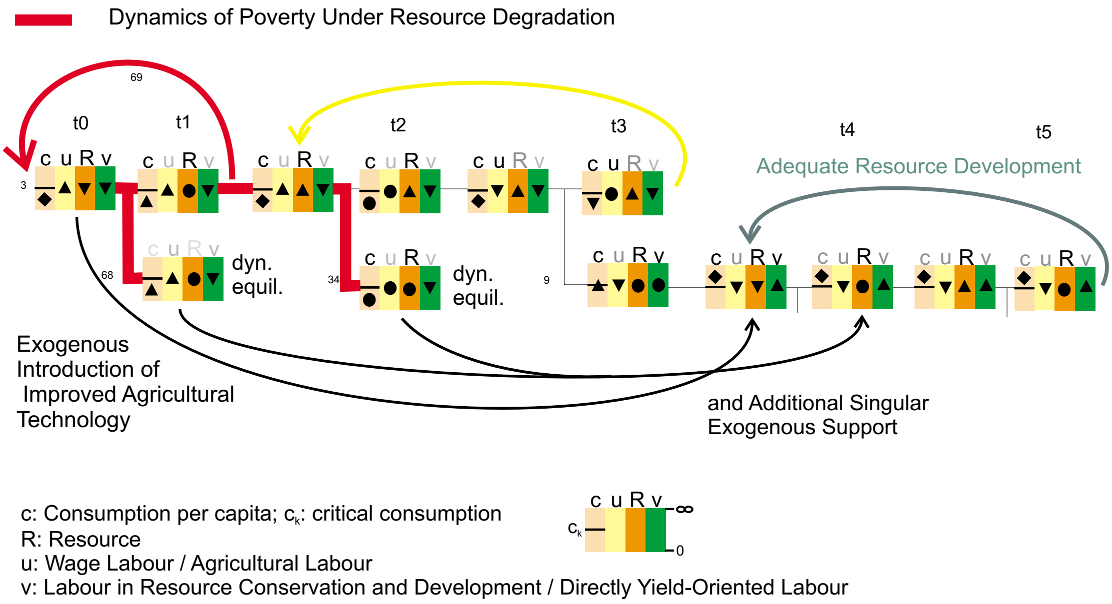

Figure 8: Ways out of poverty under permanently decreasing resource (hourly wage is less than c_k, population (L_T) permanently growing)

6. Discussion

So far some properties of a new method to evaluate qualitative models or "mental maps" with respect to the qualitative dynamic behaviours which they generate were introduced. An important point was that one has to "pay" for the vagueness of a purely qualitative model by giving up unambiguous time developments as a result – instead a "behaviour tree", i.e. several trajectories which are compatible with the qualitative model, is generated. On the other hand, that is exactly what one would expect with respect to "predictions" regarding man-environment systems: a kind of "weak" predictions in the form of consistent "scenarios". Here the qualitative differential equations offer a powerful mathematical tool.

Another important aspect is the use of qualitative models for the generalisation of detailed case studies. Generalizing a variety of agricultural activities under, for example, the term “yield oriented labour” will not allow for the formulation of a unique quantitative relation between this aggregated variable and, for example, resource degradation. The only consistent way to deal with this level of generality is the application of qualitative modelling techniques as, for example, introduced in this paper. This leads to the question of how to validate a qualitative model. To illustrate the method we take an example from a case study on the Highlands of Peru and Jamaican Hill lands by Collins, 1987. She reports:

“To maintain the constant levels of income necessary to meet short-term needs and spread risk, smallholder producers engage in a multiplicity of both on- and off-farm activities **(L_W: inc,** diversification of formerly mainly agricultural orientation, **u: inc)** that reduce their ability to input labour intensive soil management/conservation practices **(L_R:dec)**, which multiplied by large number of producers **(L_A: inc or steady)** over the long term translates into ecological degradation **(R: dec)** and decline and further impoverishment **(c: dec, $c<c_k$)**”

In brackets I added the interpretation of the text with respect to the aggregated qualitative variable of the smallholder model introduced in this paper. The table below summarizes the interpretation and identifies exactly one state in the behaviour tree (Figure 6, Figure 7):

from L_A: inc or steady and L_W: inc $\Rightarrow$ L_T:inc from L_A: inc or steady and L_R:dec $\Rightarrow$ v :dec R: dec; c: dec; $c<c_k$; u: inc	Trajectory 3, t0

This agreement is a step towards the validation of the qualitative model: the observed qualitative state is in accordance with the constraints of the model (which strongly reduces the number of possible qualitative states). Up to now several case studies were found which observe one qualitative state (or at least most of its variables) and correspond to a state in the behaviour tree. A much stronger test for the model would be the comparison with observed “pieces” of qualitative trajectories, i.e. time series of observed qualitative states. We are still searching for such observations and would appreciate very much hints with respect to existing material or ongoing observations.

6. References

Barbier, E.B. (1990). The farm-level economics of soil conservation: The uplands of Java. Land Economics 66, 2, 199-211.

Barret, S. (1991). Optimal soil conservation and the reform of agricultural pricing policies. Journal of Development Economics 36, 167-187.

Collins, J.L. (1987). Labor Scarcity and Ecological Change. in: Lands at Risk in the Third World: Local-Level Perspectives, ed. by Little, P.D. and Horowitz, M. M. with Nyerges, A.E. Boulder, CO: Westview Press.

Grepperud, S. (1997). Poverty, land degradation and climatic uncertainty. Oxford Economic Papers 49, 586-608.

Kasperson, J.X., Kasperson, R.E. and Turner, B.L.II (eds) (1995), Regions at Risk: Comparisons of Threatened Environments, United Nations University Press, Tokyo, New York, Paris.

Kates, R.W. and Haarman, V. (1992), 'Where the Poor Live: Are the Assumptions Correct?', Environment, vol. 34, pp.4-11, 25-8.

Kuipers, B. (1994), Qualitative Reasoning: Modeling and Simulation with Incomplete Knowledge, MIT Press, Cambridge, MA.

Leonhard, H.J. (1989), Environment and the Poor: Development Strategies for a Common Agenda, Transaction Books, New Brunswick, Oxford.

Lüdeke, M.K.B., Moldenhauer, O. and Petschel-Held, G. (1999), 'Rural Poverty driven Soil Degradation under Climate Change: the Sensitivity of the Disposition towards the SAHEL SYNDROME with respect to Climate', Environmental Modelling and Assessment 4, 315-326.

Petschel-Held, G., Block, A., Cassel-Gintz, M., Kropp, J., Lüdeke, M.K.B., Moldenhauer, O., Reusswig, F. and Schellnhuber, H.J. (1999), 'Syndromes of Global Change: A Qualitative Modeling Approach to Assist Global Environmental Management', Environmental Modelling and Assessment 4, 295-314.

Schellnhuber, H.J., Block, A., Cassel-Gintz, M., Kropp, J., Lammel, G., Lass, W., Lienenkamp, R., Loose, C., Lüdeke, M.K.B., Moldenhauer, O., Petschel-Held, G., Plöchl,M. and Reusswig, F. (1997), 'Syndromes of Global Change', GAIA: Ecological Perspectives in Science, Humanities and Economics, vol. 6 (1), pp. 19-34.

Turner, B.L.II, Skole, D., Sanderson, S., Fischer, G., Fresco, L. and Leemanns, R. (1995), *Land-Use and Land-Cover Change: Science and Research Plan,* IGBP-Report No. 35/HDP-Report No. 7, Stockholm, Geneva.