UNRAVELING THE UNSUSTAINABLITY SPIRAL IN SUBSAHARAN AFRICA: AN AGENT BASED MODELLING APPROACH

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SUMMARY

Sub-Saharan Africa is trapped in a complex unsustainability spiral with demographic, biophysical, technical and socio-political dimensions. Unravelling the spiral is vital to perceive which policy actions are needed to reverse it and initiate sustainable pro-poor growth. The article presents an evolutionary, multi-agent modelling framework that marries a socio-ecological approach to a world system perspective and takes agriculture as the engine for sustainable development in Sub-Saharan Africa. A number of possibilities for empirical validation are proposed.

KEY WORDS

multi-agent systems, development, poverty trap, degradation, social capital, sub-Saharan Africa

CLASSIFICATION

JEL: O13, O33, O55, Q20

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INTRODUCTION

For three decades, Sub-Saharan Africa has been trapped in economic stagnation, coupled to pathologies like widespread poverty, child malnutrition, violent conflict and the HIV-Aids epidemic. That a new boom of the world economy now entails somewhat higher growth rates does not alter the fact that per capita GDPs have hardly increased since the 1980s in Africa below the Sahara.

Today, it is once more recognized that this stagnation is rooted in agricultural crisis. Both the World Bank and scientists [1, 2] already stressed that modern growth requires agricultural development as a starter, but many believed that "globalization" would allow export demand for manufactures or services to assume this role. The absence of cases of successful development without agricultural growth has belied this view (cf. [3]). In Sub-Saharan Africa, agricultural crisis caused a flight from the land, but no incentives for non-farm development, so that urbanization entailed a proliferation of marginal activities and fights over public sector jobs.

Why is agriculture stagnating? For a long time, experts forwarded mono-causal explanations. They pointed to adverse natural conditions (e.g. [4]), high population growth (e.g. [5]), overtaxation of farmers [6], and so on. When donor prescriptions to redress some of these conditions failed, a new mono-causal bogey was looked for. The blame was put on "bad governance" and "social capital problems" that would stem from Africa's particular culture and history [7-9].

Gradually, some experts came to realize that Africa's problems had multiple and mutually reinforcing drivers rather than single causes. Various vicious cycles or 'poverty traps' were identified: of poverty, population growth and soil degradation [10]; of poverty and low public investment [11]; of thin markets and low private investment in agro-industrial chains [12]; of dependence on traditional commodities and low export earnings [13], and so on and so forth. All these explanations are right, but each lifts only one corner of the veil. In fact, Sub-Saharan Africa is trapped in a complex unsustainability spiral with demographic, biophysical, technical and socio-political dimensions. Unravelling it is vital to perceive which social actions could reverse this spiral and initiate a positive dynamic of sustainable pro-poor growth.

In our opinion, such unravelling requires an evolutionary framework that marries a socio-ecological approach to a world system perspective. Sub-Saharan Africa is a region that has retained certain pre-industrial traits, with consequences for its internal dynamics, but that is integrated in an industrialized world economy which makes its dynamics deviate from pre-Industrial Revolution societies. This paper sketches a broad vision that is based on this premise, and proposes a computer model that can serve to elaborate it, test its consistency, and explore ramifications. At the end we discuss possibilities for empirical validation.

VISION

In pre-industrial societies, centuries of demo-economic growth alternated with Malthusian crises [14, 15] (for theoretical interpretation [16]). Central to it was Ricardo's classical "law" that farm production could only be raised by reclaiming less fertile lands or labour-demanding intensification, so that population upswings raised agricultural prices [17]. It made food dear for the poor, but as Malthus [18, pp.29-31] already observed, it lowered real wages and prompted investment and innovation in larger farms (also [19]). This fuelled the phases of agricultural intensification that historians have called 'agricultural revolutions'. The resulting increases in food supply moderated the rise in food prices. More mouths could be fed, rural markets for commerce and industry expanded, and no severe distress precluded co-operation and the maintaining of soil fertility. In these phases the farm economy was more or less robust; harvest failures caused suffering but no collapse. However, risk aversion and time-consuming communication made innovation a slow process [20]. Sooner or later, agricultural growth ran up against diminishing returns. For some time, a precarious stability could be maintained by elaborate safety nets, intricate social hierarchies, and small technical improvements (cf. [21]), but in the end, strong increases in scarcity could not be avoided. Food prices skyrocketed, squeezing the demand for non-farm products; artisans lost their livelihoods swelling the ranks of the rural poor and small farmers over-exploited their plots in an effort to minimise their dependence on food markets (cf. [22]). Harvest failures or other shocks pushed society into a spiral of interlocking vicious cycles of soil degradation, food insecurity, rising conflict and disruption, which ended in demographic crisis. This “Malthusian correction” released the pressure of population on the food supply. Wages rose and farm prices fell, causing a decline in large farms and halting or reversing the process of intensification. It initiated a low tide in economic development, which lasted until a new population upswing prompted a new cycle.

In the late 19th century, a new phase of the Industrial Revolution broke the Ricardian constraints [23]. Modern transport enabled the tapping of land reserves in temperate zones outside Europe; industrial fertiliser accelerated the increase in yields; and fossil substitutes freed farm production capacity that had been used for non-foods. For the first time in history, international agricultural prices went through a series of price falls without this being caused by a crisis in population. It ended the age-old problem of scarcity, but at the same time it brought a new challenge. Low prices squeezed farm profits which entailed a decline of large farms and threatened to slow agricultural growth. Western countries responded through government support and co-operatives that bolstered knowledge infrastructures, moderated the diseconomies of small farms, and ensured that frugal household producers kept margins for investment [24]. Rather than leaving a sector with low earnings, farm families seized upon the new technical and market opportunities to defend their incomes. It started a treadmill of production growth, low prices and new innovations [25] that became the engine of a new agricultural revolution of agri-chemicals, high-yielding varieties and mechanization.

The regime change that emanated from the ‘western’ world deeply affected other countries too. The impacts varied depending on local conditions. East and South Asia had gone through a long history of population growth, state formation, class differentiation and market development. Farmers tended to organize on class basis, and a political class had emerged with some feeling for long-term national interests. It stimulated ‘developmental states’ (cf. [26]) that followed the western response at some distance. The Japanese Empire invested in irrigation and rural infrastructure and protected its farmers at the outer border. It enabled significant agricultural growth, which after WWII got a new impulse by redistributive land reform and US aid [27]. Rural incomes became an important demand factor for industries that produced simple goods for domestic consumption. It facilitated the cross-subsidization of industrial exports by which these countries established themselves as industrial powers.

Meanwhile in Asian colonies of European countries farmers were not supported. Population increased, but low world market prices discouraged the farmer investment in land management that was needed for sustainable intensification. Rural societies were pushed in vicious spirals of poverty, population growth and resource degradation that suffocated economic development [21, 28]. It reminded of pre-industrial Malthusian crises, but these occurred because an agricultural revolution was exhausted, while here an agricultural revolution was nipped in the bud. However, independence was a historical watershed. Several new governments introduced supportive farm policies [29-32]. Together with the high-yielding seeds from international research institutions it led to the Green Revolution, which became an engine of industrialization.

In the Americas, pre-Columbian Stone Age societies had been overrun by European invaders with superior weapons and diseases for which they had no immunity [33, 34]. In the (sub)tropical parts, where profitable export crops could be grown for the European market, large plantations evolved that employed coercive labour systems to prevent workers from using the abundance of land and setting themselves up as independent peasants. It created a social divide between planter elites and rightless masses of rural workers, which encouraged ‘oligarchic’ political structures, hampered the development of simple consumer goods industries, and reinforced the export orientation of the plantations [35, 36]. When international agricultural prices fell, agrarian elites kept to open trade policies. Rather than calling for protection, they used their dominance to shift the burden to the rural poor. In the end, they evicted large numbers of rural workers to pave the way for cost-cutting mechanization. It allowed a development of a kind, but one that involved more inequality, slower growth and more socio-political tensions than in the West or the industrializing Asian countries [37, 38].

In Sub-Saharan Africa, endemic diseases and iron-armed warriors postponed the colonial scramble until the time that international agricultural prices declined. It limited the establishment of European-owned farms and plantations, as well as the evolution of larger indigenous farms. Africa's agriculture became even more a smallholder agriculture than it already was. Like in Asia, colonial governments failed to protect indigenous smallholder farmers, and signs of Malthusian crisis appeared where land had been confiscated for white settlers [39-41]. Elsewhere, however, relative abundance of land provided an outlet for population growth. In the 1960s, per capita incomes in Sub-Sahara Africa were still higher than in Southern Asia. However, national independence brought no real breach with colonial farm policies. Sub-Saharan African societies were little differentiated, had property rights in people rather than material assets, and had more fluid and personalist socio-political relations [42, 43]. People tended to organize in clientelist factions rather than in class-based movements. Politicians saw themselves obliged to remunerate large numbers of supporters with public sector jobs, while farmers were too weakly organized to prevent footing the bill [6, 44]. Meanwhile, population growth was closing the safety valve that abundant land had provided. The effect was felt when oil shocks and a new fall of international agricultural prices deteriorated the input-output price ratios for farmers. On-farm investment in land management remained too small to make the increase in population pressure sustainable [45]. The resulting poverty pushed individual discount rates up. It reduced the value that people attached to the future benefits of soil conservation or cooperative solutions for social dilemmas. Intra- and inter-household conflicts increased [46], and civil society in the countryside degenerated into counter-democratic networking [47]. The malaise drove many young people from the land, but squeezed the demand for domestic industries and services, so that the rural exodus fuelled political markets that were based on the doling out of public sector jobs. Civic organizations became vehicles of competing migrant networks [48]. The burden of civil servants’ salaries was shifted to farmers and squeezed investment in rural infrastructure, which only deepened the agricultural crisis [49]. Donor-imposed reform sought to roll back the bureaucracies, but the dominance of free market ideas obscured the underlying dynamics that made supportive policies (including price policies) a sine qua non for development. Failing to redress the root cause of the agrarian crisis, the reforms went not further than the liberalization of macro-policies, and foundered on the resistance to public sector retrenchment.

APPROACH: MODELLING

To elaborate this vision, test its consistency, and explore ramifications, we need a model that can handle the co-evolution of population, natural resources, techniques and social strategizing at local, regional and global scales. Although computer modelling is praised an important tool in understanding complex, long term phenomena and assessing policy instruments [50], traditional economic or ecological models are ill-suited for our study. However, we think that a spatial specific multi-agent model can be used for this purpose. Such a model provides a flexible structure [51] that can represent interactions between phenomena that belong to different layers and scales of reality [52], and that are at the focus of different disciplines [53, 54]. It also allows for the internal representation and goal-seeking behaviour that characterizes human actors, without falling in assumptions of perfect information and rationality of orthodox economic models [53].

There is a current tendency towards spatially explicit, highly sophisticated models that try make concrete a one to one simulation of reality (examples PALM [55]), but our model is abstract and theoretical like the FEARLUS model [56] and the early contributions to agent based modelling (e.g. [57]). We use CORMAS software for building our multi-agent model.

There are important challenges in agent based modelling: the first is they demand much computer power. Second, agent based models are difficult to test and validate [58]. A later section of this paper, therefore, is dedicated to new methods for testing and validating the model assumptions. A third drawback is that the details of agent based models are difficult to describe and communicate [59]. To tackle this point we will use a widely tested protocol for describing our model [59].

THE MODEL: DESCRIPTION

The model description follows the ODD (Overviews, Design Concepts and Details) protocol for describing individual and agent based models [59] and consists of seven elements. The first three elements provide an overview, the fourth element explains general concepts underlying the model's design, and the remaining three elements provide details. The last element, containing an overview of the calculations and procedures in the models' sub-modules, is provided in the appendix.

PURPOSE

The main purpose of the model is to gain insight in the long-term agricultural and environmental changes of Sub-Saharan Africa, based on the hypothesis that Africa operates as a pre-industrial society in an industrialized world economy. This insight is needed to unravel the current unsustainability spiral in order to provide policy recommendations. The unsustainability spiral has many dimensions and multiple scales. The model will serve as a discussion support tool for the Dutch Directorate General for Development Cooperation (DGIS) of the Ministry of Foreign Affairs.

STATE VARIABLES AND SCALES

Grimm [59] defines state variables as low-level variables that characterize the low-level entities of the model. State variables are variables that characterize a level and cannot be derived from other variables. However defining which variables are state variables is not unambiguous in a system containing many feedbacks. Our model comprises the following 5 levels or entities without a clear hierarchy: 1) brain, 2) teams, 3) villages, 4) area, and 5) the world market. The relations between the levels are described further on.

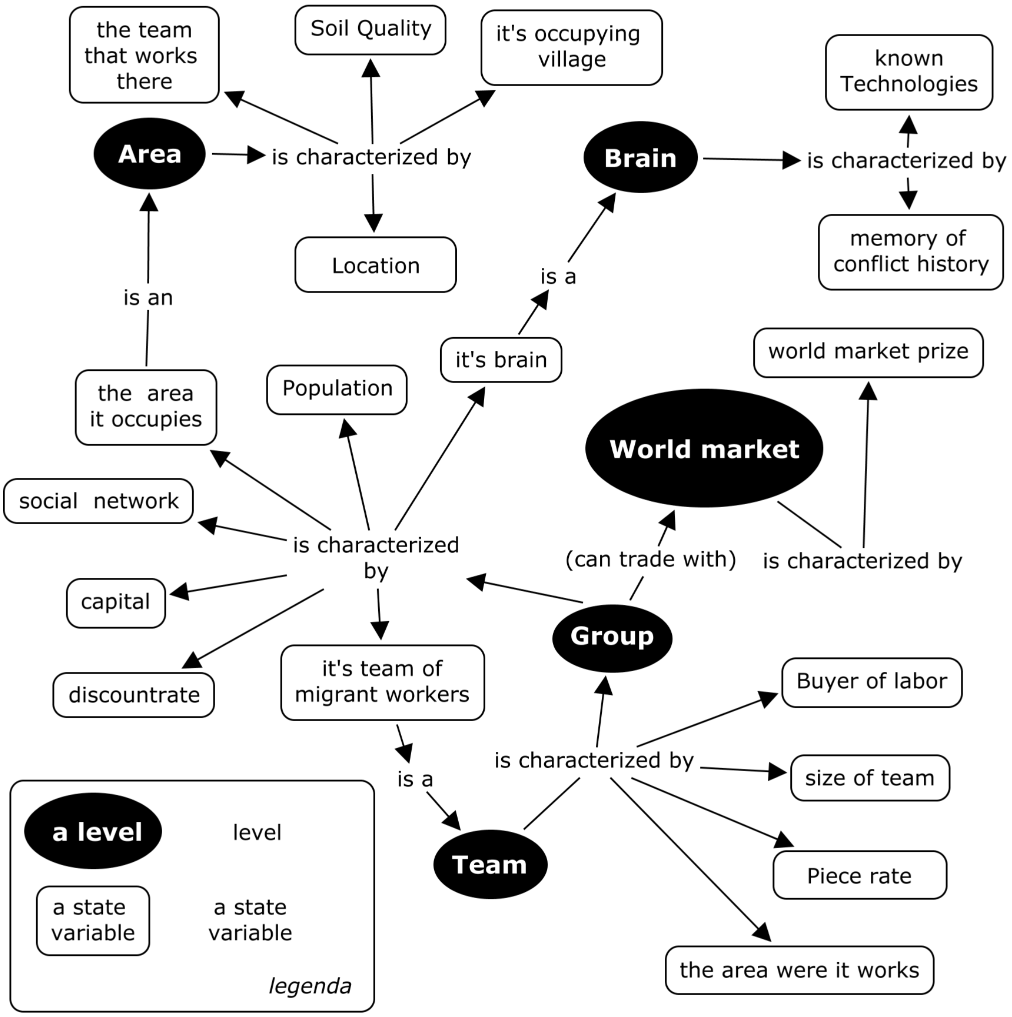

Figure 1. Overview of levels and subsequent state variables.

The first entity of the model is the brain which is characterized by the village that holds it. The brain contains a list of technologies that are available to the holder, and a list of its conflict history. A brain can invent, imitate and forget production technologies. The technologies a brain knows are an element of a big list of technologies, which is an input variable.

Villages (groups) form the second entity. They are the Sub-Saharan farmer villages which are characterized by the state variables: population, the characteristics of the area they occupy, the list of other villages they know (their social network), their brains, teams, capital, and discount rate. Instead of discount rate, nutrition status can also be used as a state variable, because the one is derived from the other. One of the villages is set to be the 'port'. By trading with the port the villages can trade with the world market. In the remainder of the article villages are sometimes called individuals or agents.

The third entity, teams, consists of migrant workers sent by one village to another village to work. The teams are characterised by their village of origin, the buyers of their labour, their size and piece rate.

Areas are the fourth entity of the model. Areas are characterized by the village which occupies it: the location on the grid, the migrant workers sent to work on it and the land quality. The latter is a lump variable representing all aspects of land quality, like a.o.: organic matter and nutrient content, texture and water availability. An area is always occupied by a village. For modelling purposes villages are not allowed to starve entirely.

The fifth hierarchical level is the world market which can be accessed by thE villages via the port. The characteristic state variable of the world market is the world market price which is the price per unit of labour (piece rate) sold by the villages to the port.

Spatial scale is abstract but can be considered an area of 400 by 400 kilometres. This will be occupied by around 10 000 villages or villages with an average population of 100 people corresponding with an average population pressure of 6,25 per square kilometre. This is a normal density in rural Sub-Sahara Africa (mostly between 5 and 10 per km, although it is much higher in urban and ore densely populated areas. The average population density of Sub-Sahara Africa, including the cities, is about 30 [60].

Table 1. Overview of parameters of the unsustainability spiral model.

Overview of parameters per module	Value* (Unit)
Initialization	
Number of areas	10000 (#)
Number of villages	10000(#)
Neighbours of each cell	8 (#)
Initial land Quality	(food)
Initial local list of technologies represented by Cobb Douglas Coefficients	
Population Dynamics	
Minimum mortality	(people/people)
Food intake per caput at which mortality does not further decrease	(food/people)
Food intake per caput at which fertility is zero	(food/people)
Food intake per caput at which fertility does not further increase	(food/people)
Evolution of knowledge	
Time after which a technology becomes forgotten	(time steps)
Threshold to experimenting	(food)
Global list of technologies represented by Cobb Douglas coefficients	
Evolution of cooperation strategy	
Time that a conflict is remembered	(years)
Plan production, trade and robberies	
World market price	(food)
Labour intensity	1 (labour/people)
Amount of food that is robbed during robbery	equals wage (food)
Transaction costs after robbery	(food/labour)
Distance to transaction costs coefficient	(food/meter)
Risk aversion threshold when accepting trade	(change)
Evolve agro-ecology	
Value at which land regenerates each time step	(food)
Rate at which land degradation takes place (food production minus conservation investment)	(food/food)
Conservation efficiency	(food/food)
Minimum land quality	(food)
Maximum land quality	(food)
Regeneration per time step	(food)
Spend harvest	
Capital Access coefficient	(food/food)

*if values are not yet determined, units are provided

PROCESS OVERVIEW AND SCHEDULING

Each time step is a cropping season, which can be considered a year. Each time step five modules are processed in the following order: evolve demography, evolve knowledge, plan production and evolve cooperation, evolve agro-ecology and spend production. Details about the procedures and calculations within these modules are provided in the appendix.

The ‘Evolve demography’ module consists of the submodules birth and death. The ‘Evolve knowledge’ module consists of the submodules: forget production technology, imitate from villages and experiment, which are processed in the given order. Subsequently, villages make their decisions on production and trade in the ‘Plan production and evolve cooperation’ module which consists of three submodules which are processed in the following order: consider agricultural production, consider trading with other villages, and allocate the inputs. Once the decisions on production have been made the module ‘Evolve agro-ecology’ calculates the crop-growth in the submodule ‘Grow crop’ and changes ‘Land quality’ in the submodule ‘Evolve land quality’. When the crop production is realised, the ‘Spend production’ module is run, which consists of a submodule that determines the capital input for the next year and a module that calculates next year’s discount rate. Finally, the village evolves its cooperation strategy, based on the conflicts in its social environment and its relative wellbeing.

Within each submodule the villages or areas are processed in a fixed order except when trade is considered. During the ‘Consider trading’ phase, the trade possibilities of a village and its partner are assessed at the same time.

DESIGN CONCEPTS

The design concepts section describes the general concepts underlying the design of the model along with concepts that are common in the field of Complex Adaptive Systems [61, 62] and facilitate the integration of this study into others.

Emergence

A certain system property or behaviour is emergent if it is not directly specified by individual traits. Here we will explain which properties of the model system really emerge from the interaction of the adaptive behaviour of the agents, and which are merely imposed. Here we differ between rather linear dependence between factors and the emergence of macro level phenomena that not linearly follow from the procedures at micro scale. First, we will deal with the first category and then describe the expected emergence of macro scale properties.

Population, capital, land quality, technology, conflict history and the discount rate are the main driving variables of the model. None of these variables, however, are imposed but are derived from each other.

Births and deaths and the subsequent population dynamics depend on a village’s nutritional status. The nutritional status emerges from all main driving forces listed above. Capital emerges from the current and expected income status and the discount rate. The discount rate is derived from the previous nutritional status, while the income status emerges from the main driving variables. Land quality depends on degradation, regeneration, and conservation investments. Degradation occurs in a fixed relation with yield (again emerging from the main variables). Regeneration is imposed and conservation investments depend on the main driving variables. Known technology is a product of imitating, experimenting and forgetting. All those are dependent on other changes in the environment. However the global list of technologies is imposed, limiting freedom in technological innovation. Conflicts are also dependent on changes in the main variables.

What is imposed is the way in which the villages make their decisions, which is based on household economics (see also fitness section). Furthermore, the social networks of the villages are imposed; the position of a village is also imposed and cannot change during the model. Other imposed parameters are shown in Table.

We expect the following emerging patterns at macro scale. In case the model is run without a port to the world market and hence a pre-industrial society is simulated we expect a sinus like wave pattern in which the up-going phase, or the Boserup phase is characterized by synergetic interaction of land quality improvement, technological progress and cooperation driven by a relative abundance of food and a consequent favourable discount rate.

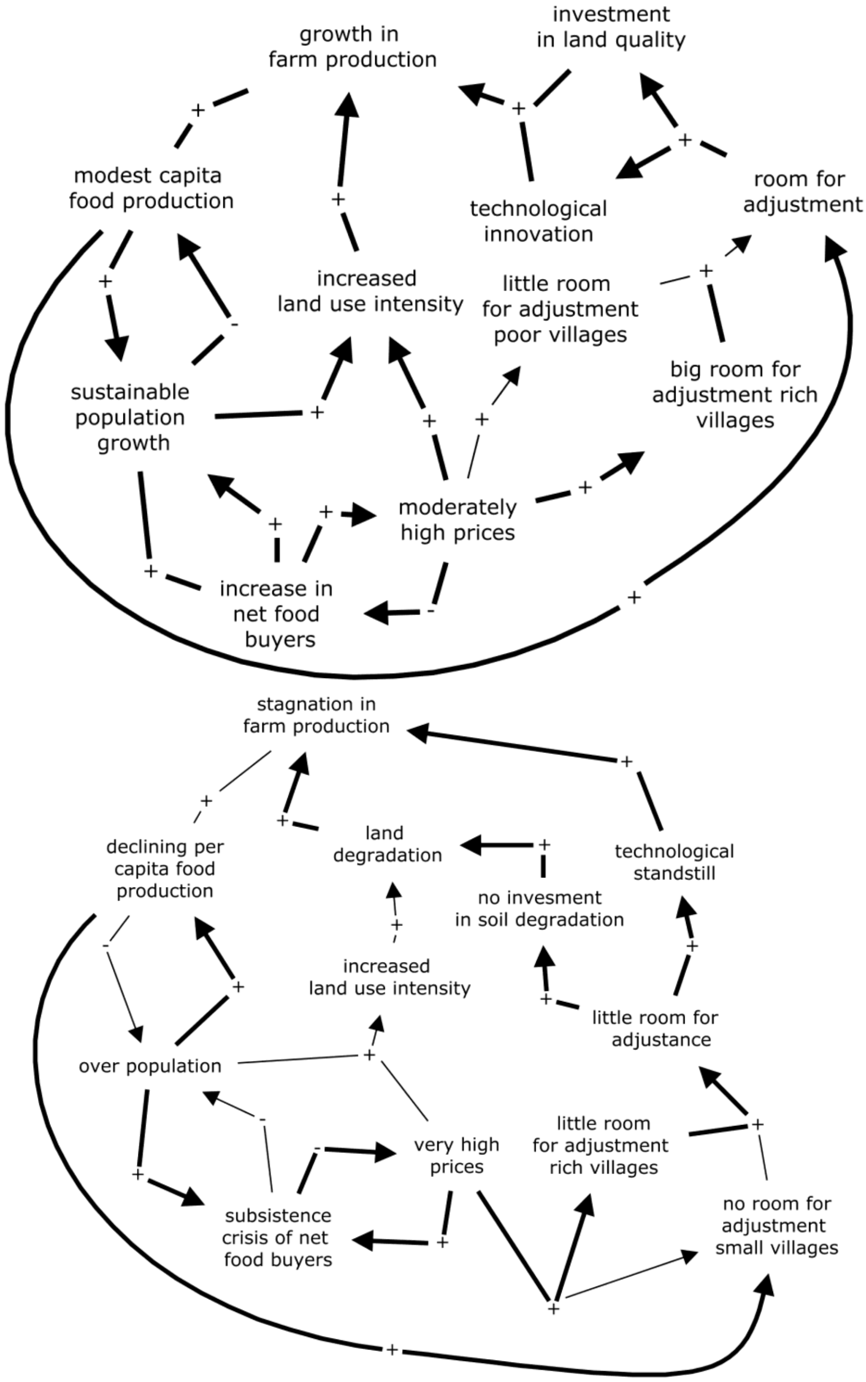

Figure 2. Overview of feedbacks that trigger growth of an agrarian market economy (left) and feedbacks that trigger a crisis in an agrarian market economy [63].

The downward or Malthusian phase is characterized by resource depletion, a technological standstill and conflicts that are triggered by a high discount rate which is caused by overpopulation. In case this pre-industrial society is connected to the world market with low food prices, poor villages send their labourers to the port, because the food to labour ratio is favourable. Rich villages, consequently, will run out of labour and this labour stress will reduce technological innovations and investments in soil quality. As a result land degradation and a technological standstill will cause stagnation in farm production, without an increase in agricultural prices. Therefore the system will find itself in a loop of impoverishment and the unsustainability spiral emerges [63].

The first sociological multi-agent models focussed on describing the emergence and dynamics of norms and values in society is found in [57]. Some of these notions are planned to be included in the model in a later stage.

Welfare maximizing behaviour

In our model the goal of the villages is to maximise welfare, which we operationalize as utility. Utility is maximized using a farm household economics utility optimising procedure based on Cobb Douglas production functions for current and future income and leisure time. Villages try to increase their long and short-term utility by making choices on investment in land quality and allocation of food and labour for on-farm production, hiring or hiring out labour and robbing.

We model goal seeking at village level and use conventional theories from household economics. In agricultural households, decisions about the management of the farm are closely linked with household decisions on what to eat or how to allocate time between farm work and other activities [64]. The farm household operates within a socio-economic and an ecological environment. It may have access to natural resources and (functioning) markets and within this context the household produces, invests and consumes. Different farm household models have been developed over the last century. The theory of Chayanov [65] has been the base of many farm household theories [66, 67]. The latter have all altered some of the conditions for specific applications, e.g. leaving out market imperfections and trade of labour.

Ellis [68] describes different farm household models based on objectives, market assumptions, predictions and practical effects. One of the special features of the household model is the integration of production and consumption decisions of the household. We will consider the farm household model of Barnum and Squire [69] as the basis for this study, although we make some minor alterations. This household model specifically provides a framework for generating predictions on the response of the farm household to a change in domestic and market variables. An important reason to use this model is that it, other than the Chayanov model, recognises the labour market and thus enables trade of labour between different villages. It considers the quantity of land available as fixed and it ignores the uncertainties that are part of the production process. These features are comparable to the assumptions in our study.

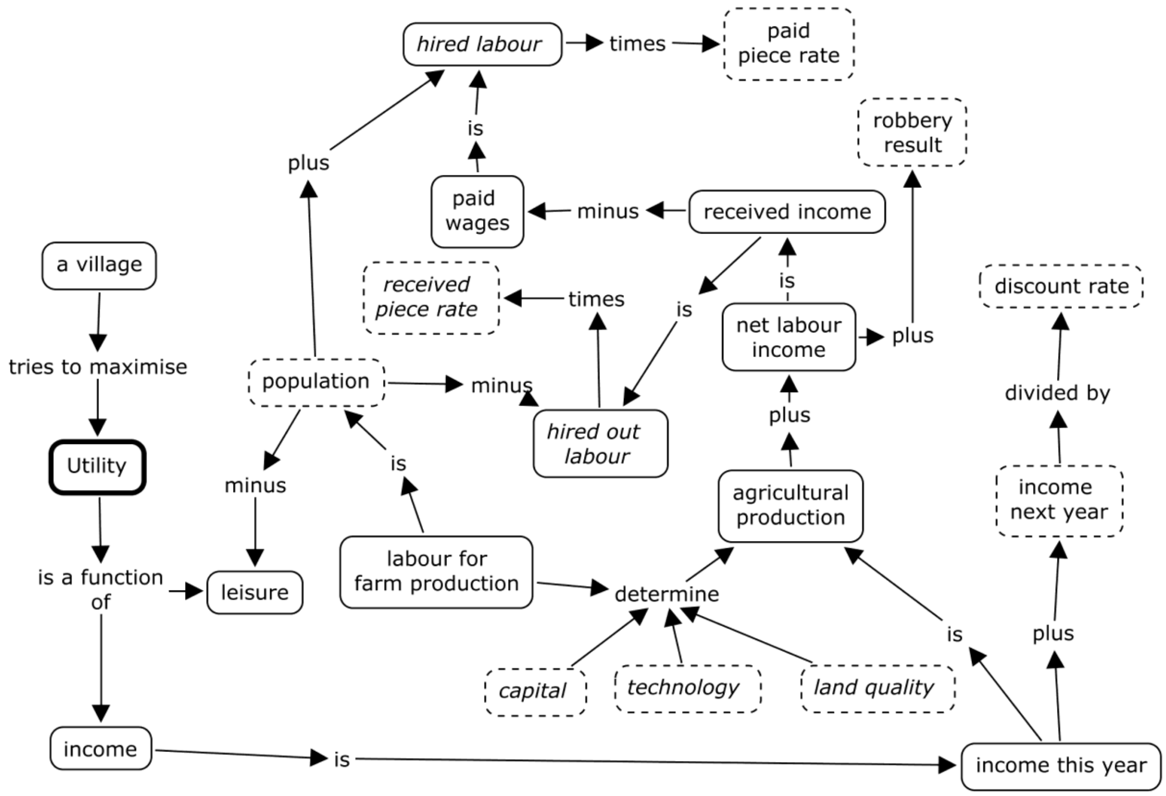

Figure 3. Conceptual map of welfare (utility) maximization of the villages. Dashed box indicates that the origin of the variable is not shown. Cursive indicates that the variable is altered by the village in order to maximise welfare.

The Barnum and Squire [69] household model also introduces a new product village: the Manufacturers. We will not use these in our model. Here, only one type of good will be produced which, considering perfect markets, can be traded for other goods. Secondly, the model introduces an alternative calculation of utility; which can be considered the driving force behind the household model. Barnum and Squire [69] do not only determine the utility by the amount of leisure time and consumption, but also by home production. We will not include this alteration but consider utility as the amount of leisure time and consumption available.

An important law when optimizing utility between different sets of products is the law of diminishing returns. This leads to a bias towards a leisure seeking behaviour of farmers with a high income and an income seeking behaviour of poor farmers. This law will form the basis for the choices made when maximum utility.

Another adaptation we make to the Barnum & Squire [69] model is the inclusion of land quality to the production function and writing it into a Cobb-Douglas production function with the elements: effective labour, total capital input and current land quality.

Adaptation & innovation

Here, we describe what adaptive traits villages have to improve their welfare in response to endogenous or exogenous changes. As explained above, we see utility as a measure for welfare.

In the long-run villages can adapt to a changing social and natural environment by changing their knowledge and investments in land quality. They can gain knowledge by investing in food or labour by experimenting, imitating and forgetting. Experimenting can yield new technologies that can result in higher utility in a specific situation. In the short-run villages can adapt to the changing demand or supply of labour and food; by trading with other villages or the world market; robbing; allocating more or less food for capital inputs. Till now, the cooperation strategy is directly related to the conflict history (a village will not trade for X years with a village that robbed another, known village last year) and the expected utility of robbing someone.

Till now we have not included any kind of game theoretical behaviour, because we assume technological learning more important because it directly affects agricultural production. However, we plan to introduce more sophisticated game theoretical strategies and game theoretical learning during further modelling efforts. Using game theoretical learning agents improve their cooperation strategies by repeatedly grappling with interaction processes over time [70].

Foresight

Foresight refers to the way a model represents how agents foresee the future outcomes of their decisions. The model uses so-called overt foresight, which means that agents explicitly forecast the consequences of each alternative decision.

The effects of selecting a known technology, doing a conservation investment and robbing a trading partner are calculated for two years in advance. Agents assume that their trading partner, their own labour input and technology will be the same during two years, but land quality, capital and transaction costs change. The latter increase when a village robs its trading partner. When assessing trade, agents take into account the conflict history of their known villages. The increased risk of conflict is represented by increased transaction costs.

Agents foresee the effects of technological innovation based on a ceteris paribus increase in utility. The foresight of the amount of capital needed for next year is done after harvest and with a ceteris paribus assumption of other factors. The effect of the prediction of the second year is altered by a discount rate which increases when the nutritional status of a village decreases.

Sensing

Sensing is the way an agent based model represents how agents obtain information about their (internal and external) environment and neighbouring agents. In line with classic economical theory, villages have complete information and awareness of their own characteristics and they know the following characteristics of their known villages: location, practiced technology, possible trade arrangements and the potential outcome, the piece rate when hiring out labour, the conflict history of the villages with other known villages. Furthermore they have full information about the characteristics of the area they live on.

Interaction

Interactions are mechanisms by which model agents communicate with each other or otherwise affect each other. In this model, agents (villages) can trade with each other, steal from each other and imitate each other’s technologies. Villages can only interact with villages within their social network and with the port. The entire network of agents in the model is a small world network.

A small world network is a connected network with two properties: each node is linked to a relatively well-connected set of neighbour nodes; and the presence of short-cut connections between some nodes makes the average minimum path length between nodes small. Such networks have both local connectivity and global reach. Small world networks are common and believed to be an emergent property of many socio-economical transactions [71].

As said under sensing, we consider the information to be complete, but subject to the limited memory capacity. Within the suitable conditions trade is subject to transaction costs, which are determined by the social and psychological costs of trade. Within societies and especially rural societies social norms, trust and social networks are of great importance for economical development [72-74]. Transaction costs can be seen as an economic reflection of the state of a relationship between two villages. Resulting in the punishment of a wrongdoer by an increase in the transaction cost between the wrongdoer and the members of social network to which the mistreated village belongs.

Interaction between agents and their environment

The effect of agriculture on land quality in Sub Sahara Africa is subject to a long and on-going debate (e.g. [45]). Within this debate the impact of population growth on land degradation and vice versa [75] is of great importance. In the model land degradation is proportional to crop production. Villages, however, can choose to diminish the degradation of their natural resources by investing in land quality. Agents can foresee the effect of both cropping as well as investing in land quality up to two years in advance.

In the model increased population can both cause land improvement as well as deterioration depending on the choices of the villages.

The production is considered to have impact on the quality of the land as well. We consider land degradation as a function of the crop produced, the natural regeneration and investments in land quality.

This on its turn is very much dependent on consumption. Demographical processes determine the consumption level of a farm village. It is of importance to consider that an extreme decrease of consumption will lead to a decrease of the population. Birth and death rates are related to consumption levels.

Stochasticity

Stochasticity in agent-based modelling means that pseudo-random numbers are used to represent a process or trait. We plan to limit stochastics to a minimum. We will only introduce stochastics during initialization when it appears necessary to get things running.

The selection of a technique as a result of modelling is done using a normal distribution. The social networks are created by (uniform) randomly changing connections of a regular square lattice network, using a power law distribution till the network shows the characteristics of a small world network.

Collectives

Villages can choose to cooperate (trade), rob each other or live in autarky. There is however no real formation of collectives. Villages interact within their interrelated social networks which are imposed.

Observation

Observation is the process of collecting data and information from an agent based model. Typical observations include graphical display of patterns over space and time and file outputs of summary statistics.

For model testing and calibration we will look at the network structure, which should represent a small world phenomenon (described by [76]). For analysis we will look at population dynamics, land quality dynamics, welfare development (which includes nutritional status and utility), and cooperation dynamics.

INITIALIZATION

During initialization, 10 000 villages and areas are created. Each village is linked to an area. The grid has closed boundaries and grid cells have a square shape. Each village is placed in a social network: a network of villages with which the village can trade. The networks are created in such a way that the entire network is a small world network. A small world network means that the path length or the degrees of separation between two villages is never more than six. To create a small network we will use the algorithm used by Wats & Strogatz [76].

During initialization villages calculate the distance to the other villages in their network. Furthermore, they are appointed a certain population and a certain amount of capital that is related to the size of the population. Furthermore, they are provided with a brain that holds a selection of technologies and a history of conflicts between the villages they know. We try to start with a community that is as homogenous as possible. We will only introduce diversity or stochastics during initialization when it appears necessary to get things running.

All areas are given a certain land quality which will be the same for all areas. Later on we plan to include some ecological zones using the land quality variable. The zoning will be loosely based on the comprehensive analysis on agro-ecosystems in Africa by Dixon et al [77].

One of the villages is changed into a port to the world market. By sending labour to the port villages can virtually trade with the world market. The price or the amount of food that the villages get per amount of labour will be set during the start. All villages have a direct access to the world market.

INPUT

Two categories of input variables can be distinguished. Those that we are not planning to change during model experiments and those that we want to change during model experiments. The latter are discussed in the paragraph Simulation experiments. The first category includes much of the parameters of table 1. We have not fixed the values of the first input category yet, but will do this based on best available knowledge and expert judgement.

MODEL TESTING & VALIDATION

The multi-agent model as described above needs empirical testing in the real world. Though the model has a bottom-up structure based on theoretical notions of agriculture, ecology, and household economics, our outcomes are at an integrated level. Therefore, we will test and validate our results using regional insights.

The more complex interactions will be worked out mostly qualitatively in several case studies. Janssen & Ostrom [58] suggest case studies as a suitable method to empirically link up multi-agent models with reality. Especially in interdisciplinary research, where causal relations between social and environmental variables play a role, they propose qualitative case studies.

We illustrate this here by two projected case studies that focus on two different parts of the unsustainability spiral: (i) natural resources: the land quality, population and agricultural prices nexus, and (ii) social capital: the trust, migration and agricultural prices nexus. For the two other domains of development, technology and demography, a vast amount of empirical evidence is already available [10, 78]. For the moment we do not foresee more empirical work in these fields.

Linking up multi-agent modelling with multiple empirical case studies is shown to be a powerful tool in integrating research from different fields of study (e.g. [79, 80]). However, as our model does not intend to be a simulation model of real events we will rather test on patterns than on exact events.

LAND DEGRADATION AND DEVELOPMENT

Within the multi-agent model notions are embedded in the nexus between population growth, land degradation and low agricultural prices. Recent multi-agent work on less favourable areas in Chile and Uganda shows that negative feedbacks exist between these variables [80], which have already been quantitatively been expressed in earlier works [10]; [81] on a small scale level. However, evidence at higher scale levels (regions) and longer time scales (decades) is lacking.

New research on sedimentation in coral reefs [82] offers great possibilities for extending the time and spatial horizon. Fleitmann et al found Ba/Ca records from the Sabaki river, Kenya, in coral reefs, that reflect the sedimentation, and hence erosion, history of the past 300 years of an aggregate area of more than 60 000 km2. The records show that especially in the last 100 years, after colonisation, erosion was most severe and erosion peaks are visible in the periods between 1930 and 1960, and again from 1975 onwards. These results are irrespective of the precipitation variability in these periods and therefore are a result of human interference. The results of this study can be linked up with the historical economic and demographic development in the Sabaki catchment and, hence, test hypotheses on the population, land quality and agricultural prices nexus.

TRUST AND DEVELOPMENT

Feedbacks exist between agricultural development, migration and trust. Networks of cooperation subsist within villages and between villages. High trust in the agricultural sector, in addition, can have positive spill over effect on the non-farm sector. However, positive effects of cooperation (e.g. knowledge sharing, cooperatives) can easily dissolve at times of resource scarcity or economic hardship. It is hypothesized that problems of social capital hamper economic development in Africa [83]. The background of these social capital problems needs a better understanding.

The interactions between trust, agricultural development and migration are hardly researched and we project a study on these linkages. Qualitative cultural-historical case studies are proposed to find out differences in trust relations between villages and find out the underlying causal relationships. We intend to interview farmers on social capital indicators that are a result of positive and negative experiences. This involves questions on a.o.: stealing, cheating and conflicts; and on: work agreements, economic cooperation and more in general people that can be trusted. These images will be linked up with the historical background of the villages with its agricultural, economical and demographic developments. Subsequently, conclusions can be drawn on the causes of trust as related to independent variables as agricultural prices, soil suitability, population density and market vicinity.

SIMULATION EXPERIMENTS

As described in the introduction, the model will be used to test hypotheses on the causes of the unsustainability spiral in Sub-Saharan Africa (see Figure 4 for some examples).

By taking into account the feedbacks, the model provides an integrative setting to study the influence of the drivers.

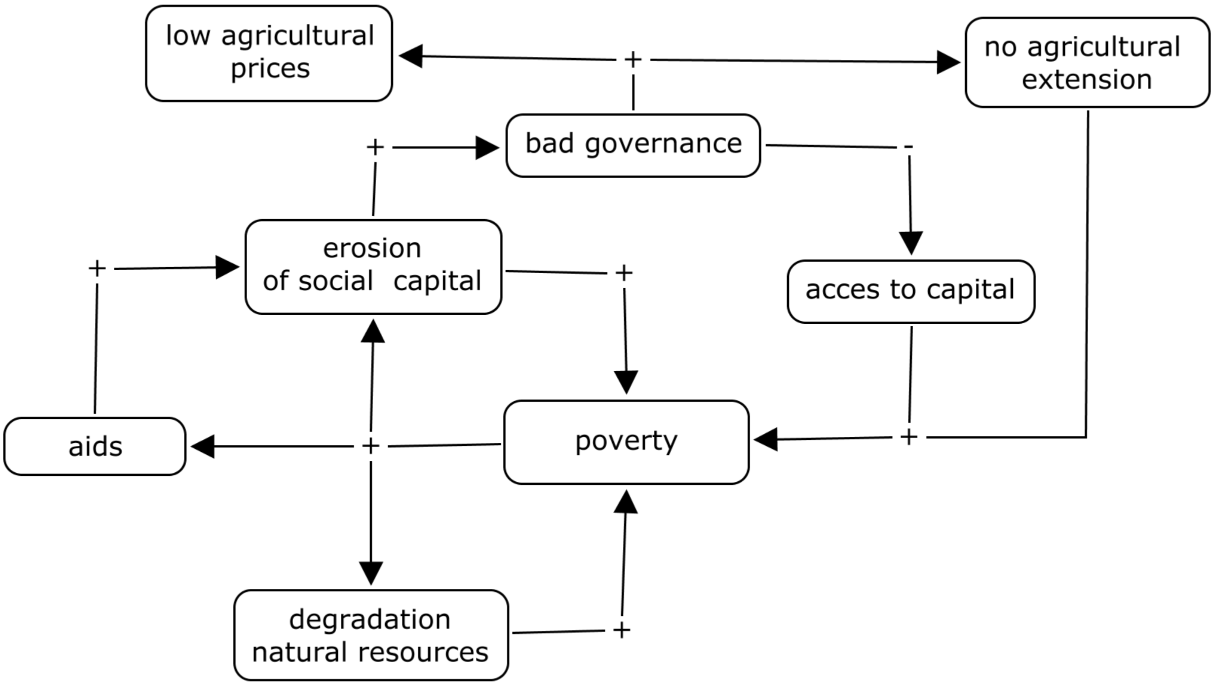

Figure 4. Some examples of factors and feedbacks that drive the unsustainability spiral in Sub-Saharan Africa. See Figure 2 and design concepts for an overview of the impact of low agricultural prices.

First of all we will test the hypothesized emergence of the unsustainability spiral (see emergence) by simulating a society isolated from the world market, where after we introduce a port to the world market with several price regimes. Besides that we will simulate the effect of governance by introducing an extra level which represents governmental bodies that can build roads (and other infrastructure), supply inputs and facilitate access to capital and spread new technologies (agricultural extension). The effect of infrastructure will be simulated by altering the transaction cost conversion coefficient. The effects of fertiliser subsidies will be simulated by increasing the soil investment coefficient. The effects of policies related to improved access to capital (loans, subsidies etc) can be simulated by increasing the capital access coefficient. Efforts of agricultural extension can be simulated by providing groups (either all or those within a certain distance from the capital) with technologies.

Furthermore, it is possible to simulate the effect of nepotism by introducing a sort of kinship, and provide villages that belong to the clique of the leader preferential access to markets in the port city. Subsequently, the effects of land degradation on poverty dynamics will be studied by simulating land improvement programmes. This will be done by increasing land quality. Additionally, the influence of access to capital will be simulated by changing the coefficient that determines access to capital. Finally, the effects of diseases like AIDS will be simulated by decreasing the labour intensity coefficient.

Large scale catastrophic events like the massive slave trade, droughts, floods, form not a central part of our vision of the unsustainability spiral. This does not imply, however, that these events are unimportant. We will simulate some catastrophes in order to see how robust the emerging properties of our model are. In other words: we will use simulated catastrophes as a way to test the sensitivity of our model outcomes.

DISCUSSION

Models are always wrong and models do not directly improve the yield of the African rural population. However, modelling can shine a new light on one of the most serious lock-in situations that our world faces today. Policy makers and scientists often focus too much on individual drivers at short time scales, whereas we hypothesise the need for integrated research and a long-term view. A multi-scale, multi-driver phenomenon as Sub-Saharan Africa's unsustainability spiral needs a multi-faceted policy approach. We believe that our research will offer valuable material to policy makers to make informed decisions on development cooperation and trade policy.

Rather than offering a blue-print like decision support model, that gives the welfare response for every change in variable *X*, we aim at offering a discussion support model that provides insights to the scientific and policy making communities on the complex interactions that cause the poverty spiral.

In the model we deliberately used rather conventional economics for describing the choices agents can make. We believe the use of conventional economics eases the communication with policy makers from governments and international bodies. Conventional methods at micro level can create easier acceptance of possible unconventional outcomes at macro scale. These outcomes at macro level will also give us a possibility to validate the patterns as found in empirical data.

A major shortcoming of working with theoretical agents is that the decision making procedure cannot be validated. However, even when using conventional theories we have to note that our model is limited. Firstly, some of our assumptions are hard to test or validate. First of all in our model we assume full information. This approach is especially questioned within the economic multi-agent modeller society [53].

Secondly, in the model we assume that land quality is a linear function of land quality investment and production. This appears not to be in line with recent findings of Giller [84] and Antle & Stoorvogel [85] who found strong hysteresis in land degradation and regeneration, while Giller found great heterogeneity in land characteristics in the fields around villages. However, we define land quality as all the characteristics of the area that is occupied by a village that influences the marginal capital and labour productivity. Although non-linear behaviour in land quality change definitely deserves attention, Antle & Stoorvogel's and Giller's findings do not provide any evidence that change in land quality shows non-linear behaviour as well.

Thirdly, an important issue is the starting point of the scale level. Although, we use a bottom-up approach with the lowest scale level being a village of farmers, behaviour of individual people is not included in the model. As a consequence individuals' decision making and diversity is not taken into account.

Finally, it might well be that non-farm production and products, which are currently ignored, play a far more important role than expected. Besides that, the use and impact of fertiliser use and application can only limitedly be simulated. Furthermore, we excluded many institutional factors (although they can be simulated indirectly) like for example property rights and legal equity.

The model description and proposed simulations and validations are all work in progress. The past efforts and planned activities will further promising and novel insights into the unravelling of Sub-Saharan Africa's sustainability spiral and the use of multi-agent methodology.

APPENDIX

Here, we describe in some detail the submodels, including the parameterization of the model.

EVOLVE DEMOGRAPHY

Calculate Births

Births are calculated using the following formula:

$$Births = x \cdot population \cdot maximum\_birth\_ratio, \quad (1)$$

in which x is calculated by:

$$x = min\ (\ (nutrionStatus - zeroFertilityNutrition)/\ maximum\ fertility\ nutrition,\ 1), \quad (2)$$

in which the *nutritionStatus* is the amount of food per capita (*income* · *population*-1, further on for the calculation of income), *zeroFertilityNutrition* the amount food intake per capita when fertility is zero and *maximumFertilityNutrition* is the level of nutrition after which the birth rate does not increase further.

Deaths

$$Deaths = \max\left(1 - \frac{(1 - minimumMortality \cdot nutritionStatus}{criticalNutritionStatus}, minimumMortality\right) \cdot population, \quad (3)$$

in which *criticalNutritionStatus* is the nutrition level from whereon the mortality rate does not further decrease, at this nutrition level the mortality will be the *minimumMortality*.

EVOLVE KNOWLEDGE

This consists of the submodules: forget production technology, imitate and experiment. Villages can also imitate technology from the villages they know.

Forget production technology

First, a village looks whether an experiment has been undertaken in the last year. If so, the resulting production technology is stored. After assessing the experiments the stored technologies are used. All technologies possess a counter that counts the years that a technology was not used. After a number of subsequent years of non-usage a technology is forgotten.

Imitate production technology

Villages copy the production technologies used by the villages they know to their list of technologies.

Experiment

A farmer will experiment if the expected, discounted increase in utility of the found technology is higher than a certain threshold:

$$(Discountrate + 1)^{-1 \cdot} U_1 > U_0 + threshold, \quad (4)$$

in which the U_1 is the utility when the old technology is used and U_0 the utility when the yet to be found technology is used.

$$U_1 = U(I_1, F) \text{ and } U_0 = U(I_0, F), \quad (5)$$

in which F is leisure and I income which is agricultural production and other income (O), which is here constant. Then:

$$I_1 = Y_1 + O \text{ and } I_0 = Y_0 + O \quad (6)$$

$$Y_0 = A_0[a_0 \cdot max(0, L - T_{L0})]^{\alpha_0} \cdot [b_0 \cdot max(0, K - T_{K0})]^{\beta_0} \cdot [c_0 \cdot max(0, P - T_{P0})]^{\gamma_0} \quad (7)$$

$$Y_1 = A_0[a_1 \cdot max(1, L - T_{L1})]^{\alpha_1} \cdot [b_1 \cdot max(1, K - T_{K1})]^{\beta_1} \cdot [c_1 \cdot max(1, P - T_{P1})]^{\gamma_1} \quad (8)$$

In which A_1, α_1, β_1, γ_1, TR_{L1}, TR_{K1}, TR_{P1} are the coefficients that represent the new technology, while A_0, α_0, β_0, γ_0, T_{L0}, T_{K0}, T_{P0} is the set of coefficients that represent the previous technology. The set of coefficients that forms the new technology is randomly selected using a uniform distribution from a pre-composed list of n technologies. The selection is done within a certain range to, literally speaking, prevent that an Iron Age community suddenly invents a tractor. The threshold is a parameter that is the same for each village. For experimenting no additional food or labour is required. The found technology will be available to the village the year after the experimenting has been done.

PLAN PRODUCTION AND EVOLVE COOPERATION STRATEGY

In the plan production and evolve cooperation strategy module, the village will try to invest its resources (food and labour) as effective as possible. This is done by maximizing the expected utility (U) which is the sum of this year's utility (U_t) and the estimated and discounted Utility of the following year (U_{t+1})

$$U = U_t + U_{t+1} \cdot (discountRate + 1)^{-1},$$

$$U_x = U_x(I, F)$$

$$I = Y + tradeResult + robResult - conservationInvestment,$$

in which Y is harvest:

$$Y = A[a \cdot max\ (0, L - T_L)]^{\alpha} \cdot [b \cdot max\ (0, K - T_K)]^{\beta} \cdot [c \cdot max\ (0, P - T_P)]^{\gamma},$$

in which Y is yield or agricultural production, L is labour, K is capital and P is land quality. α, β, γ, a, b, c, T_L, T_K, T_P and A are technology dependent variables. T_x is for the threshold value of an input x. Before x reaches T_x no production is realised.

$$L = labourIntensity \cdot (population - outworkers),$$

in which *labourIntensity* is an input variable with a default value of 1. *outworkers* is the number of people from the village who work at another village. Below is explained how this number is determined.

The trade result (*tradeResult*) is the food paid to the migrant workers of the village minus the transaction costs and the wages paid to other villages. Wages of normal villages equal the marginal labour productivity of the village that sends the workers. The wage of the port is a fixed parameter which represents the world market price. Transaction costs are determined by the physical distance to a village and trust. The latter is affected by robbing (see details further in the appendix).

A village can only trade with one of the villages it knows. It can either be an importer of labour or an exporter of labour. If a village trades with another village, it might also decide to rob the other village. If a village is importer, this is done by not paying the migrant workers of the other village. In case a village is an exporter, robbing is done by stealing of food that equals the wage of the workers. The *robResult* is the result of robbing and be robbed.

First a village calculates the best expected two year income in case it will be self-subsistent using the optimal combination of technology, conservation investment (using the *consider producing* submodule).

Subsequently, each village will search the best combination of send workers, technology, conservation investment and robbing for each of the known villages (in the *consider trading* submodule). The best amount of workers sent to the port to the world market (*sendWorkers*) is calculated as follows:

$$sendWorkers = population - L \cdot labourIntensity^{-1},$$

in which L is the labour needed on farm, which is calculated as follows:

$$L = \left(\frac{opportunityCost}{\alpha \cdot A \cdot K^{\beta} \cdot P^{\gamma}} \right),$$

in which the *opportunityCost* is the price of labour at the world market minus transaction costs. In this way a village will self-employ workers till the marginal productivity equals opportunity costs. From that point onwards, workers are sent to the world market.

The best possible combination of technology and the amount of conservation investment is simply searched by assessing all possible combinations. When trading with a village (which is not the world market) the best amount of workers is searched by checking all possibilities until the best combination is found. To limit the amount of calculations, conservation investment is considered a discrete value.

Using these best combinations a list is compiled (see Table 2). This list is used to select the best trading partner. This best trading partner is invited to trade with the village (the *allocate inputs* submodule). If the trading partner is the world market, the answer will be positive. In case the partner is a normal village it will asses its preferential trading partners, which are villages that can offer a better trade deal than the deal that is currently on the table. Subsequently, it counts for each preferential partner the amount of worse options they have than dealing with the village (the village that is offered the deal). The village that is offered the deal uses this information to calculate the probability that the village can realise a better trade deal, than the one that is offered now. If this change exceeds a certain risk aversion threshold the trade offer will be rejected.

When estimating the income of the second year, the amount of capital and the land quality are updated (see the outline of the *spend harvest* module for more details). So the village can take into account the effect of investments in conservation (*conservationInvestment*). In estimating the trade part of the income of the second year the village assumes that it keeps the same trading partner. If a village decides to rob from its trading partner, an extra transaction cost will be added when trading with any village from the known village list of the robbed village.

If a partner cannot find a trading partner it will be self sufficient.

Table 2. Example of a trade outcome list of a village that contains the expected income of trading with all known villages at optimal combinations of technique, amount of hired out workers, conservation investment and robbing. In this example a village will first try to realize trade with village 2.

Trade with	Expected income (food)	Hired out workers (#)	Technique	Conservation investment (food)	Rob? (Y/N)
self (autarky)	200	0	T1	10	NO
known village 1	300	3	T3	10	YES
known village 2	400	4	T6	20	NO
known village 3	200	2	T2	10	NO

EVOLVE AGRO-ECOLOGY

GrowCrop

Crop production is calculated per area using a Cobb Douglas production function:

$$Y = A \cdot \max(0, L - T_L)^{\alpha} \cdot \max(0, K - T_K)^{\beta} \cdot \max(0, P - T_P)^{\gamma}$$

In which Y is yield or agricultural production, L is labour, K is capital and P is land quality. α, β, γ, T_L, T_K, T_P and A are technology dependent variables. T stands for the threshold value of a certain input before it has any effect.

Evolve LandQuality

In this submodule the area updates the land quality. *Land quality* is the sum of the previous land quality, regeneration and degeneration with a minimum value and maximum value.

Regeneration is a constant value. *Degeneration* is calculated as:

$$Degeneration = crop\ production - conservation\ investment \cdot conservation\ efficiency.$$

SPEND PRODUCTION

The villages spend production module consists of a submodule that stores the capital (including seed) for next year and a module that sets the discount rate. The amount of capital available to the village is chosen in such a way that the sum of the current year's utility and next year's discounted utility is maximized assuming ceteris paribus of other factors.

Once the seed is stored a new discount rate is calculated using the following formula:

$$discountRate = \frac{discountParameter}{nutritionstatus},$$

in which the discount parameter has a default value of 100, and the nutrition status is food consumption per capita with a minimum of 1,106. The discount rate cannot be higher than 100.

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RAZVEZIVANJE SPIRALE NEODRŽIVOSTI U PODSAHARSKOJ AFRICI: PRISTUP MODELIRANJEM POMOĆU AGENATA

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SAŽETAK

Podsaharska Afrika zarobljena je u kompleksnu spiralu neodrživosti demografskih, biofizičkih, tehničkih i socio-političkih dimenzija. Razvezivanje te spirale nužno je za spoznavanje akcija koje su potrebne za njeno invertiranje i podsticanje održivog razvoja. Članak prezentira evolucijski višeagentski okvir koji povezuje socioekonomski pristup i svjetsku perspektivu te uzima poljoprivredu kao motor pokretač održivog razvoja u podsaharskoj Africi. Razmotreno je više mogćnosti empirijske validacije.

KLJUČNE RIJEČI

višeagentski sustavi, razvoj, zamka siromaštva, degradacija, socijalni kapital, podsaharska Afrika