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Implications of poverty traps across levels

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ABSTRACT

Recent research has demonstrated the multidimensional nature of poverty and the multi-level organization of social-ecological systems that display poverty traps. The traps on these different levels can reinforce each other, and therefore multi-level traps pose particular challenges for poverty alleviation. Yet, poverty trap models rarely consider more than one level of organization and only a few attributes of the system at each level. These limitations constrain our understanding of the mechanisms that generate poverty traps and may hinder or even mislead development efforts. Here, we present a series of two-level dynamical system models of poverty traps and use these models to investigate the combined influences of biophysical and economic factors, farmers' habits and community decisions on creating and alleviating persistent poverty. Our results indicate that neglecting key interactions can lead to incorrect assessments and potentially inadequate alleviation strategies. Moreover, we obtain necessary conditions for the existence of fractal poverty traps, and show that (i) cross-level interactions can open possibilities for escaping from poverty, (ii) that farmers' behavioral changes may create or impede a way out of poverty, and (iii) that the effectiveness of development interventions depends on the combined influences of biophysical and economic dynamics, farmers' behavior and community spending on agricultural and social activities.

1. Introduction

Poverty traps are states of social-ecological systems in which self-reinforcing mechanisms keep individuals or communities in persistent poverty (Haider, Boonstra, Peterson, & Schlüter, 2018). Poverty traps in rural settings are often multi-dimensional: that is, economic, biophysical and social processes interact to produce reinforcing dynamics that maintain the trap (Haider et al., 2018; Lade, Haider, Engström, & Schlüter, 2017; Radosavljevic, Haider, Lade, & Schlüter, 2020; Alkire and Robles, 2015; Anand and Sen, 1997). Moreover, these dynamics often unfold at and across several spatio-temporal scales or levels of organization, given that social-ecological systems (SES) in which poverty traps occur are generally characterized by dynamics at and across multiple levels and scales (Levin et al., 2013). These observations have motivated researchers in recent years to conceptualize multi-level or fractal poverty traps in an attempt to account for trap dynamics that may reinforce each other across scales (Barrett and Swallow, 2006; Maru et al., 2012). For example, in a development context individuals may not be able to access credit due to insufficient collateral, the local community cannot offer adequate social services because of limited welfare funding and distribution, and, on the country level, perhaps the political climate is not conducive to wealth distribution or the government has received aid funding tied to specific sectors. The traps on these different levels can reinforce each other, and therefore multi-level traps pose particular challenges for poverty alleviation. Better understanding of different types of multi-level traps, and how they appear and are maintained by cross-level dynamics can provide valuable insights for targeting interventions for poverty alleviation.

In economics, poverty traps have commonly been conceptualized and modeled as stable, low well-being equilibria of systems (Barrett and Bevis, 2015). Moving out of poverty thus entails shifting the system out of this equilibrium into an alternative equilibrium with higher well-being. Barrett and Swallow (2006) have introduced the concept of a fractal poverty trap to account for the multi-level nature of traps. A fractal poverty trap is defined as a poverty trap where several low-level equilibria exist on different levels at the same time and self-reinforce through cross-level feedbacks. Barrett and Swallow hypothesized that small changes in dynamics at only one level are likely to be inefficient in alleviating poverty and that interventions have to be applied on all levels where low productivity strategies reinforce one another. An informal theory of fractal poverty traps was presented by Barrett and

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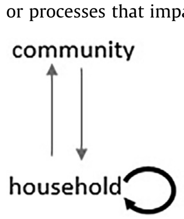
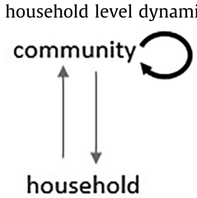
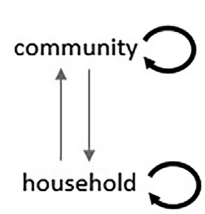
Swallow (2006), but dynamical models and full understanding of the diversity of mechanisms that may operate within and across levels are still missing. Neglecting key interactions at or across scales can result in wrong assessments and subsequently in inadequate alleviation strategies. Models of traps in multi-level systems as proposed here can help identify where in the system to intervene to produce a change in its overall behavior.

Here, we show that fractal traps are only one particular type of multi-level poverty trap in SES. We propose a typology of multi-level traps in order to better understand trap mechanisms and the effectiveness of interventions at different levels. We define a multi-level poverty trap in the most general sense as a poverty trap that exists in a multilevel system due to within- and cross-level interactions. Our definition builds on dynamical systems theory (building on Lade et al. (2017), Radosavljevic et al. (2020)) and we will use dynamical systems models to explore the different types of traps. Based on this definition three types of multi-level traps can be distinguished of which fractal traps are one (Table 1). The first type, a *single-level poverty trap*, is a situation in which a trap is maintained by processes or structures at one level, e.g. the trap of an individual household is maintained by a rigid institutional setting that does not allow the farmer to innovate (Cumming, 2018; Maru et al., 2012). In other words, a mechanism that creates a trap may exist only at one level in a multilevel system, while cross-level interactions propagate effects of the trap to multiple levels. Another type of a multi-level trap is a *fractal trap*, where dynamics on each level creates a trap, which may be reinforced by cross-level interactions. Maru et al. (2012) point out the link between poverty and rigidity traps in an indigenous context where marginalization still exists. A rigidity trap with inflexible institutions may exist among those who appropriate resources, which can lock out others from having access to economic opportunities and increase their vulnerability to poverty traps. We propose a third type of poverty traps in multilevel SES, a *cross-level trap*, where traps at multiple levels are introduced by cross-level interactions. With relatively little existing research available to illustrate this type of multi-level trap, we have chosen to explore them using theoretical models; we call however for greater empirical research on cross-level traps in the future.

The aim of the paper is to shed light on the occurrence, the mechanisms and potential alleviation strategies of different types of multi-level traps in rural agroecological settings. In particular, we explore how individual farmer and community decisions under different combinations of biophysical and economic conditions shape the dynamics of poverty of households and communities in rural agricultural settings (the left panel in Fig. 1). Our focus is on poverty traps in agroecological settings because the majority of the global poor live in rural areas and their livelihoods are tightly linked to agricultural production and exploitation of common property resources. We use stylized dynamical system models that build on empirical understanding of poverty dynamics in order to guide our intuition and deepen understanding of persistent poverty in multi-level systems. The models represent poverty trap dynamics in multidimensional social-ecological systems characterized by interacting biophysical, economic, social and behavioral aspects. Specifically, we investigate an example of a rural community where individual farmer households and the overall community can be caught in savings traps that lead to persistent poverty. We explore the multi-level dynamics of this community under different social-ecological settings and assumptions on farmers' decisions and community strategies, with a particular interest to i) assessing the importance of cross-level interactions

Table 1
We distinguish types of multilevel traps by the location of the mechanisms that generate the trap. In our framework, a single-level trap is a type of multilevel trap where trapping mechanism exists at a single level, a fractal trap is a type of multilevel trap where trapping mechanisms exist at multiple levels and reinforce each other, and a cross-level trap is a type of multilevel trap that has cross-level trapping mechanism. For the purposes of this table, 'displays a trap' means the model has an undesirable attractor. Commonly, models displaying traps have one undesirable ("poor") and one desirable ("non-poor") attractor. The figures in the last row are examples of mechanisms and their location and different levels may also be community and state.

Type of trap	Single-level	Fractal	Cross-level
Trapping mechanism	At one level	At multiple levels	Cross-level
Consequences	Effects of the trap are propagated to multiple levels through cross-level interactions	Trapping mechanisms at multiple levels reinforce each other through cross-level interactions	Multiple levels experience the trap due to cross-level interactions
Sub-types	Trapping mechanisms create traps at (A) individual level, (B) community level	(A) Same trapping mechanism at each level (self-similarity) (B) Different trapping mechanism at each level	(A) Cross-level interactions create traps across multiple levels (B) As in A, but cross-level interactions also provide an alternative non-poor state
Examples	(A) Savings trap (households cannot save enough to invest in infrastructure that would increase production) (B) Savings or rigidity trap at community level (e.g. a community cannot save enough to invest in communal infrastructure, or it cannot adjust institutions to new conditions, respectively)	(A) Separate savings traps at individual and community levels (Barrett and Swallow 2006) (B) Savings trap at household level and rigidity trap at community or national level	(A) High government tax rate leads to low personal income and government revenue (B) Social safety net funded only under high government revenue
Cross-level interactions	Bottom-up: aggregation of individual contributions to community assets Top-down: investment of community assets in structures or processes that impact household level dynamics		
Illustration Black arrows denote trapping mechanism. Grey arrows denote mechanisms that do not produce traps.	 		

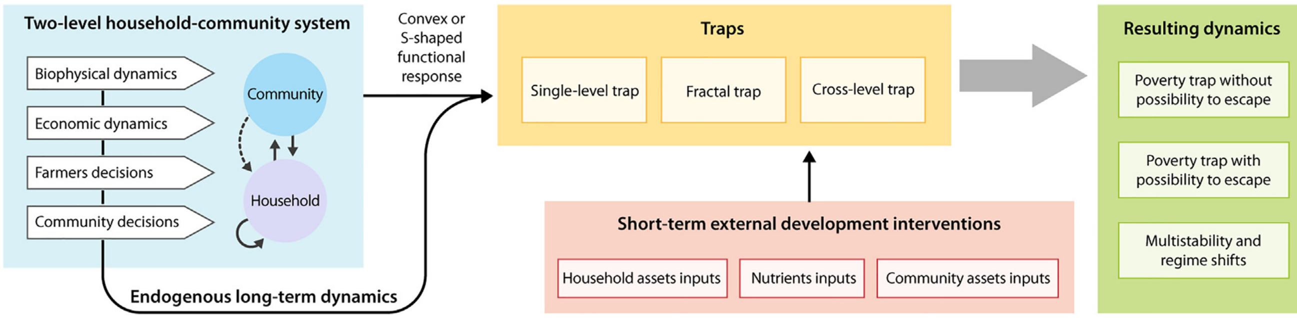


Fig. 1. We investigate how long-term biophysical and economic factors interact with farmer and community decisions and create two-level household-community social-ecological systems (left panel). Thick lines in the left panel represent flow of assets and dashed line represents social and cultural benefits farmers might have from community level activities. Depending on dynamics on household and community levels and cross-level interactions, the system has single-level, fractal or cross-level poverty trap. The system is then treated with different combinations of external development interventions (middle panel). The resulting dynamics is created through combined effects of long-term dynamics and short term interventions (right panel). The causal loop diagram is in Fig. 2.

for the occurrence and alleviation of poverty traps, ii) identifying the conditions under which fractal poverty traps exist, iii) exploring when farmers' decisions to support a community-level public good can alleviate poverty and, lastly, iv) assessing which strategies may stabilize the SES in a non-poor state. Our models allow assessment of the effectiveness of development strategies and development interventions and provide nuanced view on relation between long and short term poverty alleviation measures. We begin by describing our model setup, where we introduce the empirical background, assumptions and mathematical basis of our models, continue with model analysis and conclude by discussing our results and their relevance for future research and development practice.

2. Poverty trap models

2.1. Empirical background

Low assets levels, financial and structural constraints (Carter and Barrett, 2006; Zimmerman and Carter, 2003), low soil quality (Barrett and Bevis, 2015) and lack of water (Enfors, 2013) or nutrients (Bationo et al., 2011; Bloem, Trytsman, & Smith, 2009; Drechsel, Gyiele, Kunze, & Cofie, 2001; Giller & Cadisch, 1995; Nziguheba et al., 2016) have been identified as some of the main causes of persistent poverty in rural agricultural areas, since they contribute to low crop yields, which in turn lead to poor health and/or low income. Poor health and spread of diseases are other well-known causes of rural poverty (Ngonghala et al., 2017). Common strategies for increasing production include: water management and irrigation (Enfors, 2013; Rockström, 2000; Rockström, 2003), intensification through the use of improved seeds, inputs of phosphorus using fertilizers or manure (Nziguheba et al., 2016; Verde & Matusso, 2014), or replenishing nitrogen by planting nitrogen fixating plants and intercropping instead of having monocultures (Bationo et al., 2011; Bloem et al., 2009; Giller and Cadisch, 1995). Reducing nutrient loss can be achieved using conservation tillage (Enfors, Barron, Makurira, Rockström, & Tumbo, 2011; Ito, Matsumoto, & Quinones, 2007) or manure for soil fertilization (Kihanda, 1996). In order for any of these strategies to be effective in the long-term, specific contexts and dynamics with other forms of social and natural capital must be considered (Lade et al., 2017).

Social capital, i.e. relations of trust and cooperation between people, plays a pivotal role in combating rural poverty (Asadi et al., 2008; Warren et al., 2001). Poor people rely on family and on community support structures across scales (individual, family, community, state) to survive (Bebbington and Perreault, 1999). Formal social safety nets may provide relief in times of crisis (Devereux, 2002), but in other situations, informal social networks may be the key factor for preventing households from sinking into poverty (Bird et al., 2002). Social exclusion, lack of information, poor education and healthcare, physical isolation or lack of access to markets due to entry barriers or infrastructure are well-known causes of persistent poverty in remote rural areas (Bird et al., 2002; Schneider and Gugerty, 2011). Farmer organizations have been demonstrated to improve living conditions through better market access, education and increased production (Bachke, 2019). There is evidence that farmers can benefit from organizing into collectives, but participation rates may vary depending on education or assets levels (Sinyolo and Mudhara, 2018). Similarly, community-based savings groups have been shown to be effective in empowering women and having positive effects on health, education and livelihoods (Kesanta and Andre, 2015). Despite being a very popular development intervention, the evidence for the impact of savings groups on the lives of the poor has been recently questioned (Karlan et al., 2017). In a large randomized evaluation in Ghana, Malawi and Uganda, Karlan et al. (2017) found no significant evidence that savings groups affect farming activities, but do find a positive effect on women's empowerment and other business activities. They do however find that there is a significant positive change in individual saving potential (demonstrating the use of groups for savings, not just risk distribution), but that it is unlikely to be transformative and they encourage further research on this topic. We situate our work in this endeavour and focus on the social capital and organisation between the individual and community level, where cooperation and coordination efforts are especially important since they determine spending and investment of assets and help creating norms that shape interactions between farmers or between farmers and environment. Savings groups may also use community assets for building social networks or funding cultural events (such as weddings and funerals) and preserving traditions (Ashe and Neilan, 2014).

2.2. Model assumptions

While the multi-dimensional nature of poverty traps has recently informed models that go beyond a focus on physical capital alone (Kraay and Raddatz, 2005), these studies generally only model a trap and trap mechanisms at one level. For example, recent work has studied: the relationship between asset dynamics and biophysical properties of the environment (Barro and Sala-i Martin, 2004; Smulders, 2000; Xepapadeas, 2005); the effects of human health and disease dynamics on poverty (Ngonghala et al., 2017); the interactions between environmental, social and cultural aspects of a rural agricultural system (Lade et al., 2017); the effects of technology on poverty traps (Mirza et al., 2019); and the effects of productivity, nutrients, water and soil quality on poverty traps in agro-ecological settings (Radosavljevic et al., 2020). These models have developed a nuanced view on the diversity of mechanisms that create poverty traps and reveal possibilities and limitations of poverty alleviation strategies that elude the purely economic view on poverty given in one-dimensional models. They have, however, fallen short of accounting for the multi-level nature of most trap dynamics.

In order to account for multiple causes of poverty mentioned above, we include biophysical and economic factors, farmers' habits and community decisions in dynamical systems models (the left panel in Fig. 1). Biophysical complexity is represented by factors that limit crop growth, such as nutrients, and economic aspects are included through asset dynamics at the household level. Incorporating social aspects in an analytical model requires incorporating variables at the community level. We therefore set up models to include both the household-farm level and community levels. We use the term household-farm to refer to the local-level social-ecological system of a farmer, their household, their assets, and their farm. The causal loop diagram in Fig. 2 gives an illustration of model variables and their relationships.

The household level is represented by interlinked dynamics of assets and nutrients, such as water, phosphorus, nitrogen or any other element that is necessary for crop growth. The dynamics of household assets is often based on standard neoclassical economic theory (Barro and Sala-i Martin, 2004; Kraay and Raddatz, 2005; Smulders, 2000; Xepapadeas, 2005), which assumes that a fraction of household assets is consumed and the rest (determined by usually nonlinear savings rate) is invested in agricultural production. Household assets can improve productivity in different ways e.g. by purchasing fertilizers, seeds or tools, by improving production technology or by improving farmers health and ability to work. Due to importance of nutrient dynamics for crop growth, we differentiate between household investments directly related to nutrients inputs and those that improve productivity in other ways (yellow panel in Fig. 1).

The community level in our models is represented by community assets, which are created by collecting individual farmers' contributions and are owned by the community. Some of the assets are lost due to depreciation or corruption and the rest can be invested in development strategies or spent on cultural and social events, depending on community level decisions (green panel in Fig. 2). We assume that community assets have positive effects on farmers well-being in two ways: 1) by funding development strategies that target biophysical and economic causes of poverty (the red arrows in Fig. 2), or 2) by preserving local culture, tradition and social structure, which in turn can improve farmers' health, agricultural production, access to information or market (the green arrow in Fig. 2). These effects are modeled as cross-level interactions directed from community to household level (i.e. top-down interactions). Spending and investing community assets can change depending on the community, which gives rise to s-shaped or convex savings rates and leads to single-level, fractal and cross-level poverty traps (the middle panel in Fig. 1, Table 1).

An important part of our models are the bottom-up interactions, represented by individual farmers contributions to the community assets (the black arrow in Fig. 2). We assume that all farm-households are identical and that farmers decide how much of the household assets they will invest in their own production and how much they will give to the community. The strength of the bottom-up interactions is therefore determined by the farmers decisions: the more assets farmers keep on the household level and invest

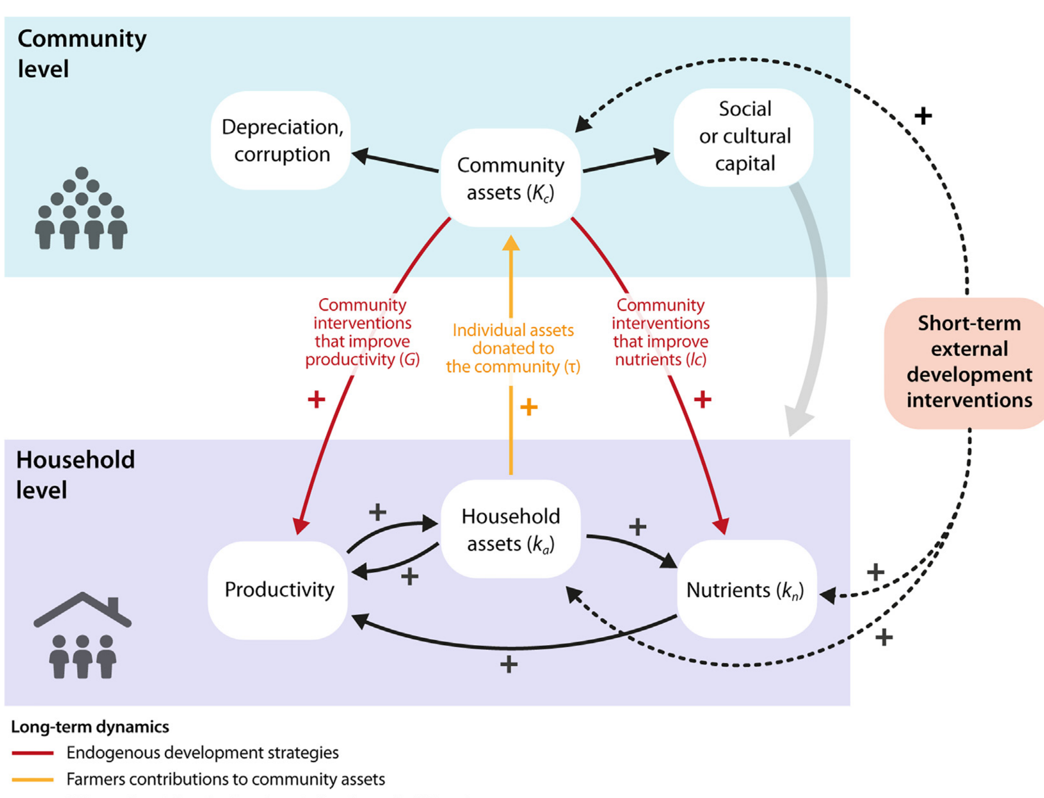


Fig. 2. Causal loop diagram (CLD) of an agroecological system showing dynamics on household and community level and cross-level interactions. The CLD expands left panel in Fig. 1.

in their own agricultural production, the less is invested in community and the weaker bottom-up interactions are. Consequently, farmers decisions affect the amount of community assets that can be allocated to development strategies and directed from community to household level. Thus, one of the focal points of our analysis are consequences of farmers decisions on dynamics of the household-community system. Note that we study the effects that different ratios of investment in own production versus community assets might have rather than the evolution of this trade-off.

2.3. Development strategies and interventions

Throughout the paper, 'development strategies' are actions taken by a community with the purpose to alleviate poverty by increasing agricultural production through improving infrastructure, providing services such as market access, education or healthcare, increasing nutrient inputs or reducing nutrient loss. Development strategies are assumed to be endogenous and long-lasting. In this paper we define 'development interventions' as short-term poverty alleviation actions carried out by external actors, such as non-governmental organisations (NGOs) or government programs. Development interventions focus on compensating for poor and undesired initial conditions in the short-term. In reality, of course short-term interventions can have long-term implications, and vice versa, development strategies can be applied to short-term solutions. For the purpose of this paper, this clear separation between strategies and interventions with regard to their duration is useful for modelling purposes to point out effects of long and short-term poverty alleviation measures. Development strategies are presented using red and orange arrows in the left panel in Fig. 1 and development interventions are listed in the middle panel of the same figure. The right panel in Fig. 1 presents possible outcomes of combined effects long and short-term dynamics.

2.4. Mathematical setup

The two-level agroecological system described above is represented by a system of differential equations with household assets (k_a), nutrients (k_n) and community assets (K_c) as state variables. The household level is defined through dynamics of household assets and nutrients, and the community level is defined by dynamics of community assets. The cross-level interactions are twofold: 1) bottom-up as aggregation of farmers' contributions, and 2) top-down, which are enacted when community assets are i) invested in development strategies that affect dynamics of assets and nutrients on the household level, or ii) spent on social networks, local culture and tradition, market access, education of health services, which in turn affect household level dynamics by increasing farmer productivity (Table 1 and Fig. 2). In what follows, we give a detailed account of dynamics of state variables on household and community level, introduce cross-level interactions and formulate two-level model.

2.4.1. Household assets

A starting point for describing household level dynamics is describing dynamics of assets using the neoclassical economic growth model (Barro and Sala-i Martin, 2004), given by equation

$$\frac{dk_a}{dt} = s(k_a)f(k_a,k_n) - (\delta_a + r)k_a, \tag{1}$$

where $s(k_a)$ is the household assets savings rate, $f(k_a,k_n)$ the production function depending on assets and nutrients, δ_a household assets depreciation rate and r the population growth rate. We assume that the function f is the Cobb-Douglas production function of the form

$$f(k_a,k_n) = Ak_a^{\alpha_a}k_n^{\alpha_n}, \quad A > 0, \quad \alpha_a + \alpha_n \leqslant 1, \tag{2}$$

and the parameter A denotes productivity.

The savings rate $s(k_a)$ represents the proportion of household assets that is saved and invested in agricultural production. It is low for low levels of assets, increases with assets and levels off for high assets values. We model it as s-shaped function of the form

$$s(k_a) = s_0 + \frac{s_1}{1 + e^{s_2 - s_3 k_a}}, \quad s_0, s_1, s_2, s_3 > 0. \tag{3}$$

The S-shaped response of the savings rate is the key factor that allows creating poverty trap on the household level (Kraay and Raddatz, 2005).

2.4.2. Nutrients

Another key variable describing the household level dynamics is the amount of nutrient in the soil. The rate of change of nutrients is the difference between nutrient inputs and nutrient loss, given by equation

$$\frac{dk_n}{dt} = I_a(k_a) + r_n - \delta_n k_n, \quad r_n \geqslant 0, \delta_n > 0, \tag{4}$$

where the function $I_a(k_a)$ defines nutrient inputs provided by household level assets, r_n is the natural nutrient input and δ_n denotes nutrient loss rate. Observe that $r_n = 0$ for nonrenewable nutrients, such as phosphorus.

The amount of nutrient inputs depends on and increases with the amount of household assets. Low levels of household assets allow purchasing small amounts of fertilizers or manure and the increase of soil nutrient level is insignificant. Higher assets levels allow more fertilizer or manure to be applied, which increases nutrient inputs to the soil. Since plants use limited amount of nutrients, there is an upper limit for recommended nutrient inputs and spending more assets on fertilizers does not increase agricultural production indefinitely. To ensure that the effects of assets used for fertilizer application saturate at high asset levels, we assume that the function $I_a(k_a)$ has form

$$I_a(k_a) = c_0 + \frac{c_1 k_a^m}{c_2^m + k_a^m}, \quad c_0, c_1 \geq 0, c_2, m > 0, \tag{5}$$

where c_0 is the minimal contribution of assets to nutrient inputs, $c_0 + c_1$ is the maximal contribution of assets to nutrient inputs and c_2 is the half-saturation value.

2.4.3. Community level dynamics

According to the neoclassical theory of growth, household assets are used for consumption and savings. We assume that saved assets are split between investment in household's agricultural production and contributions to the community's assets. Let τ be the proportion of assets that each farmer invests in agricultural production and $1 - \tau$ is the proportion of assets given to the community. The community level assets K_c increases through farmers' contributions and decreases due to depreciation or corruption.

The dynamics of community assets can reflect community decision making. For example, a community that values social ties and networks, tradition and local culture may split its assets and spend it on social and cultural events and invest in development strategies. While some social interaction and traditions can increase farmers' productivity by, for example, preserving local knowledge and networks, other investments may be beneficial in ways that do not affect farmers' productivity. Moreover, a certain level of corruption can be present in a community and lead to loss of community assets. In order to include all these variations in how community assets can be spent, saved and invested, we define function $s_c(K_c)$ as the community assets savings rate, i.e. the fraction of community assets invested in development. The rate of change of community assets is then expressed by equation:

$$\frac{dK_c}{dt} = (1-\tau)Ns(k_a)f(k_a,k_n)s_c(K_c) - \delta_c K_c. \tag{6}$$

The $1-s_c(K_c)$ fraction of the community assets that is not saved can reflect assets invested in social and cultural aspects or lost due to corruption. In the first case, it should not be seen as a loss of assets that could be used for funding agricultural development strategies. Social networks can be essential to spread of information, while keeping traditions may preserve knowledge and practices beneficial for farmers well-being. Here, we model only the effects of development strategies and community level activities that improve productivity on the household level, while effects of social and cultural aspects that can be seen in improved well-being are not modeled. In the second case, when the spent fraction of assets represents corruption, we can see it as an additional nonlinearity that makes system dynamics more complicated.

The most general form of the community assets savings rate is given by Hill function in the form:

$$s_c(K_c) = s_4 + \frac{s_5 K_c^r}{s_6^r + K_c^r}, \quad s_4, s_5 \geqslant 0, s_6, r > 0, \tag{7}$$

where r is Hill coefficient. Changing parameter values allows us to express different properties community assets savings rate might have. For $s_5 = 0$ we get constant savings rate. For $s_5 > 0$ and $0 < r \leqslant 1$, the function $s_c(K_c)$ is convex, while for $r > 1$ it is s-shaped. In this case, if community asset levels are low, only a small fraction is invested in development strategies and the rest is dedicated to social and cultural events that do not improve productivity or is lost due to corruption. This fraction rises as the total amount of community assets grows. In other words, for low values of community assets, the savings rate $s_c(K_c)$ is low, but it increases and levels off for high values of community assets. The properties and shape of the savings rate depend on the community and they are reflected in the minimal and maximal value and steepness of the slope.

2.4.4. Linking community level and household level dynamics

Eqs. (1), (4) and (6) define coupled dynamics of household level assets, nutrients and community assets and include bottom-up interactions through aggregation of farmers' contributions in forming community assets (Fig. 2). Until now, top-down interactions such as investment of community assets into development strategies beneficial for farmers have not been considered. Given the structure of Eqs. (1) and (4) and observations about development strategies (Table 1 in SI), we express the effects of community assets on household level dynamics through factors that amplify the production function $f(k_a,k_n)$ and nutrient input rate $I_a(k_a)$ and that reduce the household asset depreciation rate δ_a and the nutrient loss rate δ_n. The model (1)-(4)-(6) of household-community dynamics can be modified to include top-down interactions, which leads us to the general form of the two-level model we will use in the rest of the paper:

$$\begin{aligned} \frac{dk_a}{dt} &= \tau s(k_a)f(k_a,k_n)G(K_c) - (\delta_a(K_c)+r)k_a, \\ \frac{dk_n}{dt} &= I_a(k_a) + I_c(K_c) + r_n - \delta_n(K_c)k_n, \\ \frac{dK_c}{dt} &= (1-\tau)Ns(k_a)f(k_a,k_n)G(K_c)s_c(K_c) - \delta_c K_c. \end{aligned} \tag{8}$$

The function $G(K_c)$ represents contributions of community level assets K_c to household production. We assume that $G(K_c)$ is an increasing function, which levels off for high community assets and define it by:

$$G(K_c) = g_1 + \frac{g_2 K_c^m}{g_3^m + K_c^m}, \quad g_1 \geqslant 0, g_2, g_3, m > 0. \tag{9}$$

This functional form of $G(K_c)$ allows variation in the slope of increase, minimal and maximal values and half-saturation value of the effects that community assets have on the production function. The parameters g_1, g_2, g_3 and m determine minimal value, maximal value, half-saturation and steepness of the slope of increase. We used $m = 2$ in the model because Hill function with coefficient larger than 1 is needed to produce desired s-shaped form.

Contributions of community assets to nutrient inputs are defined by the function $I_c(K_c)$. We assume low values of $I_c(K_c)$ for low levels of community assets, an increase in values as K_c increases and higher, but limited, values of $I_c(K_c)$ for high K_c. The steepness of the slope of increase and the minimal and maximal values of the function vary for different types of interventions. To include this variation, we model community asset contributions using the function:

$$I_c(K_c) = c_3 + \frac{c_4 K_c^n}{c_5^n + K_c^n}, \quad c_3 \geq 0, \quad c_4, c_5, n > 0. \tag{10}$$

Community assets can be used for reducing depreciation rate of household assets and loss of nutrients (e.g. they are used to fund paving roads or water reservoirs). To describe these types of effects we assume that the depreciation rate of assets and the loss rate of nutrients can vary depending on community assets, being higher for low community asset levels, declining and leveling off at some lower level for higher values of community capital. We represent them by strictly positive, decreasing functions $\delta_a(K_c)$ and $\delta_n(K_c)$ with form that corresponds to this behaviour:

$$\delta_a(K_c) = \delta_a\left(1 - \frac{d_1 K_c^p}{d_2^p + K_c^p}\right), \quad 0 \leqslant d_1 < 1, \quad d_2, p > 0, \tag{11}$$

$$\delta_n(K_c) = \delta_n\left(1 - \frac{d_3 K_c^q}{d_4^q + K_c^q}\right), \quad 0 \leqslant d_3 < 1, \quad d_4, q > 0. \tag{12}$$

The list of parameters, their definitions and values can be found in Appendix.

2.5. Remarks

One of the assumptions of the models is that development strategies can be funded by any amount of community assets. Some interventions, such as building a road or acquiring new technology, may require substantial assets and having less than a certain threshold amount means that intervention cannot be realized. To model these interventions one can use step functions $I_c(K_c), \delta_a(K_c), \delta_n(K_c)$ and $G(K_c)$ to represent different responses when community assets are below or above the threshold value. This implies piecewise continuity instead of continuity that is present in model (8). The mathematical consequences of lost continuity are a loss of uniqueness of the solution to the system and bifurcations originating not only from parameter variation, but also from the discontinuity in the right hand side of the differential equations (Jeffrey, 2018). We are aware that these properties of dynamical systems deserve proper investigation, but it is beyond the scope of this paper to go into detailed mathematical analysis of piecewise continuous dynamical systems.

3. Results

We use the general setup of dynamical systems analysis to investigate the relationship between household and community dynamics and cross-level interactions. We elaborate the typology of poverty traps in household-community systems that was introduced in Table 1 in Section 2. We systematically test the different system configurations while keeping cross-level interactions constant to investigate the dynamics of each level separately (Section 3.1, Table 2). We then deploy the two models to analyse the importance of cross-level interactions for reinforcing or mitigating poverty traps (Section 3.2) and then test the effectiveness of interventions at different levels for the different types of multi-level traps (Section 3.3).

3.1. Typology of traps in multilevel systems

Poverty traps are closely related to the notion of bistability, i.e. the existence of two attractors, where one attractor represents a poor state and the other represents a non-poor state. A positive feedback loop is a necessary, but not sufficient, condition for bistability (Soulé, 2003). Other requirements for bistability often include s-shaped (sigmoidal) functional response within the feedback loop, typically represented by the logistic function or by the Hill function with Hill coefficient larger than 1 (which grants desired curvature and s-shape). The question of bistability should be observed in the context of the whole system and not in isolation, meaning that particular dynamics or a particular positive feedback loop that produces bistability in one system does not have to do so in another.

We can distinguish Single-level, Fractal and Cross-level traps by analyzing the stability (number and type of equilibrium points) of the household and community levels separately (Table 2, Fig. 3). Table 2 contains information on types of functional forms and mechanisms that give rise to different types of traps. In the case of the Single-level trap, an s-shaped functional response is either on the household level (e.g. household assets savings rate) or on the community level (e.g. community asset savings rate). For the Fractal model, both levels have s-shaped functions. The Cross-level trap does not contain any s-shaped functional response on a single level, but cross-level interactions have an s-shaped form. Fig. 3 represents examples of trap types identified in Table 2, where the first row shows community level dynamics, the second row shows household level dynamics and the third row shows dynamics of the whole system (8). Depending on the functional forms and parameters used to define the system, it can exhibit a range of possible dynamics, such as having one, two or more attractors and different shapes of basins of attraction. As a consequence, understanding poverty traps in multi-level systems and assessing effects of alleviation strategies may require knowing within and cross-scale interactions and the locations of positive feedback loops and s-shaped functional responses.

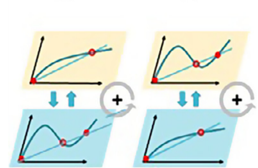
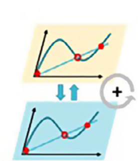
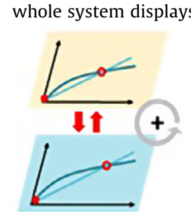
3.2. Cross-level interactions can reinforce or mitigate poverty traps

The parameter τ in model (8) determines the proportion of household assets that farmers invest in their own agricultural production, while the rest of household assets is given to the community. Using bifurcation analysis, we investigate how changes in farmers decisions regarding investment of their assets affect dynamics of the household-community system.

One of the key characteristics of the Single-level, Fractal and Cross-level models is that a poor state exists for all values of τ and for different savings rates and development strategies (the horizontal red line in Fig. 4). Poverty is therefore possible regardless of farmers choices and community decisions. What farmers choices however affect is the existence of alternative non-poor states and their position in relation to a poor state. The nearer poor and non-poor states are, the easier it is to fall into poverty due to external shocks and the lower well-being of a non-poor state.

If farmers invest most of the assets in their own production and very little in the community (high τ value), effectiveness of a community funded development intervention can be reduced to the point where a poor state is the only outcome (Fractal and Cross-level traps in Fig. 4). Changes in farmers decisions that lead to bigger investments in community (lowering τ value) may open up the possibility for escaping poverty by creating a non-poor attractor. However, the poor state never undergoes a bifurcation (the horizontal red line exists and is unchanged for all parameter values) and even though a non-poor state exists, some initial conditions belong to the poor basin of attraction (area below black line). It

Table 2
Three types of poverty traps in multi-level system obtained from the general model (8) by analysing properties of system's dynamics and identifying location of trapping mechanism. Detailed explanation of mechanism identification is given in Fig. 3 and in Supplementary Information.

Model	Single-level model	Fractal model	Cross-level model
Functional forms on household and community level	(A) S-shaped savings rate $s(k_a)$ and convex savings rate $s_c(K_c)$ (B) Convex savings rate $s(k_a)$ and s-shaped savings rate $s_c(K_c)$	(A) Self-similar mechanisms. S-shaped savings rates $s(k_a)$ and $s_c(K_c)$ (B) Different types of mechanisms. S-shaped savings rates $s(k_a)$ on the household level, but not on the community level	Savings rates $s(k_a)$ and $s_c(K_c)$ are convex, linear or constant
Cross-level interactions	Top-down interactions (i.e. functions $G(K_c)$, $\delta_a(K_c)$, $I_c(K_c)$, $\delta_n(K_c)$) do not have to be s-shaped in either of the above cases.	(A) Top-down interactions (i.e. functions $G(K_c)$, $\delta_a(K_c)$, $I_c(K_c)$, $\delta_n(K_c)$) do not have to be s-shaped. (B) Community contributions to household productivity (i.e. function $G(K_c)$) must be s-shaped.	At least one of the interactions (i.e. functions $G(K_c)$, $\delta_a(K_c)$, $I_c(K_c)$, $\delta_n(K_c)$) has to be s-shaped.
Model test	Only one level displays a trap when cross-level interactions are held constant	Multiple levels display traps when cross-level interactions are held constant	Traps are not detected when levels are observed separately, but the whole system displays a trap.
Illustration household level (bottom), community level (top) ● attractor ○ saddle point ⊕ positive feedback loop ⇅ cross-level interactions x-axis time, y-axis well-being	**A** **B** 	**A, B** 	

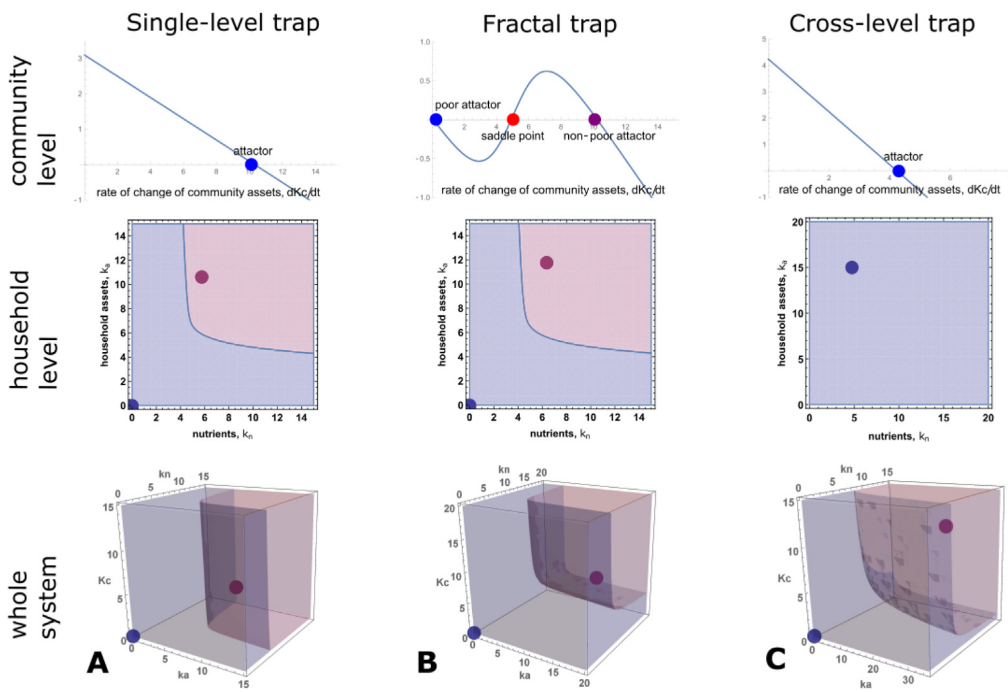


Fig. 3. Type of multilevel trap can be identified by keeping cross-level interactions constant and examining dynamics on each level separately (Table 1). (A) Single-level trap. Community assets reduce nutrient loss. (B) The Fractal trap. Community assets reduce nutrient loss. (C) Cross-level trap. Community assets affect household productivity. Blue dot denotes poor attractor and purple dot denotes non-poor attractor.

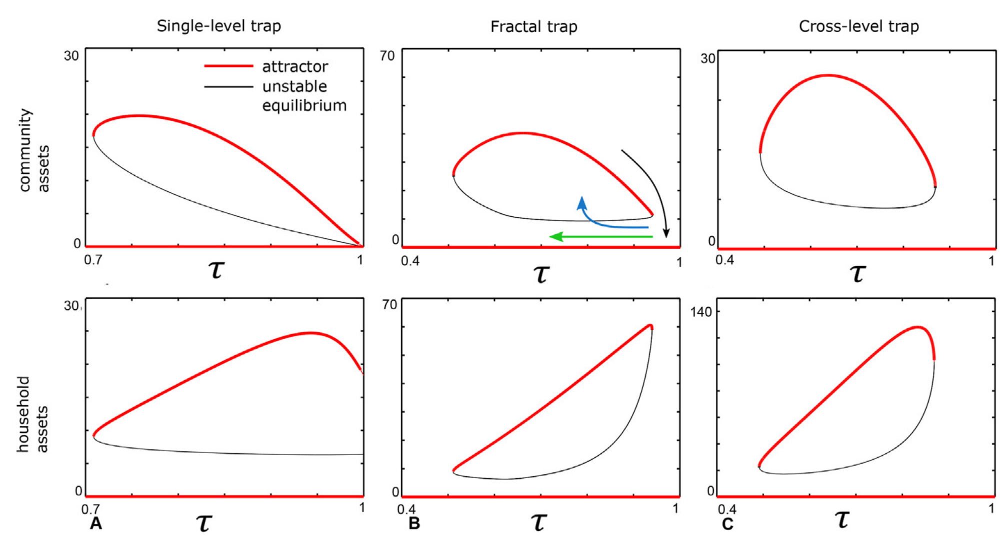


Fig. 4. Bifurcation diagram with τ as a bifurcation parameter. A non-poor attractor exists only for some τ, while poor attractor exists for all τ. The black and green arrows show how system's dynamics change when farmers decide to invest more, respectively less, in household production. The blue arrow shows combined effects of farmers' decision change and external intervention. The Single-level model has savings trap on household level and community assets improve nutrient supply. The Fractal and the Cross-level models with community assets contributions to household productivity.

is, therefore, unlikely that farmers habit change alone would push poor farmers out of poverty (the green arrow), i.e. it is a necessary, but rarely a sufficient, poverty alleviation strategy and it should be complemented with other strategies, such as external assets and nutrient inputs (the blue arrow), to be effective.

Fig. 4A shows another possible outcome of farmers decisions and household-community systems dynamics: even for very low investment in community (τ value near 1), bistability is possible. Position of the non-poor attractor for large τ implies drop in household assets and severe decrease of community level assets. Such lack of community assets may contribute to the loss of social or cultural capital, but further analysis and detailed models are needed for investigation of this dynamics.

In addition to traps created by farmers decisions, poverty traps can also be created through top-down interactions such as the Cross-level trap in Fig. 3C where community assets increase household productivity. In this case, the household level does not have a trap prior to community intervention because this level in isolation has a non-zero attractor. Introducing cross-level interactions moves the non-poor attractor to a more desired location (higher values of assets and nutrients), but it also creates an undesired attractor (with extremely low assets and nutrient values). Thus, poverty traps can appear as unintended consequences of alleviation strategies that did not consider initial conditions.

3.3. The level at which the external intervention is targeted can lead to drastically different results

The number of attractors and the shape of their basins of attraction suggests that the Single-level, Fractal and Cross-level models are sensitive to initial conditions and shocks in many cases (Fig. 3 and Fig. 5). There are also situations of globally persistent poverty when initial conditions do not play a role and poverty is the only outcome of inherently unsustainable dynamics (as indicated by Fig. 4 and explained in Section 3.2).

Assuming undesired initial conditions of a bistable or multistable household-community system (low levels of assets and nutrients and belonging to a poor basin of attraction), effective alleviation strategies may take different forms, depending on the type of trap and specific long-term dynamics. A Single-level model given in Fig. 3A depicts a situation when community assets are used to decrease nutrients loss. Starting from any point in the poor basin (the blue volume in the figure), the edge of the non-poor basin of attraction can be crossed by increasing household assets and/or nutrients (i.e. moving horizontally), but not by increasing community assets (i.e. moving vertically). This suggests that interventions on community level are ineffective and therefore development activities should be focused on household level.

In the case of the Fractal trap in Fig. 5B, the shape of the basins of attraction suggests that increase in community assets does not cause a shift from poor to non-poor basin. Unlike this, the edge of the non-poor basin might be crossed after an increase in household assets and/or nutrients. Thus, even in the case of a fractal poverty trap, it can be sufficient to improve conditions only at the household level to alleviate poverty.

The same model shows different behaviour when the proportion of household assets invested in agriculture is changed (i.e. the parameter τ is changed from 0.8 in Fig. 5B to 0.9 in Fig. 5C). The non-poor attractor E_1 has changed its position and an additional non-poor attractor E_2 has appeared. The shape of the poor basin *P* has remained the same, but there are now two non-poor basins *I* and *II*. Households starting from basin *P* have the same responses to interventions as in the previous case and development interventions need to target household level to be effective. The difference in system's behavior is visible for households starting from the non-poor basin *II*. Here, development intervention can either increase nutrients or community assets to cause crossing the edge of the non-poor basin *I*. While in the previous case ($\tau = 0.8$), the non-poor state was resilient to shocks that reduce community assets, this property does not hold in the case with higher proportions of farmer assets invested in production. Shocks that decrease community assets or nutrients might push the system to the non-poor basin *II* characterized by lower well-being in comparison to *I*.

The cross-level trap in Fig. 5D is created when community assets are used to reduce nutrient loss. Prior to the intervention, there was only a poor state on the household level. The non-poor attractor is created by the intervention. The shape of the non-poor basin of attraction suggests that an external intervention should focus on increasing nutrients on the household level, but increasing household or community assets is not effective.

However, not all Single-level, Fractal and Cross-level models behave in the same way, meaning that there are situations when a development strategy must target both household and community levels to enable escape from poverty. Typical examples are Fig. 3B for the Fractal model (when community assets increase nutrient supply), Fig. 3C for the Cross-level model (when community assets increase household productivity) and Fig. 5A for the Single-level model (when community assets are increasing household productivity and the functional response is s-shaped). In these cases, for the initial conditions characterized by low levels of household assets, nutrients and community assets, it is necessary that development interventions act on both levels. In the Single-level and Fractal model, an intervention should increase the amount of all variables, while in the Cross-level model it seems that increasing household assets will have significantly smaller effect than increase in other variables.

4. Application of typology to case studies

In this section, we demonstrate the applicability and added value of this type of modeling approach and clarify the use of the typology presented in Table 1 and Table 2 through applying it to two case studies representing a single and fractal trap in Swallow et al. (2009) and Lybbert et al. (2004) respectively.

4.1. Single-level trap in the lake Victora basin

Swallow et al. (2009) describe a poverty-environmental trap in the lake Victoria basin where some households were caught in a vicious cycle of low household assets, low investments in soil fertility, declining nutrient rates, while others were able to achieve higher income, provide for nutrient inputs and maintain soil quality. In other words, the authors report that low and medium resource endowment result in low income, insignificant land improvements and declining soil quality. High resource endowment led to land improvements, maintained soil quality and higher income. This confirms nonlinear relationship between soil quality and productivity. Water management system, credit access may contribute to bifurcation of household income.

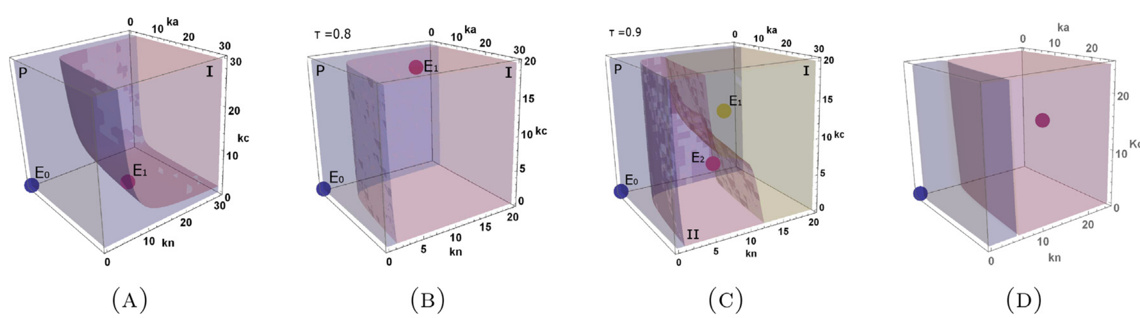


Fig. 5. (A) The Single-level model when community assets increase household productivity. (B and C) The Fractal model when community assets are used to improve nutrient supply. P denotes poor basin of attraction corresponding to poor attractor E_0, I and II are the non-poor basins of attraction corresponding to attractors $E_1(20.9, 8.63, 19.92)$ or $E_1(23.65, 8.88, 12.6)$ and $E_2(21.63, 8.12, 7.21)$. (D) The Cross-level models when community assets decrease nutrient loss.

The livelihoods of the population mainly depend on rainfed agriculture for domestic and commercial purposes. The lake also provides hydroelectric power, water transport and supports trade, tourism, wildlife and fishery sectors. Ecosystem management has been highly extractive and poverty levels are high. Lake Victoria is becoming eutrophic due to phosphorus and nitrogen inputs from the surrounding catchments and municipal centres. Severe erosion in parts of the catchment contributed to sediment deposition in the lake. An invasion of water hyacinth in the 1990s affected fisheries, water supply systems and transport.

Swallow et al. (2009) suggest that agricultural development (helping farmers with their enterprises), coupled with the promotion of appropriate land and water management practices (e.g. conservation agriculture, planting sugarcane that reduces sediment yield alongside crop with higher market value), seems to be the main pathway for development. The authors conclude that more research into household and community level dynamics is needed to explain poverty traps in multilevel systems.

Our understanding is that this case study corresponds to the Single-level trap with nonconvex savings rate at household level since some households in the lake Victoria basin are caught in a vicious cycle of lack of investments and environment degradation, but on a community level a trapping mechanism is not observed. Water, nutrients (phosphorus and nitrogen) and soil quality are necessary for agricultural production. Household assets are used for maintaining soil fertility through inputs of nutrients, but some of the nutrients reach lake water due to erosion and leaching, leading to eutrophication. It decreases quality of lake water, which affects household productivity, fisheries and transportation. Thus, increase in productivity (and household assets) have positive effects on nutrients levels in soil, but may have negative effects on water quality. According to the authors, it is important to promote nutrient conservation and to provide help to farmers to secure success of their enterprises. We understand this as community level interventions toward reducing nutrient loss and increasing household productivity.

Our results suggest that poverty can only be alleviated if the multi-level nature of the system in which the trap occurs is taken into account. In particular, a sufficiently high level of cooperation among farmers at the community level is needed. Community level dynamics, however, have not been included in the analysis of the poverty trap in this study, although the authors have pointed out the need for additional research of household and community level dynamics. Knowing those dynamics would allow us to model this particular single-level poverty trap and its multi-level context and identify the number and shapes of basins of attraction. This would shed some light on the risks for falling into poverty and opportunities for poverty alleviation.

4.2. Fractal trap of East African pastoralists

Lybbert et al. (2004) present a case study from Southern Ethiopia in which they use herd history data from pastoralists to study climate effects on household wealth dynamics. We highlight this case because it has been used to theorise fractal poverty traps (Barrett and Swallow, 2006) and we wanted to explore whether our typology of multi-level traps aligns with the fractal poverty trap theory. Pastoralists in this case are faced with two main livelihood strategies, to sedentarise or to be mobile. Mobile pastoralists tend to have a higher wealth equilibrium than those who are sedentary. Pastoralists depend on their herds for food, but also for manure, traction and transportation. In arid and semi-arid lands, the most precious resource is water, provided by rainfall and community managed wells. The community managed wells are an important community resource contributing to resilience in the face of unexpected climatic events. Climatic shocks such as prolonged periods of drought present the biggest risk for household to fall below poverty line, most likely because lack of water means lack of food for cattle. In such situations, poorer households may sell or lose herds due to increased mortality, while wealthier households may cope by transporting their herds to different pastures. The risk that poor pastoralists face when their herds become too small is the need to switch to a sedentary lifestyle, which is characterized by extreme poverty. Pastoralists' land is divided among permanent complexes and managed by clans using a cooperative community based management system. This ties households together and fosters cooperation. Complex rules of interhousehold reciprocity (through loans and gifts) exist within the community to help rebuild herd sizes lost to climatic or epidemiological shocks.

We have interpreted this case in the following way. Pastoralists' wellbeing is dependent on their herd size through which household owned assets are represented. A minimal heard size is identified, differentiating between a poor and nonpoor state, i.e. a threshold in nonlinear savings rate that produces a trap on the household level. Water is a necessary resource, without which herds cannot survive. Households are organized in villages where asset dynamics follows the same pattern as household assets dynamics. In other words, a savings trap present on a household level is reflected at the community level (a.k.a. fractal trap). Community owned water wells are maintained by individual contributions and are collectively organised, which we identify as bottom-up interactions in our model. Community level benefits, i.e. distribution of water in the dry season, is seen as a top-down interaction that increases water level and household productivity. Rules regarding gifting and restocking herd size represent endogenous poverty alleviation strategies. Depending on the initial conditions (herd size), pastoralists may escape poverty through an endogenous strategy (such as restocking by interhousehold loan) or through external credit. Pastoralists thus experience a fractal poverty trap with self-similar mechanisms on household and community levels. Lybbert et al. (2004) assume that lack of water will influence biomass availability and therefore influence livestock productivity.

One of the most important questions for development practitioners is to know where in the system to intervene to produce change (in most cases alleviate poverty). Our model demonstrates that a minimal level of cooperation is needed (e.g. around water wells but also reciprocal agreements with gifting cows) for the existence of a non-poor attractor. In other words, an intervention will only be effective if the level of cooperation among pastoralists is high enough. Figs. 5A and B, show that different cooperation ratios (τ parameter) can lead to different levels of household well-being. Fig. 5A shows two alternative stable states, one of which is a relatively high well-being attractor. Fig. 5B (with a higher τ, representing less cooperation) shows three stable states, none of which are better than in Fig. 5A.

Fig. 4 shows a range of possible system outcomes based on different cooperation ratios τ. As τ varies, changes in the dynamics of the system can be observed, while fixing one value of τ shows system's dynamics in that particular case. In this sense, Lybbert et al. (2004) have just taken one particular system's trajectory (observed for a certain level of cooperation) without considering alternative trajectories that would be possible for different cooperation levels. In the light of our models, this is seen as a snapshot taken from a manifold of possibilities.

5. Discussion and conclusions

Our work advances understanding of persistent rural poverty by combining economic poverty trap models, biophysical complexity and cross-level interactions between farmers and communities. It conceptualizes and analyses traps as embedded in multi-level systems where interactions across levels can lead to different poverty dynamics which require different alleviation strategies. In addition, our work bridges the gap between case studies with high empirical realism and stylized theoretical models of multidimensional and fractal poverty traps by capturing a diversity of possible causal relationships between economic, social and biophysical variables documented in empirical cases to systematically explore them with the models. This allows assessing the range of possible outcomes given different (assumptions about) empirical relationships, thus supporting the development of better informed and targeted alleviation strategies. Social and cultural capital introduced in Fig. 2 are not studied in depth. Due to their importance for household-community dynamics, we leave them for the future research.

5.1. Implications for research

The three key insights produced by our analysis have several implications for future research on poverty traps in multilevel systems. First, we identified a typology that places previous work on fractal poverty traps (Barrett and Swallow, 2003) within a broader family of traps in multilevel systems (Table 1). This typology provides a framework for empirically identifying different types of traps in multilevel systems and for accumulating knowledge about interventions that are effective for each type of multilevel trap. Second, we showed that interactions between levels can reinforce or mitigate different types of traps. A theoretical example of a trap created through cross-level interactions is a cross-level trap in Fig. 3C. An empirical example of a situation when cross-level interactions mitigate traps is that of east African pastoralists, the community fosters cooperation through which maintaining livelihoods under climatic stress is possible (Lybbert et al., 2004). Future research is needed to theoretically identify and empirically test specifically how different cross-level interactions modify different types of poverty traps. Third, we showed that interventions do not necessarily need to act on all levels directly to be effective, even in the case of fractal traps (Fig. 3A, Fig. 5B and D), but sometimes interventions must directly act on multiple levels even for single-level, fractal and cross-level traps (Fig. 3BC, Fig. 5A). Future theoretical and empirical research should rigorously map and test when each of these conditions hold.

5.2. Implications for development practice

The fact that poverty is multi-dimensional and interacts and is reinforced across levels is well accepted. Until now, most poverty trap models, however, have failed to consider these cross-level dynamics. The modeling approach we present here sheds light onto these dynamics and their implications for development practice. Most importantly, the findings of the paper show that neglecting key interactions at or across scales can result in wrong assessments and subsequently in inadequate alleviation strategies. For example, the system may experience a trap, but there may be no evidence of Cross-level traps when only one level is examined. Models of traps in multi-level systems can help identify where in the system to intervene to produce a change in its overall behavior and how to prevent unintended consequences, such as creating a trap instead of alleviating poverty.

The main advantage of using a cross-level poverty trap approach is that it can make resource allocation better targeted and effective by specifying appropriate levels of intervention. For example, in some contexts just intervening at one level will have multi-level effects, while other times what may seem like a local (or single) level problem may need coordinated effort across levels. Rather than relying on ad hoc decisions or previous anecdotal experience, the type of stylized modeling approach presented in this paper can support processes of reasoning through different poverty alleviation strategies and outcomes with practitioners.

We propose that this type of modelling approach could be useful at a country-level development collaboration office, in which regional and local projects are administered and resources prioritized, and where projects are monitored and evaluated. The typology could guide an assessment of the within and across-level interactions and factors that may affect poverty in a given location and thus inform which strategies may be most successful. Likewise, donors could use such stylised models to make more targeted calls for funding, or for cross-checking potential outcomes specified in proposal applications for poverty alleviation in agro-ecological contexts. As with country-level offices, donors could use stylized cross-level poverty trap models for post hoc monitoring and evaluation analysis in order to better understand which interactions mitigated, reinforced or broke poverty trap dynamics. We would like to emphasise that in order to make this type of modelling approach useful and directly applicable for practice, co-production processes would need to be instituted between researchers and development practitioners to tailor the models and their interfaces better to the needs of the user.

CRediT authorship contribution statement

Sonja Radosavljevic: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **L. Jamila Haider:** Conceptualization, Writing - original draft, Funding acquisition. **Steven J. Lade:** Conceptualization, Software, Funding acquisition. **Maja Schlüter:** Conceptualization, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttps://doi.org/10.1016/j.worlddev.2021.105437.

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