Agricultural Systems 219 (2024) 103949

Contents lists available at ScienceDirect

Agricultural Systems

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

Improving livelihood through crop-livestock integration: Insights from a farm trajectory model

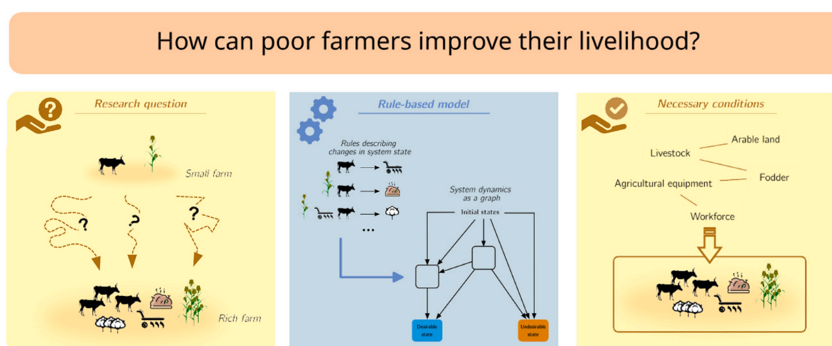
Maximilien Cosme [a,*], Arouna Koné [b], Franck Pommereau [c], Cédric Gaucherel [d]

[a] UMR DECOD, Institut Agro Rennes, Angers - Bat. 4, 65, rue de Saint-Brieuc, Rennes 35042, France
[b] Direction Provinciale de l'Agriculture, des Ressources Animales et Halieutiques, Dano, Ioba Province, Burkina Faso
[c] IBISC, University of Evry Paris-Saclay, 23, Boulevard de France, Evry 91034, France
[d] UMR AMAP, University of Montpellier, INRAE, CNRS, IRD, Cirad, 2196 Boulevard de la Lironde, Montferrier-sur-Lez 34980, France

HIGHLIGHTS

- The trajectories of smallholder farms are driven by events triggered by social, environmental and economic conditions.
- We studied in which management conditions a poorly endowed farm can develop and maintain a sustainable agropastoralism.
- For that purpose, we used a discrete-event modelling framework to predict all possible trajectories of a generic farm.
- Model predictions matched reported farm trajectories from southwestern Burkina Faso.
- Access to arable land, workforce, soil fertility, livestock and equipment are key for building a sustainable agropastoralism.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Mark van Wijk

Keywords:
Livelihood trajectories
Farm typology
Model-checking
Social-ecological system
Qualitative model
CTL

ABSTRACT

CONTEXT: Smallholder farmers in sub-Saharan Africa seek to improve their livelihoods by investing in new assets. These investments and their effectiveness are constrained by current capital and management practices. Therefore, to understand farm trajectories, the combined effects of different management practices and the timing of investments and losses must be considered.
OBJECTIVE: The present study aimed to determine, under 128 distinct scenarios, which ones enable a poorly endowed farm to develop and maintain a sustainable agropastoralism in southwestern Burkina Faso.
METHODS: For this purpose, we used the Ecological Discrete-Event Network (EDEN) modelling framework. This framework includes a formalism based on if-then rules describing economic and ecological events (e.g. investments and losses) that affect qualitative variables. The model rules were built from a literature review, expert interviews, and direct observations. Based on this model, the software then computes all trajectories the farm can

* Corresponding author.
E-mail addresses: maximilien.cosme@protonmail.com (M. Cosme), franck.pommereau@ibisc.univ-evry.fr (F. Pommereau), cedric.gaucherel@cirad.fr (C. Gaucherel).

https://doi.org/10.1016/j.agsy.2024.103949
Received 9 October 2023; Received in revised form 20 February 2024; Accepted 4 April 2024
Available online 5 July 2024

take. Based on empirically-reported farm types and trajectories, we then attempted to falsify the modelled dynamics using model-checking techniques.
RESULTS AND CONCLUSIONS: Model predictions matched all observed farm types and trajectories, thus not falsifying the model. Results highlighted that, for this system, livelihood improvement relied on the ability of the farm to to increase its cultivated area, workforce, livestock and fodder resources, all while producing and applying organic inputs to maintain or recover soil fertility. Although qualitative, model predictions are consistent with available observations and provide explanations about farm trajectories in southwestern Burkina Faso.
SIGNIFICANCE: The EDEN modelling framework, through its qualitative — yet rigorous — exploration of all possible trajectories, can help the decision-making process by highlighting the far-reaching consequences of management actions.

1. Introduction

Understanding how farm households maintain, accumulate, or lose their assets and capabilities is crucial for designing socially and environmentally relevant management policies. To approach this question, it is common to start by discriminating farm types based on their activities, assets, and/or objectives (Thiombiano, 2015; Vall et al., 2006; Diarisso et al., 2016; Dixon et al., 2001). Usually, a few farm types are found to coexist (Dixon et al., 2001) and differ by a few factors (e.g. livestock capital, farm size, labor force, market orientation or dependence on non-farm income) (Ouédraogo et al., 2016; Kuivanen et al., 2016; Chikowo et al., 2014; Zorom et al., 2013). Since the last two decades, farm trajectories (i.e. how a specific farm changes over time) have also received increasing attention (Haan and Zoomers, 2005; Novotny et al., 2021). Indeed, farmers' livelihoods are historical objects. They emerge out of past actions, and decisions are made within and shaped by a particular context (of policy setting, politics, history, agro-ecology and socio-economic conditions) (Scoones and Wolmer, 2002; Scoones, 2015). Such trajectories depend on the farmers' ability to maintain or enhance their capabilities and assets, to increase their resistance and resilience to stresses and shocks, and maintain their natural resource base (Carney, 1998). In this study, we will draw upon existing knowledge of farm dynamics to model farm trajectories and assess how small farmers can develop a persistent production of food crops, cash crops, and livestock.

Observational studies have highlighted the dynamic nature of poverty (Camfield and Roelen, 2013), while others pinpointed major drivers of transition/diversification (Novotny et al., 2021) and the persisting coexistence (Tittonell, 2014) of multiple household types. One of the most prominent examples is persisting poor households, stuck in a self-reinforcing poverty (Barrett and Bevis, 2015) whose pathways to exit have been studied empirically. Modelling studies also offer explanations of farm trajectories by enabling us to formulate and test hypotheses about their drivers e.g. (Dou et al., 2020). Agent-based models are widely used in social-ecological modelling (for a review, see (Verburg et al., 2016)) and are the main type of model for studying livelihood transitions. For instance, an agent-based model predicted that improved crop management combined with forest protection in Madagascar was able to improve food self-sufficiency and household income, and reduced wealth inequalities (Brinkmann et al., 2021). Another agent-based model highlighted the central role of market influence in smallholders' livelihood transitions (Magliocca et al., 2013). However, this kind of model generally requires abundant data for parameterization, which are generally unavailable. On the other hand, expert knowledge and qualitative information are abundant for many farm systems. Therefore, a formalism that would handle qualitative information on interactions between system components may ease the modelling process while making predictions more general (Levins, 1966).

The Ecological Discrete-Event Network (EDEN) dynamical modelling framework has been developed with this objective (Gaucherel and Pommereau, 2019). This framework relies on a discrete-event formalism involving qualitative variables. System states (here, farm types) change through discrete transitions resulting from the application of predefined "if-then" rules. The modelled dynamics are non-deterministic, yet non-probabilistic (i.e. *possibilistic*). Therefore, it computes all possible states and transitions resulting from the successive rule applications. Such qualitative models proved useful in systems biology for modelling regulatory networks (Thomas, 1991; Abou-Jaoudé et al., 2016) and recently emerged in ecology (Campbell et al., 2011; Gaucherel et al., 2017; Robeva and Murrugarra, 2016) and social-ecological studies (Cosme et al., 2021; Gaucherel et al., 2020; Mao et al., 2021).

In this paper, we aimed to model the dynamics of a farm system [defined by the limits of the sphere of household decision-making, (Garrity et al., 2012)] under various scenarios in Southwestern Burkina Faso (West Africa). Using a farm typology (Vall et al., 2006) and reported farm trajectories (Ouédraogo et al., 2016) from a specific village, we assessed under which scenarios (i.e. combinations of environmental conditions and management practices) our model predictions matched observations. Once model predictions agreed with observations, we determined which scenarios and events enabled small farmers to develop a sustainable (i.e. persistent) agropastoralism. Based on empirical evidence e.g. (Ouédraogo et al., 2016), we hypothesized that (H1) the observed farm types were reachable by the smallest farms (i.e. they can step out of poverty), (H2) livestock was critical for improving livelihood (Diarisso et al., 2016) and (H3) maintaining fertility was a key factor in improving livelihood (here, agropastoralism) (Diarisso et al., 2016; Tittonell et al., 2010).

2. Materials and methods

2.1. Field surveys and study area

Two field surveys were conducted in March and November 2019 in Dano (Ioba Province, Southwestern region). During these surveys, we interviewed researchers, local farmers, NGOs and extension services. Interviews consisted in open, informal discussions (with the support of local colleagues) about farmers' production strategy (e.g., proportion of maize/millet and cotton, gardening). Soil and water management practices were also discussed, with observation of different techniques (e.g., grass strips, stone bunds, digues or diguettes). The management schedules and objectives at various time scales, within the set of financial and environmental constraints, was an important part of interviews. This area is considered representative of the South Sudanian agroecological zone in Burkina Faso. In this region, the climate is characterized by one rainy season running from May to October with a mean annual rainfall of 900 to 1000 mm since the 1950s (Schmengler, 2010). In the last few decades, changes in the precipitation regime increased the vulnerability of rainfed food production, which is the predominant form of agriculture. Additionally, the shortening of fallow periods induces a widespread reduction in soil organic carbon and nutrients. Predominant soil types are Plinthosols, Lixisols, Luvisols, Gleysols (Hounkpatin et al., 2018; Yira et al., 2016). Natural vegetation is a wooded savanna and is mainly determined by water availability, seasonal fires and wood collection by local people.

Agriculture is the main economic activity. Today, traditional crops include sorghum, millet and maize for household consumption, and cotton is the main cash crop. Agriculture and livestock husbandry are generally combined, albeit to different degrees. This region has experienced an important agricultural expansion. This has led to a drastic reduction or abandonment of fallowing and a widespread reduction of soil fertility through water erosion and soil carbon mineralization. Fertility loss, in turn, constrains crop yields and thus agriculture-derived income. To tackle these issues (fertility loss and constraints on income), several management options have been proposed, including crop residue collection, regulation of dry season free grazing (to reduce outgoing carbon and nutrient fluxes (Manlay et al., 2004)), erosion control (by means of stone bunds, diguettes or grass stripes) or non-farm activities which provide complementary incomes which can then be invested in agriculture. When possible, farmers generally tend to complement cash crop production with livestock and manure production, thus adopting an agropastoral livelihood. Livestock provides many services, among which animal traction, production of organic fertilizers (manure) or social-cultural value during traditional ceremonies. Livestock relies on rangelands and fallows in rainy season, and on crop residues in dry season. When fodder is lacking, the wealthiest farmers may send their livestock on transhumance. Some farmers also complement livestock feed with cottonseed cake in dry season. In the last decades, fodder plants have also been highly promoted but are not yet widely adopted.

2.2. Farm types

We compared predicted farm types with a farm typology proposed for the village of Koumbia in Tuy province (Southwestern Burkina Faso) (Vall et al., 2006), and farm trajectories (i.e. farms switching from one type to another) with recent studies carried out in the same village (Ouédraogo et al., 2016; Fayama et al., 2018). Indeed, we did not find any literature on farm types and trajectories at the southwestern region scale. Despite being limited to one village, Vall's typology (Vall et al., 2006) overlaps with typologies done in the whole neighboring Ioba Province (Thiombiano, 2015) and elsewhere in Burkina Faso (Diarisso et al., 2016). Consistencies between typologies include e.g. the existence of subsistence-based farm and wealthier agropastoral farms. Other groups such as non-farm based households exists in Ioba and Yatenga (Thiombiano, 2015; Diarisso et al., 2016) and were not reported in Vall's typology (Vall et al., 2006).

In Koumbia, three main farm types have been identified: agriculture-oriented farms (A), agropastoral farms (AP) and livestock-oriented farms (i.e. breeders, B). Following (Vall et al., 2011), agriculture-oriented farms were further refined here in small (A1), medium (A2) and large (A3) farms. A1 includes small subsistence-based farms focusing on food crop production and/or non-farm activities. They have a few or no draught animal and few or no equipment and low cultivated area (<7ha) (Diarisso, 2015). A2 own a few draught animals and equipment and tend to increase cotton production and cultivated area (≈ 10 ha). A3 cultivate large areas (>10ha), but still have a limited livestock capital. However, their access to fertilizers allow them to increase grain and crop residues production. Agropastoral (AP) farmers focus more on multi-crops and cotton production and increase their cattle herds with the money earned with cash-crops (cotton and maize) and sometimes with non-farming incomes. Their cultivated area is highly variable (from ≈ 5 ha (Diarisso, 2015) up to >30ha (Vall et al., 2006)). Finally, breeders (B) own relatively small farm areas and large cattle herds. Although they may include a small portion of cereal production for their own consumption, they heavily rely on fodder availability. Note that AP and B types can be split in two sub-types [as in 2] which, however, mostly differ by quantitative aspects (e.g. herd size or cultivated area).

2.3. Farm trajectories

Five trajectories involving the previously mentioned farm types are identified in the literature (Ouédraogo et al., 2016; Fayama et al., 2018): (1) A1 → A2 → A3 → AP; (2) A1 → A2 → A3; (3) A2 → A1; (4) B → AP and (5) A1 → A2 → AP. Since trajectory (2) is included in trajectory (1), we will not consider trajectory (2). We used these observed trajectories to falsify the model, that is, to reject the model if observed farm trajectories were not predicted by the model.

2.4. Discrete-event modelling

The EDEN modelling framework relies on a qualitative and discrete-event formalism. A discrete-event framework describes system dynamics in terms of events, i.e. changes possibly occurring at irregular intervals (Cassandras and Lafortune, 2008).

In EDEN, no quantitative parameters are required. Variables take two values, + or −, and are thus *Boolean*, an abstraction that facilitates model conception, computation and analysis. This Boolean abstraction can be interpreted as follows: if a variable `A` has a positive influence on another variable `B` and its density is sufficient (`A+`), then B can become active (`B+`). This "sufficient density" defines a hypothetical threshold above which `A` is functionally active (i.e. able to change the value of `B`). Below this threshold, `A` is unable to change the value of `B` and is thus functionally inactive. We assume that such a threshold exists for each considered variable and interaction. The value of all variables at a given time defines a system *state* (Table 1).

The EDEN framework uses a formalism based on "if-then" rules representing social-ecological events. A rule specifies the *conditions* for an event to occur, and the *consequences* of this event on variables values. For instance, the rule `rainfall+ > > grass+` indicates that grass growth (i.e. the event) is conditioned by rainfall. When a system state satisfies a rule condition, this rule is executed and generates a new state. The switch from one state to another is called a *transition*. Rules are executed one by one (or, technically speaking, asynchronously). As a consequence, when several rule conditions are satisfied, each rule is executed independently and thus opens alternative trajectories exploring each possible sequence of events. This makes the model robust to changes in the speed or probability of events and, ultimately, to the order of events. The model is thus *non-deterministic*. Note that no trajectory is "chosen": all possible trajectories are computed. We call this non-probabilistic non-deterministic approach *possibilism*.

In brief, the EDEN framework is based on a qualitative, asynchronous and possibilistic approach. The model computes all alternative sequences of rules execution. The model output is a State-Transition Graph (STG) whose nodes and edges represent system states and transitions, respectively. An illustrative model of the method is provided in (Cosme et al., 2021). Additionally, technical details on model functioning are provided in previous works (Gaucherel and Pommereau, 2019).

Table 1
Glossary.

Rule	A relationship stating that if a certain condition is met, then some state variable values must change.
State	Set of variables with associated values.
Transition	State change induced by a rule execution. Therefore, it is a change in one or more variables' values.
Trajectory	Sequence of one or more transitions.
STG	A State-Transition Graph is a graph whose nodes are states and edges are transitions.
Control/State variable	The value of a state variable can change over time, whereas the value of a control variable is initially fixed and does not change.
Scenario	Combination of control variable values or, equivalently, a set of rules that can be triggered.
CTL	Computation Tree Logic is a temporal logic used to express temporal properties of a system's dynamics.
Farm type	A predefined combination of state variable values corresponding to certain characteristics of an empirically observed farm type.
Model falsification	A model is falsified if it does not predict some empirical pattern.

2.5. Definition of the farm model: Rules and variables

Model conception was based on information gathered during field surveys and literature review about soil fertility management, non-farm activities, livestock management and crop production. It aimed to address the following questions:

Q1. Are observed farm types and trajectories predicted by the model?

Q2. For a newly settled and small farm household, which scenarios and management actions enable improving its livelihood (i.e. switching to a better endowed farm type)?

Q3. Under which scenarios is it (im)possible for a small farm to develop and maintain agropastoralism?

The model and its detailed analyses are fully available at Appendix A. It is aimed at computing farm trajectories (resulting from management actions and ecological events) under various scenarios and favorable climatic, market and safety conditions. The model has two kinds of variables: state variables, which are modified by rules applications, and control variables, which are set initially and are not affected by rules. A specific combination of control variables valuations defines a *scenario*. Since control variables are not affected by rules, their appear in rules' conditions and thus constrain rule application. Therefore, a scenario also corresponds to a set of allowed events. The model does not explicitly include perturbations (e.g. drought, market fluctuations or conflicts), which are partly represented by scenarios.

The model includes nine state variables, seven control variables (Table 2) and 38 rules, plus 16 constraints (i.e. rules applied in priority to represent fast and/or mandatory events) (Tables B.1 and B.2).

Following Q1, initial variables values are chosen to represent a small farm (A1, Table 3). The seven control variables and the state variable `Lv` have unspecified initial values (noted "*") and can thus be either present or absent. Therefore, $2^7 = 128$ scenarios are considered simultaneously, with each declined in two versions (with and without livestock), thus making 256 initial states.

2.5.1. Definition of farm types and trajectories within the model

Each farm type was defined as a combination of present/absent state variables (Table 3) such that each state belongs to a single farm type. However, some states did not match any of the predefined farm type and were thus left uncharacterized. Farm trajectories were defined as sequences of at least two farm types such as A1 → A2, which by the way implies that A2 is directly preceded by A1, with no intermediate farm type.

Table 3
Typology of farm types used in the model. Each farm type is defined in our model by a specific combination of six state variables (Table 2) based on the literature (Vall et al., 2006; Vall et al., 2011; Vall et al., 2017; Ouédraogo et al., 2016). Variables are `Cc`: cash crops; `Ca`: cultivated area; `Ma`: manure; `Eq`: farm equipments; `Cr`: crop residues; `Lv`: livestock. Symbols: "+", the variable must be present; "−", absent; "*", either present or absent. Note that control variables are not used in the definition of farm types.

	Variables					
Farm type	Cc	Ca	Ma	Eq	Cr	Lv
A1 (Subsistence farmers)	−	−	−	*	*	*
A2 (Medium farmers)	+	−	−	+	*	+
A3 (Large farmers)	+	+	−	+	+	+
AP (Agropastoralists)	+	*	+	+	+	+
B (Breeders)	−	−	+	*	*	+

2.6. Verification of farm types and trajectories

The verification of the existence of farm types and trajectories in the STG (i.e. the computed states and transitions) was assessed using a temporal logic. Temporal logics express dynamical properties about discrete dynamics [for applications of temporal logic in agricultural or ecological studies, see e.g. (Largouët and Cordier, 2000; Hélias, 2003; Cordier et al., 2014)]. Such dynamical properties can be, for instance, "*currently*, the farm is small (A1)", "the farm *will necessarily* become A1" or "medium-sized farm type (A2) *is possibly preceded by* A1".

Here we chose a temporal logic fitted to the non-deterministic nature of our model: the Computation Tree Logic [CTL, (Clarke et al., 2018)]. This logic is used to express whether, from a given state of a system, a dynamical property holds for some or all of its futures.

For instance, one can ask whether an A1 farm *possibly* or *necessarily* leads to an A2 farm or, in other words, whether A2 eventually occurs *for some* (∃) or *for all* (∀) trajectories starting from A1.

These ∃ and ∀ *branching operators* are combined with *temporal operators*, namely X (for neXt), F (Finally), G (Globally) and U (Until). Intuitively, these temporal operators express the following properties:

- X: what happens in the immediate next state (e.g. "A2 occurs at the next time step")
- F: what happens at some point in the future (e.g. "A2 occurs at some subsequent step")
- G: what happens from now on and forever in the future (e.g. "A2 remains always present")

Table 2
Variables and their initial values in the model. State variables are changing in the model, while control variables are predefined. The initial values of variables are either "present" (+), "absent" (−), or unspecified (*) when both initial values are considered. Note that livestock (`Lv`) is the only state variable whose initial value is not specified, as we assume that a family can own livestock since its establishment. For the description of their dynamics, see Tables B.2 and B.1.

Type	Acronym	Variable	Description	Initial value
State variables	Fe	Soil fertility	Soil nutrient and organic matter content	+
	Cr	Crop residues	Residues from cereals (maize, sorghum, millet)	+
	Fp	Fodder plants	Woody or non-woody plants grew for feeding livestock	-
	Lv	Livestock	At least two draught animals	*
	Ma	Manure	Manure production. Implies a large livestock herd.	-
	Cc	Cash crops	Income-generating crops (mostly cotton)	-
	Ca	Cultivated area	Area used for agricultural production (mostly for cash crops)	-
	Eq	Equipments	Ploughs, seeders, carts or truck	-
	Wf	Workforce	Family or hired workers	-
Control variables	Flw	Fallowing	Sufficient fraction of land under natural or managed fallow for maintaining overall soil fertility	*
	Rg	Rangelands	Available and sufficiently productive rangelands for maintaining livestock	*
	CRC	Crop residue collection	Removal of crop residues after harvesting	*
	Fg	Free grazing	Animals allowed to freely graze crop residues	*
	EC	Erosion control	Efficient soil and water conservation measures (e.g. stone bunds, grass stripes or diguettes)	*
	Nf	Non-farm income	Gold mining, remittances, wage earning or petty trade	*
	Al	Available land	Available land to develop agriculture and extend cultivated area.	*

- U: a chronological sequence (e.g. "A2 is systematically preceded by A1)

Note that in this paper, we only use qualitative dynamical properties, without any quantitative detail about *when* or *how long* a property holds.

Additionally, a temporal logic formula can also include logical operators AND (∧), OR (∨) and NOT (¬). All these operators may combine to express more complex dynamical properties such as:

$$A1 \ \wedge \ \exists\mathbf{F}(\exists(A3 \ \mathbf{U} \ \forall\mathbf{G}(AP)))$$

which can be translated as "Among *small farmers* (A1), some *can eventually* (∃**F**) become *large farmers which may develop* (∃(*A*3 U) a *persistent* (∀**G**) *agropastoralism* (AP)".

2.7. Answering model questions

A CTL formula is tested on a State-Transition Graph using an automated tool called *model-checker*. Using the ITS-tools model-checker (Thierry-Mieg, 2015), we verified the existence of observed farm types and trajectories in the model (Q1) (see Table 4 for detailed CTL formulas of trajectories). States that satisfy a given CTL formula and transitions between them can then be visualized (Fig. 1).

Then (Q2), we determined in which scenarios an A1 farm can reach A2, A3 and AP. A farm type is said *reachable* from a state if there exists at least one trajectory from that state to that farm type. This was done in three steps (Fig. 1): (1) isolating states satisfying the property of interest, (2) obtaining the values of control variables for each of these states (i.e. the scenarios) and (3) factoring these scenarios by applying the distributive law of Boolean algebra. Finally (Q3), we also defined "sustainable agropastoralism" as a CTL formula (Table 4) and assessed under which scenarios (i.e. control variables) and management actions (i.e. transitions) an A1 farm cannot, can or necessarily develops sustainable agropastoralism. Finally, we conducted a sensitivity analysis by systematically drawing each rule with replacement. As the model includes 38 rules, we generated 38 alternative models and tested the same trajectories as in the original model (Appendix E).

Table 4
Dynamical properties verified in this study. Each property is translated as a CTL formula where *U*, *G* and *F* are the temporal operators *until*, *globally* and *finally*, respectively. Farm types are defined in Table 3.

CTL formula	Interpretation
Observed trajectories	
∃(A1 *U* A2)	An A1 farm can switch to A2
∃(A2 *U* A3)	An A2 farm can switch to A3
∃(A3 *U* AP)	An A3 farm can switch to AP
∃(B *U* AP)	A B farm can switch to AP
∃(A2 *U* A1)	An A2 farm can switch to A1
∃(A1 *U* (A2 ∧ (∃(A2 *U* (A3 ∧ (∃(A3 *U* AP)))))))	An A1 farm can switch to A2, then A3 and then AP
∃(A1 *U* (A2 ∧ (∃(A2 *U* AP))))	An A1 farm can switch to A1, then A2 and then AP
Reachability of sustainable agropastoralism	
∀*G*(AP)	Sustainable AP
∀*F*(∀*G*(AP)	An A1 farm necessarily reaches sustainable AP
∃*F*(∀*G*(AP) ∧ ¬(∀*F*(∀*G*(AP))	An A1 farm may or may not reach sustainable AP
¬∃*F*(∀*G*(AP)	An A1 farm cannot reach sustainable AP

3. Results

3.1. Comparing observations and model predictions

3.1.1. Farm types

The model predicted all reported farm types (Fig. 2). Note that this does not mean that they were stable, as some can be reached and then lost due to inadequate environment or management. Farm types were reachable in specific conditions, with A2, A3 and AP being reachable in multiple scenarios (Fig. 3).

This Boolean expression indicates that arable land (`Al`) and livestock (`Lv`) are prerequisites for stepping out of A1. Livestock had to be combined with a sufficient fodder in rainy (`Flw` ∨ `Rg`) and dry season (`CRC` ∧ `Fg`). Alternatively, if the household did not own livestock initially and earned income from non-farm activities, it could purchase livestock and then, either (1) engage in fodder plants production (implied by `Flw-`, see R24 in Table B.9) or (2) adopt a more traditional management, relying on free grazing in dry season and fallows or rangeland in rainy season. In addition, the sensitivity analysis (E) revealed that increasing workforce is crucial for A1 farms to improve their livelihood, as workforce is a necessary condition to increase cash crop production. Therefore, the ability of A1 farmers to step out depends on access to arable land, livestock (whether inherited or acquired through non-farm income), workforce and fodder management.

Therefore, if these initial conditions are not met, A1 farmers cannot step out towards A2. Some predicted farm types were not included in Vall's typology, such as those based on non-farm activities, and were grouped under the A1 farm type.

3.1.2. Farm trajectories

The model predicted all observed trajectories. Trajectories A1 → A2 and B → AP were driven by an increase in cash crop production, A3 → AP by an increase in manure production (implying an increase in livestock), A2 → A3 by an increase in cultivated area and A2 → A1 by soil fertility loss (Table D.1).

Observed trajectories were possible for scenarios in which (1) access to arable land was guaranteed and if either (2a) fodder was sufficient (in both seasons) for feeding livestock or, (2b) in an intensive context (`Flw-`), if non-farm income was sufficient for purchasing livestock (and if fodder plants production was developed before soil fertility loss).

Trajectories A1 → A2 → A3 → AP and B → AP were interruptible, i.e. it was possible for the trajectory to be diverted or reversed. In particular, it was always possible for medium farmers (A2) to fall down (i.e. not to become large farmers). Therefore, some events should be avoided for an household to step out, which are discussed in the next section.

3.2. How (not) to reach a sustainable agropastoralism?

The ability for small farmers to reach a sustainable agropastoralism (AP for short) was context-dependent (Table 6). Five main factors determined this reachability: (1) the availability of arable land, (2) the access to livestock, (3) fodder availability, (4) workforce and (5) the ability to maintain or recover soil fertility. We studied in which scenarios an A1 farm could reach sustainable AP impossibly, possibly or necessarily.

When sustainable AP was reachable (central, yellow area, Fig. 4), the farm did not practice fallowing (`Flw-`) but used erosion control techniques (`EC`) (Table 6). To keep sustainable AP reachable, the farm had to produce food and cash crops, which require sufficient soil fertility, which in turn required agricultural equipment and sufficient workforce to apply organic inputs (crop residues or manure) (rules R28–29, Table B.2). If the farm acquired agricultural equipment and started production of organic inputs before soil degradation (Table 7), sustainable AP became necessary (blue area, Fig. 4, Fig. F.1). Note that once this transition had occurred, soil fertility could be still be lost, but could also always be restored, provided sufficient manure was applied (result

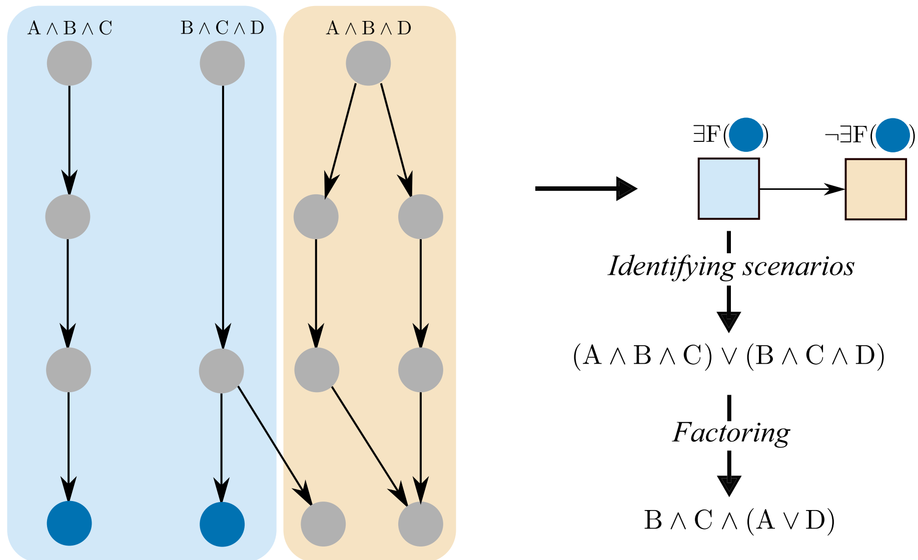


Fig. 1. Summary of the analysis technique. A state has *state properties* (here, the property "blue" or "gray") and *dynamical properties*, i.e. the trajectories it belongs to. Dynamical properties are expressed as CTL formulae. In this illustration, some states have the state property "blue". All states either have the dynamical property "blue is reachable" (noted ∃F(blue) in CTL, and corresponding to the blue shade) or not (¬∃F(blue), light orange shade). The CTL formula ∃F(blue) is used to (1) determine which states satisfy it and (2) split the State-Transition Graph accordingly. The resulting graph (right-hand side) thus has two nodes gathering states according to their ability to reach "blue". This graph highlights the fact that the system can permanently lose its ability to reach the property "blue". In a second step, the model-checker enables to determine the value of the variables A, B, C and D (representing scenarios) are determined for each initial state satisfying the ∃F(blue) formula. This is expressed as a Boolean expression using SymPy (Meurer et al., 2017), that can be further factorized using the distributive law of Boolean algebra to provide a more concise and interpretable expression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

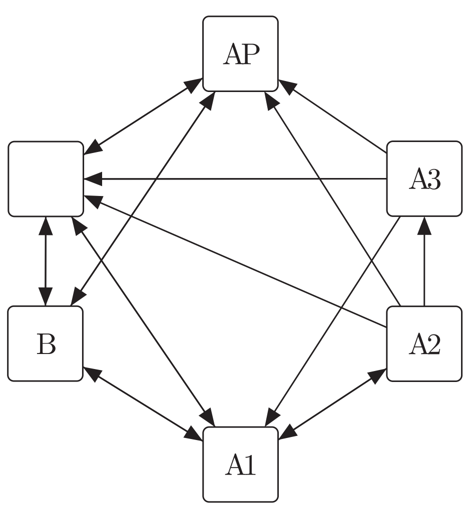


Fig. 2. Farm types and transitions. Each node in this STG corresponds to a *set of states* of the same farm type and each edge corresponds to a farm transition. A path corresponds to a farm trajectory. Squares include at least one stable state (i.e. states with no outgoing transition). Rounded squares include no stable state. The unlabeled node indicates intermediate, transient farm types. The triangle indicates initial states (all A1).

not shown). A1 farms would necessarily reach sustainable AP when the farm owned livestock, had sufficient dry season fodder and practiced fallowing (Table 6). Finally, scenarios preventing sustainable agro-pastoralism were highly heterogeneous (see Table 6 for a detailed interpretation of the corresponding scenarios).

4. Discussion

Our study uses a qualitative and discrete-event modelling framework - named EDEN - to predict farm types and trajectories in Southwestern Burkina Faso. Based on knowledge from scientific literature, field observations and interviews of experts, it describes which farm types a small farm (noted A1) can reach and how to reach them. This answer is twofold, as it both includes the specific events responsible for a given transition and the scenarios in which they may occur. Model predictions were compared with observed trajectories in the Koumbia village, which is located in the Tuy Province (southwestern region, Burkina Faso).

4.1. Farm types

Our model predicted that A1 farm type (i.e. the initial, poorly endowed farm type) was able to reach all other farm types (A2, A3, AP and B), which does not falsify hypothesis H1. It also predicted new farm types which were not reported in Vall's typology, but reported elsewhere in the region (Thiombiano, 2015), such as households oriented towards non-farm activities (which were merged with A1 farms for the sake of clarity). Such strategies have nonetheless been observed in

$$\mathtt{A1} \wedge \Big(\mathtt{Lv} \wedge \overbrace{(\mathtt{Flw} \vee \mathtt{Rg})}^{\text{Rainy season fodder}} \wedge \underbrace{(\mathtt{CRC} \vee \mathtt{Fg})}_{\text{Dry season fodder}}\Big) \vee \Big(\mathtt{Nf} \wedge \overbrace{(\mathtt{Flw-}}^{\text{No fallows and fodder plants production}} \vee \underbrace{\mathtt{Fg})}_{\text{Free grazing and fallows}}\Big)$$

Fig. 3. Boolean expression summarizing the scenarios in which A2, A3 and AP were reachable. Variables noted "-" are absent (and present otherwise), ∧ and ∨ mean "AND" and "OR", respectively. Overbraces and underbraces indicate the interpretation of portions of the formula.

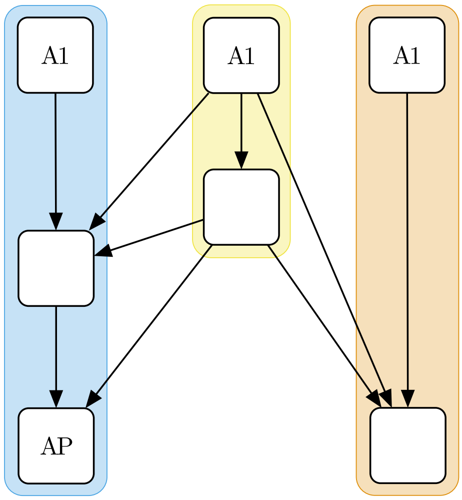


Fig. 4. Transitions between reachability sets of sustainable agropastoralism. A reachability set is a set of states sharing the same dynamical properties with respect to sustainable agropastoralism. Blue set: sustainable AP will be reached; Yellow set: sustainable AP can be reached; Orange set: sustainable AP will not be reached. Each node corresponds to a set of states belonging to initial states and/or to the same reachability set with A1 nodes the initial states and AP node the set of sustainable agropastoralist farm states. Unlabeled nodes include several farm types. Edges correspond to transitions between reachability sets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Koumbia (Ouédraogo et al., 2016). They are described as an income source for investing in agriculture (Mélanie Blanchard, pers. comm.), which is consistent with our model predictions. Predicted farm types overlapped with those described in other farm typologies in West-Africa (Thiombiano, 2015; Diarisso et al., 2016; Kuivanen et al., 2016; Douxchamps et al., 2016; Sanon et al., 2014) or elsewhere in sub-Saharan Africa e.g. (Tittonell et al., 2005). The consistency of model predictions with other West-African typologies involving other farm types e.g. (Thiombiano, 2015) could be assessed in a future study.

4.2. Farm trajectories

The model also predicted all observed farm trajectories. Arable land was a necessary condition for A1 farms to step out, as it is crucial for developing cash crop production. Livestock ownership was also crucial (Tables 5 and C.1) as it enables to purchase and use agricultural equipment, and thus increase cash crop production. This is consistent with hypothesis H2 and reported drivers of farm dynamics in south-western Burkina Faso (Ouédraogo et al., 2016; Savadogo et al., 1994) and is also confirmed by studies highlighting the role of non-farm income such as remittances, gold mining or petty trade for enabling agricultural investments (including livestock) in rural areas (Barrett et al., 2001). Note, however, that livestock requires sufficient fodder all year long, that is, rangelands or fallows during rainy season and crop residues (collected or available by free-grazing) during dry season. Such fodder could also come from fodder plants production such as mucuna (*Mucuna* sp.), cowpea (*Vigna unguiculata*) or local trees and shrubs such as *Faidherbia albida* or *Pterocarpus erinaceus* (Vall et al., 2012; Sib et al., 2020). The role of rules must also be highlighted, as sensitivity analysis (Appendix E) revealed the role of cultivated area, cash crops and labor, and whose removal of rules resulted in falsified models (their predictions did not match all observations). When manure production could not be increased, the richest type of farm was A3, which corresponds to the current situation of some farms whose growth is limited by their ability to produce sufficient manure. Therefore, this farm type seems to be a good alternative when livestock herd is small or fodder is insufficient.

Some unlikely transitions were also observed, such as those leading to the farm types oriented towards livestock production (B). This is (at least) partly due to the fact that we did not consider cultural constraints, as children from a given family will tend to engage in the same activities as their parents and their ethnic group. In this case, exclusive livestock production is in large part practiced by people related to the Fulani ethnic group. Therefore, this transition, albeit theoretically possible, will in practice be rarely or never observed. In this study, we did not distinguish AP farms which, in Vall's typology, are split in medium and large agropastoralists. Large AP farms are characterized by large cultivated areas ($>$ 15ha) and livestock herds ($>$ 20 Tropical Livestock Units). Although available literature does not discuss the impossibility for a small farm to grow this large, it is highly unlikely in reality. Therefore, two solutions could be combined to overcome this issue: developing a multivalued model to distinguish medium and large AP farms, and using probabilistic rules to yield more realistic results in terms of the actual feasibility of certain trajectories.

4.3. Reaching and maintaining agropastoralism

Demographic pressure and the resulting agricultural expansion have led African smallholder to reduce or abandon fallowing as a soil management technique. However, high mineralization rates observed in the tropics (Wang et al., 2021) quickly deplete soil organic matter and put crop production at risk. As a response, many farmers have developed a form of mixed-farming or agropastoralism involving (cash and food) crop and livestock production in which livestock is used as a source of income, as a tool for tillage and transport and as source of organic amendments for improving and maintaining soil fertility (Moritz, 2010; Harris, 2002).

As this form of agropastoralism represents an improved livelihood compared with that of subsistence farmers, we determined the conditions under which it is impossible, possible or necessary for such small farmers to develop a sustainable agropastoralism. Sustainable agropastoralism was reachable (N.B.: not necessarily reached) if (1) arable land was accessible and sufficient, (2) farmers adopted erosion control techniques, (3) workforce was sufficient, (4) owned livestock or had means to purchase it and (5) if fodder was sufficient and available all

Table 5
Predicted scenarios for observed trajectories. Each observed trajectory was translated as a CTL formula (Table 4), and then tested in the model. Then, the scenarios enabling each trajectory were computed. Variables noted “ – ” are absent (and present otherwise). Symbols ∧ and ∨ mean “AND” and “OR”, respectively. For variables acronyms, see Table 2.

Observed trajectory	Scenarios
A1 → A2	$\mathtt{Al} \wedge (\mathtt{Lv} \wedge (\mathtt{Flw} \vee \mathtt{Rg}) \wedge (\mathtt{CRC} \vee \mathtt{Fg}))\ \vee\ (\mathtt{Nf} \wedge (\mathtt{Flw}- \vee \mathtt{Fg}))$
A2 → A3	$\mathtt{Al} \wedge \mathtt{Lv} \wedge (((\mathtt{Flw} \vee \mathtt{Rg}) \wedge (\mathtt{CRC} \vee \mathtt{Fg})) \vee (\mathtt{Nf} \wedge \mathtt{Flw}-))$
A3 → AP	
B → AP	$\mathtt{Al} \wedge \mathtt{Lv} \wedge \mathtt{Nf} \wedge (\mathtt{CRC} \vee \mathtt{Fg} \vee \mathtt{Flw}-)$
A2 → A1	$\mathtt{Al} \wedge \mathtt{Lv} \wedge \mathtt{Flw}- \wedge (((\mathtt{Nf} \vee \mathtt{Rg})\ \wedge (\mathtt{CRC} \vee \mathtt{Fg}))\ \vee\ (\mathtt{Nf} \wedge \mathtt{EC}-))$
A1 → A2 → A3 → AP	Same as A1 → A2
A1 → A2→AP	

Table 6
Reachability of a sustainable AP under various scenarios. Each scenario is a specific combination of control variables. A variable marked " − " is absent, otherwise it is present. Note that Lv is not a control variable, but can either be present or absent in initial states, and is thus included in scenarios (Table 2).

Scenario	Interpretation
Sustainable AP cannot be reached	
Flw ∧ Fg- ∧ (CRC- ∨ Lv)	The farm practices fallowing, but either does not own livestock, or dry season fodder is lacking.
Flw- ∧ (EC- ∨ (Nf- ∧ Rg-))	Fallows are insufficient. In addition, erosion control is insufficient or the farm is lacking income and rangeland.
Nf- ∧ (Lv- ∨ (CRC- ∧ Fg-)	Income is lacking and the farm has no livestock or insufficient fodder.
Al−	Access to arable land is insufficient, preventing the farm from increasing its cultivated area and cash crop production.
Sustainable AP can be reached	
Al ∧ Flw − ∧ EC ∧ (Nf ∨ (Lv ∧ Rg ∧ (CRC ∨ Fg)))	Fallows are insufficient for feeding livestock and preventing soil fertility loss, which is now prevented by erosion control techniques. In addition, the farm either owns livestock (which requires forage) or be engaged in non-farm activities (which allow to purchase livestock). Arable land is available to develop cash crop production.
Sustainable AP will be reached	
Al ∧ Flw ∧ ((Lv ∧ (CRC ∨ Fg)) ∨ (Fg ∨ Nf))	Fallows prevent soil fertility loss and fodder is available. Livestock is either initially owned or can be purchased by means of non-farm income. Arable land is available to develop cash crop production.

year long. This was achieved by maintaining rainy season pastures (rangelands or fallows) and dry season fodder (crop residue production and collection or free grazing), or alternatively, by producing fodder plants. However, these conditions were not sufficient per se, as the lack of organic inputs could lead to an irreversible soil fertility loss. Farmers thus have to develop their capacity to rebuild soil fertility and prevent its depletion, which is consistent with hypothesis H3. For that purpose, the farm has to produce sufficient manure (or any appropriate organic input) and purchase appropriate equipment for transporting and applying these organic inputs. In this case, the persistence of most endowed farms was thus closely linked to the persistence of soil fertility, which is consistent with current knowledge (Barrett and Bevis, 2015; Tittonell et al., 2010).

4.4. Limitations and perspectives

4.4.1. Disturbances, resilience and shifts between scenarios

Our model is a preliminary step for understanding farm dynamics in an undisturbed context. However, economic shocks (Novotny et al., 2021), climate change (Jones and Thornton, 2009), extreme weather events (Motsholapheko et al., 2011), political instabilities or health crises are known to impact livelihood dynamics (Marschke and Berkes, 2006). Additionally, authors have promoted resilience as a relevant concept for managing farm systems (Darnhofer, 2021; Sallu et al., n.d.). However, the concept of resilience is intrinsically linked to that of shock (or perturbation) (Walker et al., 2006). Hence, as our model does not include perturbations, it cannot assess the resilience of farm systems. Yet, methods used in this study remain valid for issues related to resilience as disturbances can easily be represented in the EDEN framework e.g. as new rules, as it has been done in a previous study (Cosme et al., 2021).

One way of accounting for shifts between scenarios and disturbances might be to label rules according to their effect. For example, an increase in cash crop production due to an increase in arable land would be labeled [Al+]. On this basis, we could resort to an extension of the CTL temporal logic (namely ARCTL, for Action-Restricted CTL) that would allow us to use these labels to filter out forbidden scenario changes and disturbances. This has been successfully applied to the study of East-African rangeland systems (Thomas, 2022) and can be applied to other social-ecological systems.

Table 7
Rules driving transitions between reachability sets. Due to the various contexts in which a transition may occur, it may be driven by one (e.g. Possible → Impossible) or several phenomena (e.g. Possible → Necessary). See Table B.2 for rules description.

Transition	Rule(s) and Interpretation
Possible → Impossible	R32 to R35 (Soil fertility loss)
Possible → Necessary	R13, R14, R17, R18, R22 (Development of manure production) R37, R38 (Purchase of agricultural equipment)

4.4.2. Interactions between farms

Our model implicitly includes the effect of neighboring farms, as in rule R33 in which free grazing implicitly prevents the maintenance of crop residues in dry season, and may thus induce soil fertility loss if fallowing is not practiced and manure is not applied. Yet, spatial interactions between farms could be more deeply investigated. Our farm-scale model predicts that agropastoral farms can persist if arable land and fodder are sufficient. However, in current conditions, such a resource-consuming farm type would probably not be generalizable at the village-scale. Indeed, it requires and concentrates lots of resources, which currently requires an intense exploitation of the local environment and induces a strong competition for fodder and nutrients with neighboring farms. For instance, it has been showed (Manlay, 2000) that between-farms nutrients transfers induced by free grazing are mostly beneficial to big cattle owners and detrimental to small farms. Such spatial processes can be studied by duplicating our farm model (and maybe adding distant rangelands for seasonal transhumance) and including farm interactions and then studying the reachability and nature of stable states. Therefore, we could assess under which scenarios multiple interacting farms could improve their respective livelihood and coexist in a sustainable way with their environment. A spatialized generalization of the EDEN framework has already been developed (Leloup et al., 2021) and could be used for this investigation.

4.4.3. Causal analysis of system dynamics

Through model-checking, the EDEN framework currently allows the automated verification of dynamical properties of interest. However, it is still limited in its ability to provide a true causal explanation, i.e., what chronological ordering of events is necessary/sufficient to reach a state of interest? For instance, although we know the conditions that make sustainable agropastoralism possibly reachable, we do not know, from these states, which events sequences guarantee reaching sustainable AP. Such explanations could be provided using additional tools, namely techniques related to Petri nets unfolding prefix. These techniques have recently been designed for ecosystem analysis (Aguirre-Samboní et al., 2022) but have never been applied to real ecosystems.

4.4.4. Towards a more quantitative approach

In its current form, the EDEN modelling framework does not consider the probability of states and transitions. For instance, the production of fodder plants has not been widely adopted in southwestern Burkina Faso (Vall et al., 2012). Yet, we could assign a low (conditional) probability to this event (rule R19, Table B.2). This could make the model more useful to land managers, but would (1) require more data for model conception, (2) add new assumptions, (3) overlook the effect or rare events and (4) perhaps reduce model robustness and reliability. This explains why, as a first step, this Boolean possibilistic model is adequate for addressing the questions we raised in this study.

In addition, Boolean variables save the modeller from having to rank variables' responses to a given condition. For instance, our model makes no assumption regarding differences in soil fertility requirement between fodder plants and cash crops. However, the former may include Fabaceae, which require lower nitrogen requirements. Multivalued variables (taking values 0, 1, 2…) could fix this issue, as each value would correspond to a fertility interval to which various crop species would respond differently. Yet, in biology, Boolean models have shown to preserve some properties of continuous ones [albeit under specific conditions, (Saadatpour and Albert, 2016; Davidich and Bornholdt, 2008)], and can thus be seen as a first step towards a better understanding of agroecological dynamics.

4.4.5. *Going beyond livelihood studies*

This work assesses the long-term effects of the combination of management practices on the economic status of rural households in Burkina Faso. Although the model investigates the effect of human actions on soil fertility, the combined socio-economic and ecological viability [or coviability, (Barrière et al., 2019)] remains unexplored. Yet, this region of Africa experiences a widespread environmental degradation (Chikanda, 2009) whose relations to farmers' livelihoods have already been pointed (Sallu et al., n.d.; Chikanda, 2009). Therefore, future works should explicitly address socio-economic viability, but also environmental degradation and biodiversity loss, thus tackling the problem of social-ecological coviability.

5. Conclusions

In this paper, we developed a qualitative, discrete-event and possibilistic model of farm trajectories in southwestern Burkina Faso. Available data were in agreement with model predictions, such that the model was not falsified/refuted. Additionally, we determined under which scenarios such trajectories may occur. Regarding the ability of small farmers to become agropastoralists, the model highlighted the role of the interplay between workforce, agricultural equipment, land availability, soil management techniques, fodder availability and manure production. Indeed, workforce and equipment are necessary to apply organic inputs, but also to increase cultivated area and cash crop production. These production factors are efficient when arable land is available and appropriate soil and water management techniques are practiced (such as fallowing or erosion control). Finally, manure production is determined by fodder availability, i.e. rangelands, fallows, crop residues or fodder plants (e.g. fodder crops and shrub banks). Therefore, in a favorable economic and environmental context (i.e. with good prices on the market, no climatic disturbance, no pests and no diseases), for an isolated farm, our model suggests that the persistence of agropastoralism depends on thefarm's ability to increase its cultivated area, workforce, livestock and access to fodder, all while producing and applying organic inputs to maintain soil fertility.

Funding

This research was funded by the SESASA Project (DLR Projektträger funding code 01DG18020) under the LEAP-Agri European call

CRediT authorship contribution statement

Maximilien Cosme: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Arouna Koné:** Investigation, Methodology. **Franck Pommereau:** Software. **Cédric Gaucherel:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision.

Declaration of competing interest

The authors have no competing interests to declare.

Data availability

No data was used for the research described in the article.

Acknowledgement

We warmly thank Marcel Somandé for his invaluable support during field surveys. We also thank Colin Thomas for his indispensable technical support with model-checking, computer science concepts and research questions. We also thank Mélanie Blanchard for her fruitful suggestions about the agronomic interpretation of model predictions.

Appendix A. Code availability

Zip archive containing:

1. "*README*" is a text file explaining how to install ecco and run the farm trajectories model
2. "*farm_trajectories_model.rr*" is a text file containing the system description of the model
3. "*farm_trajectories_model.ipynb*" is a Jupyter notebook covering the model analysis
4. "*farm_trajectories_model.html*" is a static HTML preview of this notebook

Appendix B. Model rules

The model includes 38 "regular" rules and 16 constraints. Constraints are executed in priority to other rules. See (Gaucherel and Pommereau, 2019) for formal definition of rules. In this model, and in contrast with other studies (Gaucherel and Pommereau, 2019; Cosme et al., 2021; Gaucherel et al., 2020; Mao et al., 2021), we chose to make as few assumptions as possible about parameters and thus opted for rules including a single variable update at a time (except in constraints). In contrast with our previous studies, we studied the "full" graph, i.e. the graph including all states (satisfying constraints or not). Indeed, in previous studies, states satisfying constraints were removed prior to analysis as they represented ecologically unrealistic or too transient states. This was not the case here as considering a state as "unrealistic" is (at least partially) arbitrary and we aimed at a maximally parsimonious model.

Table B.1
Model constraints. Constraints with the same effect are grouped within the same row. The comma (,) is equivalent to the logical "AND". Variables noted with "−" are inactive, and active otherwise. Variables are Fe: soil fertility; Fp: fodder plants; Cc: cash crops; Ca: cultivated area; Ma: manure; Eq: farm equipment; Cr: crop residues; Lv: livestock; Wf: Workforce; EC: erosion control; Nf: non-farm activities; CRC: crop residues collection; Rg: rangeland; Fg: free grazing; Flw: fallows; Al: available arable land.

N°	Condition	Realization	Description	References
C1 C2	Fe-, Ma- Fe-, Eq-	Cr-	Crop residues production requires a sufficient fertility or manure inputs with equipment for collecting, transporting and applying it.	(Bationo and Mokwunye, 1991; Bationo et al., 2007) (Bationo and Mokwunye, 1991; Bationo et al., 2007)
C3	Lv-	Ma-	Manure requires livestock to be produced.	Common sense
C4 C5 C6	Lv- Eq- Wf-	Ca-	Without livestock or animal traction or sufficient workforce, cultivated area must be reduced.	Assumption
C7 C8 C9	Fe- Wf- Cr-	Fp-	Fodder plants require a fertile soil ans sufficient workforce (besides, food crops have priority over fodder crops).	(Klein et al., 2013)
C10 C11 C12 C13	Eq- Wf- Lv- Fe-	Cc-, Ca-	Without fertility or animal traction or draught animals or sufficient workforce, cultivated area must be reduced, which reduces cash crop production.	Assumption
C14 C15 C16	Rg-, Flw-, Fp- CRC-, Fg-, Fp- Cr-, Fg-, Fp-	Lv-, Ma-, Eq-, Ca-	Without rainy season forage or dry season forage, the livestock herd (and components depending on it) cannot be sustained.	Assumption

Table B.2
Model rules. Rules with the same effect are grouped within the same row. The comma (,) is equivalent to the logical "AND". Variables noted with "−" are inactive, and active otherwise. Variables are Fe: soil fertility; Fp: fodder plants; Cc: cash crops; Ca: cultivated area; Ma: manure; Eq: farm equipment; Cr: crop residues; Lv: livestock; Wf: Workforce; EC: erosion control; Nf: non-farm activities; CRC: crop residues collection; Rg: rangeland; Fg: free grazing; Flw: fallows; Al: available arable land.

N°	Condition	Realization	Description	References
R1 R2	Fe Ma, Eq	Cr	Soil fertility or manure may increase crop residues yield.	(Bationo et al., 2007) (Bationo and Mokwunye, 1991)
R3 R4 R5 R6 R7 R8 R9 R10 R11 R12	Cc, Flw-, Rg, Cr, Eq, CRC Nf, Flw-, Rg, Cr, Eq, CRC Cc, Flw, Cr, Eq, CRC Nf, Flw, Cr, Eq, CRC Cc, Flw-, Rg, Fg Nf, Flw-, Rg, Fg Cc, Flw, Fg Nf, Flw, Fg Cc, Fp Nf, Fp	Lv	If forage (fallows or rangelands in rainy season and freely grazed or collected crop residues in dry season, or fodder plants in both) and income (from the sale of cash crops or non-farm activities) are sufficient, then livestock may be purchased. It is assumed that the production of crop residues in neighboring farms is sufficient.	(Blanchard, 2010; Diallo and Vall, 2010) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Klein et al., 2013) (Klein et al., 2013)
R13 R14 R15 R16 R17 R18 R19 R20 R21 R22	Cc, Lv, Rg, Cr, Eq, CRC Cc, Lv, Rg, Fg Cc, Lv, Flw, Cr, Eq, CRC Cc, Lv, Flw, Fg Cc, Lv, Fp Nf, Lv, Rg, Cr, Eq, CRC Nf, Lv, Rg, Fg Nf, Lv, Flw, Cr, Eq, CRC Nf, Lv, Flw, Fg Nf, Lv, Fp	Ma	If the farm earns agricultural or non-farm income, and livestock and forage (in all seasons) are present, then more livestock can be bought and thus manure can be produced.	(Manlay et al., 2004; Diarisso et al., 2015; Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Klein et al., 2013; Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Richard et al., 2019) (Klein et al., 2013; Richard et al., 2019)
R23	Al, Wf, Lv, Cr, Eq	Ca	If arable land is available and workforce is sufficient, then animal traction enables farmers to increase cultivated area.	(Havard et al., 2010)

(continued on next page)

Table B.2 (*continued*)

N°	Condition	Realization	Description	References
R24	Al, Wf, Fe, Flw-, Cr	Fp	Soil fertility enables farmers to produce fodder plants.	(Klein et al., 2013)
R25	Al, Wf, Eq, Lv, Fe, Cr	Cc	Soil fertility and animal traction enable farmers to produce cash crops. Cash crop producers are assumed to also produce food crops (and thus crop residues).	(Kidron et al., 2010; Kidron and Zilberman, 2019)
R26	Wf-	Wf+	Workforce increases with time (i.e. spontaneously).	Assumption
R27	Flw	Fe	If organic matter is applied and erosion controlled, then soil fertility can be restored.	(Manlay, 2000)
R28	Wf, EC, Fg-, Eq, Cr, CRC-			(Bationo and Mokwunye, 1991; de Ridder and van Keulen, 1990)
R29	Wf, EC, Eq, Ma			(Gross and Glaser, 2021)
R30	Flw-, EC-	Fe-	Without erosion control nor organic inputs nor equipment nor workforce, continuous cultivation may reduce fertility	
R31	Flw-, Cr-, Ma-			(de Ridder and van Keulen, 1990)
R32	Flw-, Eq, CRC, Ma-			(de Ridder and van Keulen, 1990)
R33	Flw-, Fg, Ma-			
R34	Flw-, Eq-			
R35	Flw-, Wf-			
R36	Cc, Lv, Cr	Eq	Income enables purchasing agricultural equipment. Note that every equipment (cart, plough, etc.) requires livestock.	(Havard et al., 2010; Havard et al., 2004)
R37	Nf, Lv, Cr			(Havard et al., 2010; Havard et al., 2004)
R38	Lv, Cr			(Havard et al., 2010; Havard et al., 2004)

Appendix C. Determining scenarios for farm trajectories

The reachability of each farm type from initial states was assessed using CTL. We recall that initial states were all A1 farm types. A farm type is said reachable if there exists at least one trajectory leading to this farm type, at some point in the future. This corresponds to the formula $\exists F(\phi)$, where ϕ is the set of states of interest (e.g. a particular farm type). If we consider all the initial states, some may reach ϕ, others may not. The Table C.11 summarizes the scenarios for which each farm type is reachable. In general, the scenarios for reaching a farm type are displayed as a disjunctive normal form (i.e. an "OR of ANDs").

For instance, A2 is reachable under six disjoint scenarios:

$$
\begin{aligned}
& (\texttt{Al} \land \texttt{Fg} \land \texttt{Nf}) \\
\lor\ & (\texttt{Al} \land \texttt{Nf} \land \texttt{Flw}-) \\
\lor\ & (\texttt{Al} \land \texttt{CRC} \land \texttt{Flw} \land \texttt{Lv}) \\
\lor\ & (\texttt{Al} \land \texttt{CRC} \land \texttt{Lv} \land \texttt{Rg}) \\
\lor\ & (\texttt{Al} \land \texttt{Fg} \land \texttt{Flw} \land \texttt{Lv}) \\
\lor\ & (\texttt{Al} \land \texttt{Fg} \land \texttt{Lv} \land \texttt{Rg}),
\end{aligned}
$$

which can be factored using the distributive law:

$$\texttt{Al} \land ((\texttt{Lv} \land (\texttt{Flw} \lor \texttt{Rg}) \land (\texttt{CRC} \lor \texttt{Fg})) \quad \lor \quad (\texttt{Nf} \land (\texttt{Flw} \lor \texttt{Fg}))),$$

where "∧" and "∨" are the logical AND and OR, respectively.

Table C.1
Scenarios for which farm types are reachable. It indicates scenarios for which A2, A3, AP and B were reachable.

Farm type	CTL formula	Scenarios
A2	$A1 \land \exists F(A2)$	$\texttt{Al} \land ((\texttt{Lv} \land (\texttt{Flw} \lor \texttt{Rg}) \land (\texttt{CRC} \lor \texttt{Fg})) \lor (\texttt{Nf} \land (\texttt{Flw} \lor \texttt{Fg})))$
A3	$A1 \land \exists F(A3)$	
AP	$A1 \land \exists F(AP)$	

Note that these scenarios *do not* guarantee reaching a farm type, at least for two reasons: on a logical perspective, a state satisfies the formula $\exists F(\varphi)$ if there is at least one trajectory from that state to φ, which does not mean that all trajectories lead to φ. On the "interpretative" perspective, the fact that a trajectory exists does not mean that the system will take it. Indeed, depending on the type events that can occur, the system could remain in the current state for an arbitrary time (e.g. if the event is very unlikely), or take another trajectory, depending on management choices or on unspecified social-ecological constraints at a given moment. Therefore, these conditions are *necessary but not sufficient conditions* for reaching each farm type.

Appendix D. Determining events for farm trajectories

Each State-Transition Graph is associated to a transition table detailing every transition. The transition table indicates the rule(s) triggering each transition. Each rule may be associated to a label, which can be used to indicate the type of transition (e.g. natural or human-driven) or anything relevant to the modeller.

Table D.1
Transition table of Fig.2. In the "rules" column, R13–22 is a shortcut for all rules between R13 and R22. Labels indicate the variables affected by the rules.

Source	Target	Rules and constraints	Labels
A3	Undefined	C1, C14, C15	Ca-, Cr-, Eq-, Lv-, Ma-
	A1	C13	Cc-
	AP	R13-R22	Ma+
A1	B	R18-R22	Ma+
	Undefined	R23	Ca+
	A2	R25	Cc+
A2	A1	C13	Cc-
	Undefined	C14, C15, C16	Ca-, Eq-, Lv-, Ma-
	AP	R13-R22	Ma+
	A3	R23	Ca+
AP	B	C13	Cc-
	Undefined	C14, C15	Ca-, Eq-, Lv-, Ma-
Undefined	A1	C10, C12, C13, C14, C15, C16	Ca-, Cc-, Eq-, Lv-, Ma-
	B	C13	Cc-
	A3	R25	Cc+
	AP	R25	Cc+
B	A1	C14, C15, C16	Ca-, Eq-, Lv-, Ma-
	Undefined	R23	Ca+
	AP	R25	Cc+

Appendix E. Sensitivity analysis

We conducted a sensitivity analysis by systematically drawing with replacement from the set of rules. This procedure involves removing the first rule, computing the model and desired properties (in this case, CTL formulas), then replacing the rule and removing the next one, and so forth. The sensitivity analysis revealed that:

- Removing rule R23 (`Al+, Wf+, Lv+, Cr+, Eq +>>Ca+`) does not predict A2 → A3, A3 → AP and all related trajectories.
- Removing rules R25 (`Al+, Wf+, Eq+, Lv+, Fe+, Cr +>>Cc+`) or R26 (`Wf- >Wf+`) did not predict any observed trajectory.

Therefore, if it is not possible to increase cultivated area or cash crop production or workforce, then the model cannot reproduce observation. This is due to the fact that we removed only one rule at a time, and that these rules are the only performing this action. For example, removing all rules increasing manure production (`Ma+`) keeps predicting A1 → A2, A2 → A3 and A2 → A1, but does not predict A3 → AP or B → AP. Therefore, when manure production is constrained - implying that livestock herd size is limited - AP cannot be reached and A3 becomes the best endowed farm type.

Therefore, an interesting extension of this procedure would be to test the powerset of rules, i.e. the set of all subsets of rules, of size 2^n with n the number of rules. This could reveal sets of rules interacting non-trivially.

Appendix F. How (not) to reach a sustainable agropastoralism?

Based on properties expressed in Table 4 we split the State-Transition Graph in three sets: states for which it is (1) impossible, (2) possible but not necessary and (3) necessary to reach a sustainable AP. We now discuss the case in which the farm can possibly reach sustainable AP (Fig. F.1). Focusing on transitions between these sets (Fig. F.1a), we saw that equipment acquisition (`Eq+`) and development of livestock herd for manure production (`Ma+`) were both required to allow the farm to reach sustainable AP necessarily. By further dividing the set of "possible" (yellow) states with respect to these two variables (Fig. F.1b), the graph now shows that it is possible to achieve a sustainable PA by acquiring equipment alone, while allowing for further development of manure production. Livestock (through manure production) is therefore essential to achieve sustainable agropastoralism, but cannot be sufficient, as spreading manure requires farm equipment and sufficient workforce.

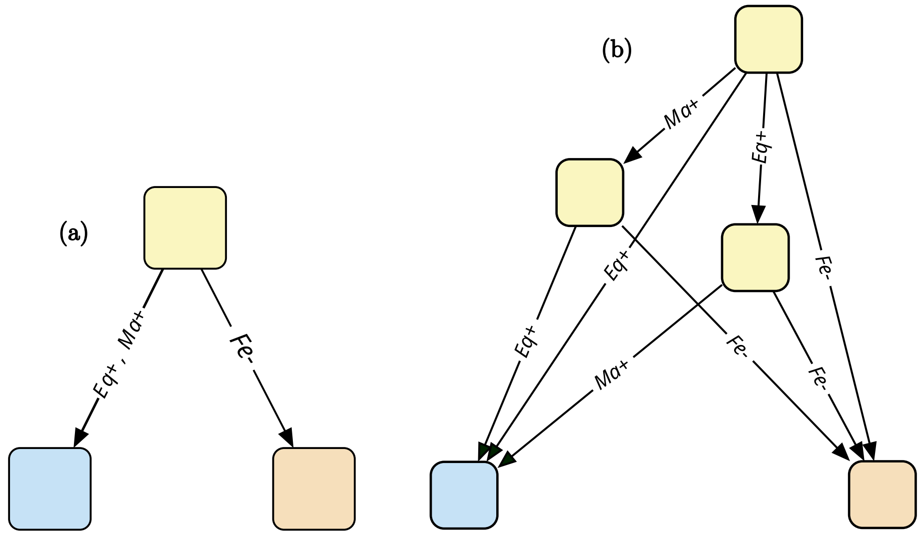


Fig. F.1. Crucial events driving the development of a sustainable agropastoralism. Edge labels are the rules' labels, as discussed in Appendix D. (a) State-Transition Graph is split by its ability to reach sustainable agropastoralism. The reachability sets are: yellow: possible; blue: necessary; brown: impossible. (b) The "possible" set is split with respect to `Eq` and `Ma`, with edge labels indicating where they are active. Acronyms are: `Eq`: agricultural equipment; `Ma`: Manure production and `Fe`: soil fertility. Node colors correspond to those of (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103949.

References

Abou-Jaoudé, W., Traynard, P., Monteiro, P.T., Saez-Rodriguez, J., Helikar, T., Thieffry, D., Chaouiya, C., 2016. Logical Modeling and Dynamical Analysis of Cellular Networks, Frontiers in Genetics 7. Frontiers. https://doi.org/10.3389/fgene.2016.00094. URL. https://www.frontiersin.org/articles/10.3389/fgene.2016.00094/full.

Aguirre-Samboní, G.K., Haar, S., Paulevé, L., Schwoon, S., Würdemann, N., 2022. Avoid One's doom: finding cliff-edge configurations in petri nets, electronic proceedings in theoretical computer. Science 370, 178–193. https://doi.org/10.4204/EPTCS.370.12.

Barrett, C.B., Bevis, L.E.M., 2015. The self-reinforcing feedback between low soil fertility and chronic poverty. Nat. Geosci. 8 (12), 907–912. https://doi.org/10.1038/ngeo2591. URL. https://www.nature.com/articles/ngeo2591.

Barrett, C.B., Reardon, T., Webb, P., 2001. Nonfarm income diversification and household livelihood strategies in rural Africa: concepts, dynamics, and policy implications. Food Policy 26 (4), 315–331. https://doi.org/10.1016/S0306-9192(01)00014-8. URL. https://www.sciencedirect.com/science/article/pii/S0306919201000148.

Barrière, O., Behnassi, M., Morand, S., David, G., Douzal, V., Fargette, M., Libourel, T., Seyler, F., Loireau, M., Pascal, L., Prost, C., Ravena-Cañete, V. (Eds.), 2019. Coviability of Social and Ecological Systems: Reconnecting Mankind to the Biosphere in an Era of Global Change. Vol. 1: The Foundations of a New Paradigm, vol. 1. Springer International Publishing. URL. https://link.springer.com/book/10.1007/978-3-319-78497-7.

Bationo, A., Mokwunye, A.U., 1991. Role of manures and crop residue in alleviating soil fertility constraints to crop production: with special reference to the Sahelian and Sudanian zones of West Africa. Fertilizer Res. 29 (1), 117–125. https://doi.org/10.1007/BF01048993. https://doi.org/10.1007/BF01048993.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94 (1), 13–25. https://doi.org/10.1016/j.agsy.2005.08.011. URL. http://www.sciencedirect.com/science/article/pii/S0308521X06001065.

Blanchard, M., 2010. Gestion de la fertilité des sols et rôle du troupeau dans les systèmes coton-céréales-élevage au Mali-Sud, savoirs techniques locaux et pratiques d'intégration agriculture élevage. thesis. UPEC. https://agritrop.cirad.fr/563855/.

Brinkmann, K., Kübler, D., Liehr, S., Buerkert, A., 2021. Agent-based modelling of the social-ecological nature of poverty traps in southwestern Madagascar. Agric. Syst. 190, 103125. https://doi.org/10.1016/j.agsy.2021.103125. URL. https://www.sciencedirect.com/science/article/pii/S0308521X21000780.

Camfield, L., Roelen, K., 2013. Household trajectories in rural Ethiopia: what can a mixed method approach tell us about the impact of poverty on children? Soc. Indic. Res. 113 (2), 729–749. https://doi.org/10.1007/s11205-013-0298-7. . URL. http://link.springer.com/10.1007/s11205-013-0298-7.

Campbell, C., Yang, S., Albert, R., Shea, K., 2011. A network model for plant–pollinator community assembly. Proc. Natl. Acad. Sci. 108 (1), 197–202 publisher: National Academy of Sciences Section: Biological Sciences. https://doi.org/10.1073/pnas.1008204108. URL. https://www.pnas.org/content/108/1/197.

Carney, D. (Ed.), 1998. Sustainable Rural Livelihoods: What Contribution Can we Make?. Dept. for International Development, London.

Cassandras, C.G., Lafortune, S., 2008. Introduction to Discrete Event Systems, 2nd edition. Springer, New York, NY. oCLC: 255370614.

Chikanda, A., 2009. Environmental degradation in sub-Saharan Africa. In: Luginaah, I. N., Yanful, E.K. (Eds.), Environment and Health in Sub-Saharan Africa: Managing an Emerging Crisis: Selected Papers from ERTEP 2007, July 17–19 2007, Ghana, Africa, Springer Netherlands, Dordrecht, pp. 79–94. https://doi.org/10.1007/978-1-4020-9382-1_6. URL. https://doi.org/10.1007/978-1-4020-9382-1_6.

Chikowo, R., Zingore, S., Snapp, S., Johnston, A., 2014. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutr. Cycl. Agroecosyst. 100 (1), 1–18. https://doi.org/10.1007/s10705-014-9632-y. URL. http://link.springer.com/10.1007/s10705-014-9632-y.

Clarke, E.M., Henzinger, T.A., Veith, H., Bloem, R. (Eds.), 2018. Handbook of Model Checking. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-10575-8. URL. http://link.springer.com/10.1007/978-3-319-10575-8.

Cordier, M.-O., Largouet, C., Zhao, Y., 2014. Model-checking an ecosystem model for decision-aid. In: 2014 IEEE 26th International Conference on Tools with Artificial Intelligence. IEEE, Limassol, Cyprus, pp. 539–543. https://doi.org/10.1109/ICTAI.2014.87. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6984523.

Cosme, M., Hély, C., Pommereau, F., Pasquariello, P., Tiberi, C., Treydte, A., Gaucherel, C., 2021. Qualitative modeling for bridging expert-knowledge and social-ecological dynamics of an east African savanna. Land 11 (1), 42. https://doi.org/10.3390/land11010042. URL. https://www.mdpi.com/2073-445X/11/1/42.

Darnhofer, I., 2021. Farming resilience: from maintaining states towards shaping transformative change processes. Sustainability 13 (6). https://doi.org/10.3390/su13063387, 3387, number: 6 Publisher: Multidisciplinary Digital Publishing Institute. URL. https://www.mdpi.com/2071-1050/13/6/3387.

Davidich, M., Bornholdt, S., 2008. The transition from differential equations to Boolean networks: a case study in simplifying a regulatory network model. J. Theor. Biol. 255 (3), 269–277. https://doi.org/10.1016/j.jtbi.2008.07.020. URL. http://www.sciencedirect.com/science/article/pii/S0022519308003652.

de Ridder, N., van Keulen, H., 1990. Some aspects of the role of organic matter in sustainable intensified arable farming systems in the west-African semi-arid-tropics (SAT). Fertilizer Res. 26 (1), 299–310. https://doi.org/10.1007/BF01048768. https://doi.org/10.1007/BF01048768.

Diallo, M.A., Vall, E., 2010. Changements paysagers et dynamiques pastorales dans l'ouest du Burkina Faso. In: Rencontres autour des recherches sur les ruminants, vol. 17, pp. 175–178. Paris. URL. http://www.journees3r.fr/spip.php?article2998.

Diarisso, T., 2015. Analyse des flux de biomasse et des transferts de la fertilité à l'échelle du territoire villageois en Afrique sub-sahélienne : opportunités d'intégration

fonctionnelle agriculture - élevage. thesis. Montpellier SupAgro. URL. https://agritrop.cirad.fr/578768/.
Diarisso, T., Corbeels, M., Andrieu, N., Djamen, P., Tittonell, P., 2015. Biomass transfers and nutrient budgets of the agro-pastoral systems in a village territory in South-Western Burkina Faso. Nutr. Cycl. Agroecosyst. 101 (3), 295–315. https://doi.org/10.1007/s10705-015-9679-4. URL. http://link.springer.com/10.1007/s10705-015-9679-4.
Diarisso, T., Corbeels, M., Andrieu, N., Djamen, P., Douzet, J.-M., Tittonell, P., 2016. Soil variability and crop yield gaps in two village landscapes of Burkina Faso. Nutr. Cycl. Agroecosyst. 105 (3), 199–216. https://doi.org/10.1007/s10705-015-9705-6. URL. http://link.springer.com/10.1007/s10705-015-9705-6.
Dixon, J., Gibbon, D.P., Gulliver, A., Hall, M., 2001. Farming Systems and Poverty: Improving farmers' Livelihoods in a Changing World, FAO. World Bank, Rome : Washington, D.C oCLC: ocm48933776.
Dou, Y., Deadman, P., Berbés-Blázquez, M., Vogt, N., Almeida, O., 2020. Pathways out of poverty through the lens of development resilience: an agent-based simulation. Ecol. Soc. 25 (4) https://doi.org/10.5751/ES-11842-250403 publisher: The Resilience Alliance. URL. https://ecologyandsociety.org/vol25/iss4/art3/#modelingthes8.
Douxchamps, S., Van Wijk, M.T., Silvestri, S., Moussa, A.S., Quiros, C., Ndour, N.Y.B., Buah, S., Somé, L., Herrero, M., Kristjanson, P., Ouedraogo, M., Thornton, P.K., Van Asten, P., Zougmoré, R., Rufino, M.C., 2016. Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa. Reg. Environ. Chang. 16 (5), 1305–1317. https://doi.org/10.1007/s10113-015-0838-6. URL. http://link.springer.com/10.1007/s10113-015-0838-6.
Fayama, T., Dabire, D., Blanchard, M., Sodre, E., Yarga, H., Kouadio, K.P., Kouakou, P., Ouedraogo, S., 2018. Une analyse des trajectoires et chemins d'intensification des exploitations de polyculture-élevage dans un contexte de changement social à l'Ouest du Burkina Faso et au Nord de la Côte d'Ivoire. Epistanalyse 1–16.
Garrity, D., Dixon, J., Boffa, J.-M., 2012. Understanding African Farming Systems: Science and Policy Implications, Food Security in Africa: Bridging Research and Practice. Australian Center for International Agricultural Research, Canberra.
Gaucherel, C., Pommereau, F., 2019. Using discrete systems to exhaustively characterize the dynamics of an integrated ecosystem. Methods Ecol. Evol. https://doi.org/10.1111/2041-210X.13242. URL. https://onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.13242.
Gaucherel, C., Théro, H., Puiseux, A., Bonhomme, V., 2017. Understand ecosystem regime shifts by modelling ecosystem development using Boolean networks. Ecol. Complex. 31, 104–114. https://doi.org/10.1016/j.ecocom.2017.06.001. URL. https://linkinghub.elsevier.com/retrieve/pii/S1476945X17300466.
Gaucherel, C., Carpentier, C., Geijzendorffer, I.R., Noûs, C., Pommereau, F., 2020. Discrete-event models for conservation assessment of integrated ecosystems. Eco. Inform., 101205 https://doi.org/10.1016/j.ecoinf.2020.101205. URL. http://www.sciencedirect.com/science/article/pii/S1574954120301552.
Gross, A., Glaser, B., 2021. Meta-analysis on how manure application changes soil organic carbon storage. Sci. Rep. 11 (1), 5516 number: 1 Publisher: Nature Publishing Group. https://doi.org/10.1038/s41598-021-82739-7. URL. https://www.nature.com/articles/s41598-021-82739-7.
Haan, L.D., Zoomers, A., 2005. Exploring the frontier of livelihoods research, development and change, 36 (1), 27–47. https://doi.org/10.1111/j.0012-155X.2005.00401.x. URL. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.0012-155X.2005.00401.x.
Harris, F., 2002. Management of manure in farming systems in semi-arid West-Africa. Exp. Agric. 38 (2), 131–148 publisher: Cambridge University Press. https://doi.org/10.1017/S0014479702000212. URL. https://www.cambridge.org/core/journals/experimental-agriculture/article/management-of-manure-in-farming-systems-in-semiarid-west-africa/CBBCFD04565BF19C5C5F08FEB6F3CF28.
Havard, M., Fall, A., Njoya, A., 2004. La traction animale au coeur des stratégies des exploitations agricoles familiales en Afrique subsaharienne. Rev. Elev. Med. Vet. Pays Trop. 57 (3–4), 183–190 number: 3–4. 10.19182/remvt.9889. URL. https://revues.cirad.fr/index.php/REMVT/article/view/9889.
Havard, M., Vall, E., Lhoste, P., 2010. La traction animale, éditions Quae. https://doi.org/10.35690/978-2-7592-0887-6. https://www.quae-open.com/produit/20/9782759210138/la-traction-animale.
A. Hélias, Agrégation/abstraction de modèles pour l'analyse et l'organisation de réseaux de flux : application à la gestion des effluents d'élevage à La Réunion, thesis, Montpellier, ENSA, publication Title: http://www.theses.fr (2003). URL http://www.theses.fr/2003ENSA0030.
Hounkpatin, O.K.L., Op de Hipt, F., Bossa, A.Y., Welp, G., Amelung, W., 2018. Soil organic carbon stocks and their determining factors in the Dano catchment (Southwest Burkina Faso). CATENA 166, 298–309. https://doi.org/10.1016/j.catena.2018.04.013. https://www.sciencedirect.com/science/article/pii/S0341816218301280.
Jones, P.G., Thornton, P.K., 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. Environ. Sci. Pol. 12 (4), 427–437. https://doi.org/10.1016/j.envsci.2008.08.006. URL. https://www.sciencedirect.com/science/article/pii/S1462901108000944.
Kidron, G.J., Zilberman, A.J., 2019. Low cotton yield is associated with micronutrient deficiency in West Africa. Agron. J. 111 (4), 1977–1984. https://doi.org/10.2134/agronj2018.07.0477. https://onlinelibrary.wiley.com/doi/10.2134/agronj2018.07.0477.
Kidron, G.J., Karnieli, A., Benenson, I., 2010. Degradation of soil fertility following cycles of cotton–cereal cultivation in Mali, West Africa: A first approximation to the problem. Soil Tillage Res. 106 (2), 254–262. https://doi.org/10.1016/j.still.2009.11.004. URL. https://www.sciencedirect.com/science/article/pii/S0167198709002177.
Klein, H.-D., Rippstein, G., Huguenin, J., Toutain, B., Guerin, H., 2013. Les cultures fourragères, éditions Quae. https://doi.org/10.35690/978-2-7592-2169-1. https://www.quae-open.com/produit/71/9782759221691/les-cultures-fourrageres.
Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., Groot, J.C.J., 2016. Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: a case study from the Northern Region, Ghana. NJAS Wageningen J. Life Sci. 78, 153–166. https://doi.org/10.1016/j.njas.2016.04.003. URL. https://www.sciencedirect.com/science/article/pii/S1573521416300240.
Largouët, C., Cordier, M.-O., 2000. Timed Automata Model to Improve the Classification of a Sequence of Images. ECAI, Citeseer, pp. 156–160.
Leloup, M., Cosme, M., Pommereau, F., Gaucherel, C., 2021. Some Slide-Cascades in Social-Ecological Systems Viewed by Spatially Explicit and Multi-Scale Models. Tech. Rep, Zenodo (Aug. https://doi.org/10.5281/zenodo.5695705. URL. https://zenodo.org/record/5695705.
Levins, R., 1966. The strategy of model building on population biology. Am. Sci. 54 (4), 421–431. URL. https://www.jstor.org/stable/27836590.
Magliocca, N.R., Brown, D.G., Ellis, E.C., 2013. Exploring agricultural livelihood transitions with an agent-based virtual laboratory: global forces to local decision-making. PLoS One 8 (9), e73241. https://doi.org/10.1371/journal.pone.0073241. URL. https://dx.plos.org/10.1371/journal.pone.0073241.
Manlay, R., 2000. Organic Matter Dynamics in Mixed-Farming Systems of the West African Savanna: A Village Case Study from South Senegal, Thesis. ENGREF, Paris. URL. http://www.theses.fr/2000ENGR0062.
Manlay, R.J., Ickowicz, A., Masse, D., Feller, C., Richard, D., 2004. Spatial carbon, nitrogen and phosphorus budget in a village of the west African savanna—II. Element flows and functioning of a mixed-farming system. Agricultural Systems 79 (1), 83–107. https://doi.org/10.1016/S0308-521X(03)00054-4. URL. https://linkinghub.elsevier.com/retrieve/pii/S0308521X03000544.
Mao, Z., Centanni, J., Pommereau, F., Stokes, A., Gaucherel, C., 2021. Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system. Ecosyst. Serv. 47 https://doi.org/10.1016/j.ecoser.2020.101220. URL. http://www.sciencedirect.com/science/article/pii/S2212041620301625.
Marschke, M., Berkes, F., 2006. Exploring strategies that build livelihood resilience: a case from Cambodia. Ecol. Soc. 11 (1) https://doi.org/10.5751/ES-01730-110142 publisher: The Resilience Alliance. URL. https://www.ecologyandsociety.org/vol11/iss1/art42/.
Meurer, A., Smith, C.P., Paprocki, M., Certik, O., Kirpichev, S.B., Rocklin, M., Kumar, A., Ivanov, S., Moore, J.K., Singh, S., Rathnayake, T., Vig, S., Granger, B.E., Muller, R.P., Bonazzi, F., Gupta, H., Vats, S., Johansson, F., Pedregosa, F., Curry, M.J., Terrel, A. R., Roucka, S., Saboo, A., Fernando, I., Kulal, S., Cimrman, R., Scopatz, A., 2017. SymPy: symbolic computing in Python. PeerJ Comp. Sci. 3 https://doi.org/10.7717/peerj-cs.103 e103, publisher: PeerJ Inc. URL. https://peerj.com/articles/cs-103.
Moritz, M., 2010. Crop–livestock interactions in agricultural and pastoral systems in West Africa. Agric. Hum. Values 27 (2), 119–128. https://doi.org/10.1007/s10460-009-9203-z. URL. http://link.springer.com/10.1007/s10460-009-9203-z.
Motsholapheko, M.R., Kgathi, D.L., Vanderpost, C., 2011. Rural livelihoods and household adaptation to extreme flooding in the Okavango Delta, Botswana. Phys. Chem. Earth Parts A/B/C 36 (14), 984–995. https://doi.org/10.1016/j.pce.2011.08.004. https://www.sciencedirect.com/science/article/pii/S1474706511001938.
Novotny, I.P., Fuentes-Ponce, M.H., Lopez-Ridaura, S., Tittonell, P., Rossing, W.A.H., 2021. Longitudinal analysis of household types and livelihood trajectories in Oaxaca, Mexico. J. Rural. Stud. 81, 170–181. https://doi.org/10.1016/j.jrurstud.2020.10.022. URL. https://www.sciencedirect.com/science/article/pii/S0743016719300531.
Ouédraogo, S., Vall, E., Bandagao, A., Blanchard, M., Ba, A., Dabire, D., Tionyélé, F., Havard, M., Kouadio, K.P., Ouattara, B., Saba, F., Sodre, E., Yarga, H., 2016. Sustainable intensification of mixed farming systems in sub-humid Savannah of Western Africa in relation to local value chains (maize, cattle, small ruminants, cotton…). PROIntensAFrica. In: Depth Case study Final Report, monograph, Cirad. INERA. URL. https://agritrop.cirad.fr/584988/.
Richard, D., Alary, V., Corniaux, C., Duteurtre, G., Lhoste, P., 2019. Dynamique des élevages pastoraux et agropastoraux en Afrique intertropicale, éditions Quae. https://doi.org/10.35690/978-2-7592-2895-9. URL. https://www.quae-open.com/produit/121/9782759228959/dynamique-des-elevages-pastoraux-et-agropastoraux-en-afrique-intertropicale.
Robeva, R., Murrugarra, D., 2016. The spruce budworm and forest: a qualitative comparison of ODE and Boolean models. Lett. Biomathemat. 3 (1), 75–92. https://doi.org/10.1080/23737867.2016.1197804. URL. https://www.tandfonline.com/doi/full/10.1080/23737867.2016.1197804.
Saadatpour, A., Albert, R., 2016. A comparative study of qualitative and quantitative dynamic models of biological regulatory networks. EPJ Nonlinear Biomed. Phys. 4 (1) https://doi.org/10.1140/epjnbp/s40366-016-0031-y. URL. http://epjnonlinearbiomedphys.springeropen.com/articles/10.1140/epjnbp/s40366-016-0031-y.
Sallu, S.M., Twyman, C., Stringer, L.C., 2010. Resilient or vulnerable livelihoods? Assessing livelihood dynamics and trajectories in rural Botswana. Ecol. Soc. 15 (4). Resilience Alliance Inc.. URL. https://www.jstor.org/stable/26268197.
Sanon, H., Savadogo, M., Tamboura, H., Kanwé, B., 2014. Caractérisation des systèmes de production et des ressources fourragères dans un terroir test de la zone soudanienne du Burkina Faso. VertigO 14 (2). https://doi.org/10.4000/vertigo.15171. URL. http://journals.openedition.org/vertigo/15171.
Savadogo, K., Reardon, T., Pietola, K., 1994. Farm productivity in Burkina Faso: effects of animal traction and nonfarm income. Am. J. Agric. Econ. 76 (3), 608–612. https://

doi.org/10.2307/1243674. URL. https://onlinelibrary.wiley.com/doi/abs/10.2307/1243674.

Schmengler, A.C., 2010. Modeling Soil erosion and Reservoir Sedimentation at Hillslope and Catchment Scale in Semi-Arid Burkina Faso. Ph.D. thesis. University of Bonn. URL. http://hss.ulb.uni-bonn.de/2011/2483/2483.pdf.

Scoones, I., 2015. Sustainable livelihoods and rural development. Practical Action Publishing. https://doi.org/10.3362/9781780448749.

Scoones, I., Wolmer, W. (Eds.), 2002. Pathways of Change in Africa: Crops, Livestock & Livelihoods in Mali. Ehtiopia & Zimbabwe, James Currey; Heinemann, Oxford; Portsmouth, N.H.

Sib, O., González-García, E., Bougouma-Yameogo, V.M.C., Blanchard, M., Vall, E., 2020. Coconception, installation et évaluation de banques fourragères arbustives pour l'alimentation des vaches laitières dans l'ouest du Burkina Faso. Rev. Elev. Med. Vet. Pays Trop. 73 (1), 27–35. https://doi.org/10.19182/remvt.31841. https://revues.cirad.fr/index.php/REMVT/article/view/31841.

Thierry-Mieg, Y., 2015. Symbolic model-checking using ITS-tools. In: Baier, C., Tinelli, C. (Eds.), Tools and Algorithms for the Construction and Analysis of Systems, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg, pp. 231–237. https://doi.org/10.1007/978-3-662-46681-0_20.

Thiombiano, B.A., 2015. Exploring Soil Nutrient Management and Production Performances to Support Building Smallholder Farms' Resilience to Climate Change: Case of South-Western Burkina Faso. Thesis. Kwame Nkrumah University Of Science And Technology, Kumasi, Ghana. accepted: 2015-07-29T12:53:41Z. URL. http://ir.knust.edu.gh:8080/handle/123456789/7386.

Thomas, R., 1991. Regulatory networks seen as asynchronous automata: a logical description. J. Theor. Biol. 153 (1), 1–23. https://doi.org/10.1016/S0022-5193(05)80350-9. URL. http://linkinghub.elsevier.com/retrieve/pii/S0022519305803509.

Thomas, C., 2022. Analysis of State-Transition Graphs of Ecosystems Using Model-Checking, these de Doctorat. Université Paris-Saclay.

Tittonell, P., 2014. Livelihood strategies, resilience and transformability in African agroecosystems. Agric. Syst. 126, 3–14. https://doi.org/10.1016/j.agsy.2013.10.010. URL. http://www.sciencedirect.com/science/article/pii/S0308521X13001340.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agric. Ecosyst. Environ. 110 (3), 149–165. https://doi.org/10.1016/j.agee.2005.04.001. URL. https://www.sciencedirect.com/science/article/pii/S0167880905001532.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – a typology of smallholder farms. Agric. Syst. 103 (2), 83–97. https://doi.org/10.1016/j.agsy.2009.10.001. URL. https://www.sciencedirect.com/science/article/pii/S0308521X09001061.

Vall, E., Dugué, P., Blanchard, M., 2006. Le tissage des relations agriculture-élevage au fil du coton. Cahiers Agricultures 15 (1), 72–79 number: 1. URL. https://revues.cirad.fr/index.php/cahiers-agricultures/article/view/30562.

Vall, E., Koutou, M., Blanchard, M., Coulibaly, K., Diallo, M.A., Andrieu, N., 2011. Intégration agriculture-élevage et intensification écologique dans les systèmes agrosylvopastoraux de l'Ouest du Burkina Faso, province du Tuy. In: Partenariat, modélisation, expérimentations : quelles leçons pour la conception de l'innovation et l'intensification écologique ?, Colloques, Cirad, Bobo-Dioulasso, Burkina Faso, p. 12 p. URL. https://hal.archives-ouvertes.fr/hal-00718613.

Vall, E., Blanchard, M., Diallo, M.A., Lecomte, P., 2012. L'innovation par simplification expliquée par le principe de moindre quantité d'action de Maupertuis: cas de l'intégration agriculture-élevage en Afrique soudano-sahélienne. In: Rencontres autour des Recherches sur les Ruminants, p. 19.

Vall, E., Marre-Cast, L., Kamgang, H.J., 2017. Chemins d'intensification et durabilité des exploitations de polyculture-élevage en Afrique subsaharienne : contribution de l'association agriculture-élevage. Cahiers Agricultures 26 (2), 25006. https://doi.org/10.1051/cagri/2017011. URL. http://www.cahiersagricultures.fr/10.1051/cagri/2017011.

Verburg, P.H., Dearing, J.A., Dyke, J.G., Leeuw, S.V.D., Seitzinger, S., Steffen, W., Syvitski, J., 2016. Methods and approaches to modelling the Anthropocene. Glob. Environ. Chang. 39, 328–340. https://doi.org/10.1016/j.gloenvcha.2015.08.007. URL. https://www.sciencedirect.com/science/article/pii/S0959378015300285.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., Schultz, L., 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecol. Soc. 11 (1) https://doi.org/10.5751/ES-01530-110113 publisher: The Resilience Alliance. URL. https://www.ecologyandsociety.org/vol11/iss1/art13/.

Wang, C., Morrissey, E.M., Mau, R.L., Hayer, M., Piñeiro, J., Mack, M.C., Marks, J.C., Bell, S.L., Miller, S.N., Schwartz, E., Dijkstra, P., Koch, B.J., Stone, B.W., Purcell, A. M., Blazewicz, S.J., Hofmockel, K.S., Pett-Ridge, J., Hungate, B.A., 2021. The temperature sensitivity of soil: microbial biodiversity, growth, and carbon mineralization. ISME J. 15 (9), 2738–2747 bandiera_abtest: a Cg_type: Nature Research Journals Number: 9 Primary_atype: Research Publisher: Nature Publishing Group Subject_term: Biogeochemistry;Ecosystem ecology;Soil microbiology Subject_term_id: biogeochemistry;ecosystem-ecology;soil-microbiology. https://doi.org/10.1038/s41396-021-00959-1. URL. https://www.nature.com/articles/s41396-021-00959-1.

Yira, Y., Diekkrüger, B., Steup, G., Bossa, A., 2016. Modeling land use change impacts on water resources in a tropical West African catchment (Dano, Burkina Faso). J. Hydrol. 537, 187–199. https://doi.org/10.1016/j.jhydrol.2016.03.052. URL. https://linkinghub.elsevier.com/retrieve/pii/S0022169416301573.

Zorom, M., Barbier, B., Mertz, O., Servat, E., 2013. Diversification and adaptation strategies to climate variability: a farm typology for the Sahel. Agric. Syst. 116, 7–15. https://doi.org/10.1016/j.agsy.2012.11.004. URL. https://www.sciencedirect.com/science/article/pii/S0308521X12001679.