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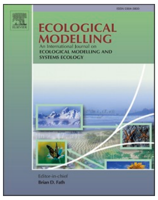

Systems modeling for agroecology and land restoration

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ABSTRACT

At the time of the development of H.T. Odum's energy system theory, the field of agroecology was not yet defined as a scientific discipline. Nevertheless, minimal models were already proposed to describe what today are referred to as agroecological and land restoration practices. In this work, we review literature from the early 1970s to nowadays by tracing a red thread to connect the original formulation of the energy system language with the current understanding of agroecology and land restoration. In the light of this picture, we draw a general application of the energy systems language and modeling to describe land use and land restoration dynamics. We apply this scheme to model and reproduce the land use dynamics of a real restoration project led by a farmers' family in Mato Grosso do Sul, Brazil. The case study of Sitio Luciana shows the transformation of a monocultural and partially degraded land into a biodiverse, food-producing area by developing a complex agroecosystem owing to human work and farmers' local ecological knowledge. As an application of the energy system language, we build a dynamical model that closely reproduces observed GIS-retrieved patterns (*global RMSE ∼2%*), highlighting human-mediated ecological succession—targeted at restoring Atlantic Forest—as key to agroecosystems development, and offering scientific validation of the farmers' local ecological knowledge. This work shows that the energy systems theory and modelling approach, as inherited from H.T. Odum, can: 1) deepen the understanding of local agroecosystem and land system dynamics, including human management; 2) inform the development of non-linear models grounded in both scientific and local knowledge; and 3) offer conceptual guidance for land management and policy strategies.

1. Introduction

The future of land systems is crucial for the stability and resilience of Earth's life-support systems, with industrial growth, population increases, and land-use changes all tightly interconnected with the climate and ecological crises humanity faces. Unsustainable agricultural practices and biosphere degradation are central to understanding the global land system and steering current trajectories toward sustainability (Arneth et al., 2021; Prăvălie, 2021; Rockström et al., 2009; Taylor and Rising, 2021). Over the past 30 years, scholars, academic institutions, and governments have worked together to classify, quantify, and model land system evolution at global and regional scales, aiming to inform land management strategies and sustainability policies (Brainich et al., 2018; Feng et al., 2022; Lawrence et al., 2016; Leeprakton et al., 2018). At the same time, agroecology emerged as a holistic paradigm, integrating scientific, traditional and local knowledge to address land-use sustainability (Altieri, Nicholls, de Molina, et al., 2024; Altieri and Toledo, 2005; Nicholls and Altieri, 2018; Floridia et al., 2024), climate adaptation (Conte et al., 2024; Altieri et al., 2015; Bezner Kerr et al., 2023; Dittmer et al., 2023), social justice, and equity (Gliessman, 2016; Lopez-Ridaura, 2022; Rosset et al., 2022), which gained growing recognition within institutional and policy frameworks.

Classical approaches in land system science have effectively quantified and forecasted spatial and temporal transformations of landscapes to support land-use planning and management. These models were used primarily to predict spatial-temporal landscape patterns and perform

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scenario analysis, typically relying on data-driven and process-based parametrization methods, including regression methods, spatial inference methods, network models, Markov models, Earth system models, integrated assessment models, and agent-based models (Chen et al., 2025; Noszczyk, 2019; Parker et al., 2003). Despite the high predictive accuracy of existing models, the explicit use of systems theory in land use modeling frameworks remains limited, motivating the need for more theoretically grounded perspectives to uncover core processes, feedback mechanisms, and non-linear behaviors that drive land-use changes and landscape dynamics (Rounsevell et al., 2012; Verburg et al., 2015, 2019).

Recently, the fields of landscape ecology and agroecology have been influencing each other, with some scholars advocating for the development of agroecological landscapes as a transformative path to guide agricultural and land systems toward sustainability (Jeanneret et al., 2021; Kremen and Merenlender, 2018; Nicholls et al., 2001; Priyadarshana et al., 2024; Redlich et al., 2018). Agroecology, historically developed also as a theoretical discipline, seeks holistic frameworks to understand and define sustainable relations between humans, agricultural environments and food (Caporali, 2015; Garcia-Polo et al., 2021; López-García et al., 2021). However, modeling approaches in agricultural sciences have been limited and generally more focused on biophysical and physiological mechanistic models, traditionally developed within the crop science and the environmental economics communities, primarily applied to study the effects of plant-environment interactions on yields and agroecosystem services, but rarely adopting a broader systems-based approach (Di Paola et al., 2016; Gavasso-Rita et al., 2024). In contrast, systems thinking and theory, underpinned by non-linear systems modeling, is increasingly seen as a promising path toward a more comprehensive understanding of agroecosystem and agricultural landscape processes and dynamics (Benítez et al., 2022; Ong and Liao, 2020; Tixier et al., 2013; Vandermeer, 2020; Walters et al., 2016).

Energy systems theory was developed by H.T. Odum in his early works (Odum and Pinkerton, 1955; Odum, 1971, 1973) and was successively developed towards emergy theory (Odum, 1996; Brown et al., 2004; Brown and Ulgiati, 1997; Tilley, 2015), also related to the maximum power principle (Hall and Mcwhirter, 2023; Odum, 1988; Odum and Hall, 1995). It has been widely applied to socio-ecological contexts, particularly in studying the sustainability of land use, agricultural productions and agroecosystems. It offers tools to integrate biophysical constraints on land systems, biotic activity, and human energy flows within a physically based framework designed: 1) to address "what if" questions through minimal non-linear systemic models, and 2) to assess sustainability of complex socio-ecological systems through integrated assessment metrics. While the emergy framework was applied to evaluate the integrated sustainability of industrialized agricultural productions, food supply-chains (Artuzo et al., 2021; La Rosa et al., 2008; Shah et al., 2019; Spagnolo et al., 2020; Wright and Ostergård, 2016; Zhang et al., 2012), food networks (Cristiano, 2021), indigenous and local food systems (Comar, 2004; Comar et al., 2019), agroecosystems (Watanabe and Ortega, 2014), and urban landscapes (Huang et al., 2007), the energy systems language and modeling tools – as originally conceived by H.T. Odum – have been underutilized to simulate the time evolution of agroecological and land systems.

To address this gap, which also relates to the trade-off between predictive accuracy of models and their ability to advance theoretical understanding, we developed a minimal, physical-based modeling framework designed to capture the dynamics of land systems in a generalizable manner, incorporating both biotic and human activities. It was applied to reproduce the land-use patterns of Sitio Luciana, a family-run agroecological farm in Central-Western Brazil. This case study investigates the transformation of approximately 15 hectares of partially degraded monocultural land into a diversified agroecosystem, including semi-natural forests, agroforestry, and horticultural areas. This complex land system evolved through human work and the integration of the farmers' local ecological knowledge, which we incorporated into the model as management practices supporting land flows. At Sitio Luciana, the key issue lies in the recovery of the Atlantic Forest habitat through the development of agroforestry and horticultural areas, where forest restoration occurs with human-managed agroforestry and horticulture supporting both biodiversity and food production. We simulated land-use change over 15 years, successfully reproducing observed temporal patterns derived from Earth observation data. Synergistic interactions between farmers' management practices and ecological successions appeared crucial to the restoration of the Atlantic Forest, offering a robust theoretical explanation for the farmers' interventions and validating their local ecological knowledge.

Our approach emphasizes the potential of minimal, physical-based non-linear models in agroecology and land system science, highlighting the ability of the energy system language to capture the dynamics of local farm and land systems, to support participatory modeling by integrating farmers' insights, and to create physical-based land-use scenarios to inform local land management decisions. This approach has significant potential for guiding sustainable land management practices and policy frameworks based on systemic analysis, which integrate both scientific and local knowledge in agroecological contexts.

2. Methodology

We introduce a physically based modeling framework for land systems and agroecosystems, integrating both biotic and human activities. The approach is conceptualized using the stock-flow energy systems language (Odum and Odum, 2000), providing a general template applicable at farm, landscape, regional, and global scales. Established socio-ecological concepts from literature are employed to define land-use categories (Ellis et al., 2010, 2021).

As illustrated in Fig. 1, the framework identifies a general land system state using five land stocks: available (L), natural (L_N), semi-natural (L_{SN}), intensive (L_I), and degraded (L_D), measured in area units (e.g., km^2). Natural land is defined as land free of human habitation. Semi-natural (or cultured) land refers to areas inhabited and cultivated sustainably by humans (e.g., polycultures, indigenous cultural systems, agroecology, permaculture), supporting habitat biodiversity. Intensive land describes areas cultivated primarily through fossil-fuel-based technologies and practices that often negatively affect natural habitats (e.g., use of pesticides, synthetic fertilizers, heavy machinery, GMOs). Degraded land refers to formerly intensive areas experiencing long-term environmental pressures and thus becoming less suitable for cultivation (e.g., severely degraded soils).

The system is assumed to be closed, conserving total land area while allowing energy flows into and out of it. We concentrate on the land cycle in relation to biotic, human and fossil available energy, defined as internal and free energy that can be transformed into useful work. Land stocks are interlinked with the different energy sources and stocks: a flow limited renewable energy source (R), encompassing solar radiation, wind kinetic energy, rainfall, and chemical energy stored in soil water; a stock of biotic energy (B), defined as the available chemical energy from biotic activity; a stock of human energy (H), defined as the available energy from human activity; and a stock of fossil energy (FF), defined as non-renewable energy stock.

In the diagram presented in Fig. 1, we illustrate the primary hierarchy of a general land system and the typical interactions among different land stocks. The available land stock can be converted into natural, semi-natural, or intensive land. Each land stock, including degraded land, has its own turnover rate and eventually cycles back into available land. Natural land can become semi-natural land through human interventions, such as management practices in buffer zones surrounding protected areas. Conversely, semi-natural land can either regenerate into natural ecosystems via ecological succession or transition into intensive land due to agricultural expansion, often resulting in

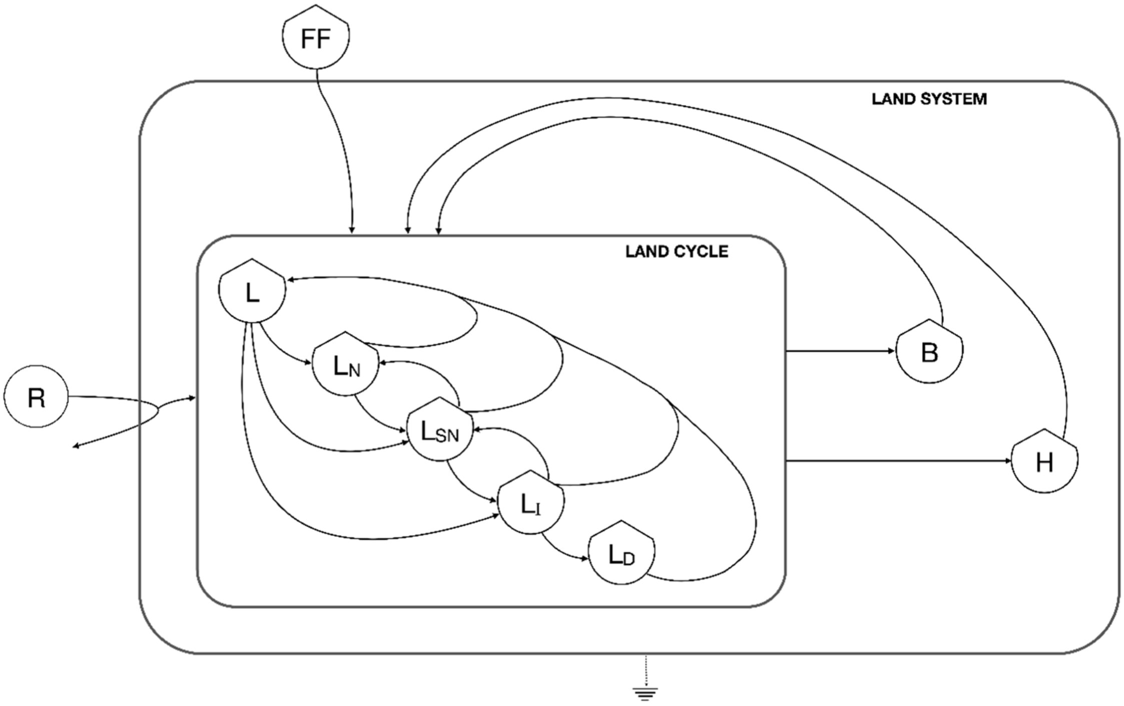

Fig. 1. The conceptual model of a land system represented by five land stocks: available (L), natural (L_N), semi-natural (L_{SN}), intensive (L_I), and degraded (L_D), measured in area units. Transitions among stocks occur through natural processes and human interventions. Natural land may shift to semi-natural through management; semi-natural may revert to natural or intensify; intensive land can degrade or be restored; and degraded land results from long-term unsustainable use. Biotic and human energy stocks influence and benefit from these transitions, while fossil energy enters externally, driving intensive land use.

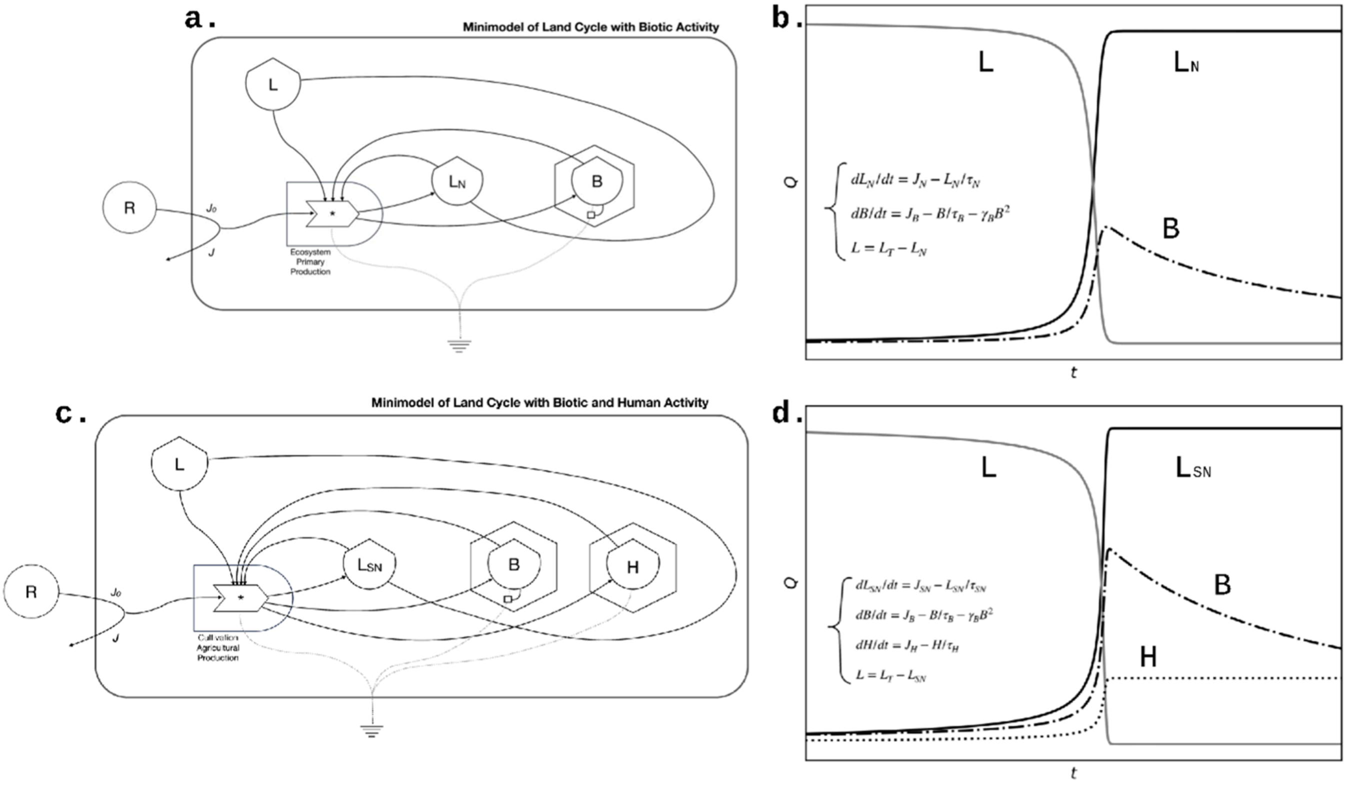

Fig. 2. Two minimal models simulating the temporal dynamics of land stocks. *Upper panels*: (a.) land cycle with biotic activity, representing dynamics typical of natural systems. (b.) Available land (L) is fully converted into natural land (L_N) through biotic energy (B) driving primary production. The biotic energy stock increases with land conversion, peaks, and then stabilizes—indicating two distinct phases of ecosystem development. *Lower panels*: (c.) semi-natural land cycle with both biotic and human activity. (d.) Human energy (H) collaborates with biotic processes to produce useful energy for both, reflecting traditional and agroecological systems where humans function as key partners in ecosystem functioning.

habitat loss. Intensive land areas may be converted into semi-natural land through targeted human interventions, including habitat restoration and the adoption of agroecological practices. Degraded land arises from the deterioration of intensive land caused by unsustainable management practices, such as use of pesticides and herbicides and intensive agricultural practices that lead to the decline of biological communities. The biotic and human energy stocks (measured in energy units, e.g., *J)* benefit from the yields produced by the land cycle, while both directly intervene on the land cycle by changing flow rates and allowing transitions between land categories. Fossil fuel energy is external to the system as generally purchased to support the growth of the semi-natural and intensive land stocks.

In Fig. 2, we illustrate two conceptual models to simulate the time evolution of land stocks. In the upper panels, we model a minimal land cycle with biotic activity. This model shows stylized dynamics typical in natural system structures, as described in early seminal works (Odum, 1973; Odum, 1969): the available land stock is completely converted into natural land by the contribution of biotic energy to the process of primary production. The stock of biotic energy grows with the land stock reaching a maximum value, then decreases to a stable value, depicting two different regimes of ecosystem development (Holling, 1973; Levin, 1998; Odum, 1969; Walker et al., 2004). In the lower panels, we model a minimal semi-natural land cycle with biotic and human activity. In this model, the3 human energy stock cooperates with the biota to yield useful energy for both, resampling Indigenous and agroecological systems (Comar, 2004, 2019) with humans contributing with diverse work as stable essential partners of the agroecosystem (Odum, 1971, 1973).

The minimal models described in Fig. 2 highlight the modularity and flexibility of the approach, favoring control on model design and parameter setting. In this realm, applying the energy system language enables building minimal models of land cycles that reduce the number of parameters and enable experts' control on the system dynamics.

2.1. *Case study*

We apply the modelling framework to simulate 15 years of agroecological land-use management at Sitio Luciana (22°09′51.9″S; 54°53′05.6″W), a farm located in Dourados (Mato Grosso do Sul, Brazil).

The area of Dourados, situated in the Central-Western Brazil, close to the border with Paraguay, lies within the humid subtropical climatic zone with a moderately pronounced seasonal cycle, characterized by hot and humid summers and mild winters (Alvares et al., 2013). The soil in this area has very peculiar characteristics. It is known as Latosol (Filho et al., 2010) a very fertile soil that originates from millions of years of decomposition of basaltic rocks, which result in its typical red color, named in the common language *"Terra roxa"* (red earth). Owing to its hydro- and pedoclimatic characteristics, the area of Dourados has seen great agricultural expansion and intensification from the 1990s, dominated by a conventional agribusiness model based on few cash crop productions - namely soybeans, corn and sugarcane - directed to the global market (Bonini et al., 2018; Song et al., 2021). Such agricultural models - oriented at production of food commodities in monocultural configuration of land, industrial and economic growth - are known to be harmful for people and the environment (Pengue, 2005; Steward, 2007;

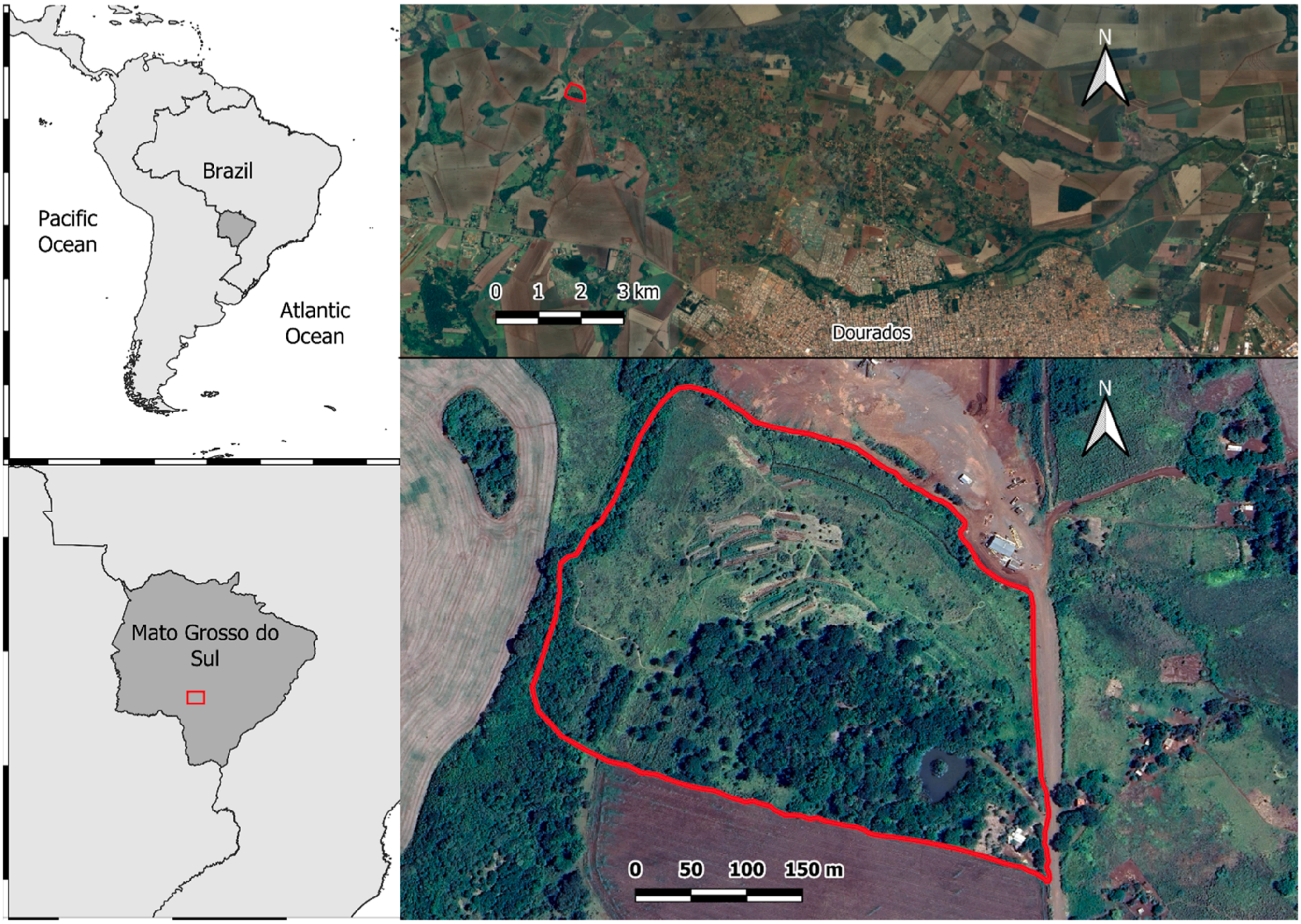

Fig. 3. Sitio Luciana lies at the border of the Bororó Indigenous Reserve in the northern area of Dourados (upper right) in Mato Grosso do Sul (Brazil). Over 15 years, this ~15 ha site was transformed from degraded monoculture into a diversified agroecological landscape (lower right) featuring semi-natural forest, agroforestry, and horticulture.

Wolford, 2008). In particular, regarding the use and fate of pesticides in the hydrologic cycle, which may severely affect the health conditions of land workers, residents and Indigenous Peoples native to the area (Abrantes et al., 2010; Albuquerque et al., 2016; Moreira et al., 2012). The potential vegetation cover of the area is the semi-deciduous tropical forest, also known as Atlantic Forest, among the Earth's biomes experiencing greater loss of natural habitat. The Atlantic Forest biome was estimated to cover around 12 % of its native distribution (Ribeiro et al., 2009), with greater negative consequences related to biodiversity loss and the survival of Indigenous Peoples.

Sitio Luciana – shown in the Fig. 3– is situated close to the borders of Bororó Indigenous Reserve area, in northern Dourados, and is one of the rare efforts in the area to support native habitat restoration by transitioning from a conventional agribusiness model to agroecology. This project contributes independently to the environmental restoration of the area. At Sitio Luciana ~15 ha of monocultural and partially degraded land was converted in 18 years into a diversified farm with semi-natural forest, agroforestry and horticultural areas, aimed at boosting Atlantic Forest restoration while producing healthy vegetables and fruits, which weekly support the diets of a self-organized and self-managed food purchasing network of ~40 local families.

2.2. Including farmers' local knowledge in agroecological systems modeling

As methodological and ethical positioning, we acknowledge that farmers, peasants and agricultural producers hold a certain degree of local ecological and environmental knowledge that allows them to carry out their activities and management (Berkes, Folke, and Colding, 2000), beyond the technical and scientific knowledge that might contribute to it. The intrinsic value and amount of local knowledge can be very substantial depending on the way it was originally acquired through practice, transmitted, accumulated through generations, and on the interactions with other knowledge forms (Šūmane et al., 2018). In this context, we used tools from qualitative research to understand and describe the human component of the socio-ecological system under study, in particular, to enter the social and cultural settings of the area, and to learn about adaptive management practices by exploring farmers' local knowledge (e.g., in Fig. 4).

The farmers' family managing Sitio Luciana was engaged owing to the collaboration with IMAD (Instituto Meio Ambiente e Desenvolvimento). Weeks were spent together as scientists and farmers, both in informal gatherings at Sitio Luciana and in public initiatives in the Dourados area, creating a relationship of trust and mutual exchange that allowed us to build the empirical basis of the research. In the case of Sitio Luciana, farmers' local knowledge concerns, but is not limited to, methods of cultivation such as rotation, polycultures, and agroforestry, knowledge on seeds, soil, plants, and animals, knowledge on meteorological and climate patterns, water resource management, food distribution, local food market dynamics. The source and origin of this local knowledge comes both from family elders practicing traditional farming in past generations, from knowledge acquired through direct observation and experimentation, and gained in farmer-to-farmer exchanges, and to a lesser extent from popular and technical-scientific formal knowledge sources. In this regard, the practical outcome of the restoration effort at Sitio Luciana can be viewed as the result of the independent application and development of local ecological and environmental knowledge with only auxiliary contributions of formal knowledge sources.

By conducting field visits, carrying out agricultural activities and in-depth unstructured interviews with the farmers' family members, it was possible to explore the agroecological farming practices at Sitio Luciana, the change in time of land-use, the characteristics of water and auxiliary resource use, the strategies to ensure economic sustainability of the project, and the needs, values and beliefs driving farmers' actions. In Fig. 4 are shown field notes from in-depth interviews with farmers'

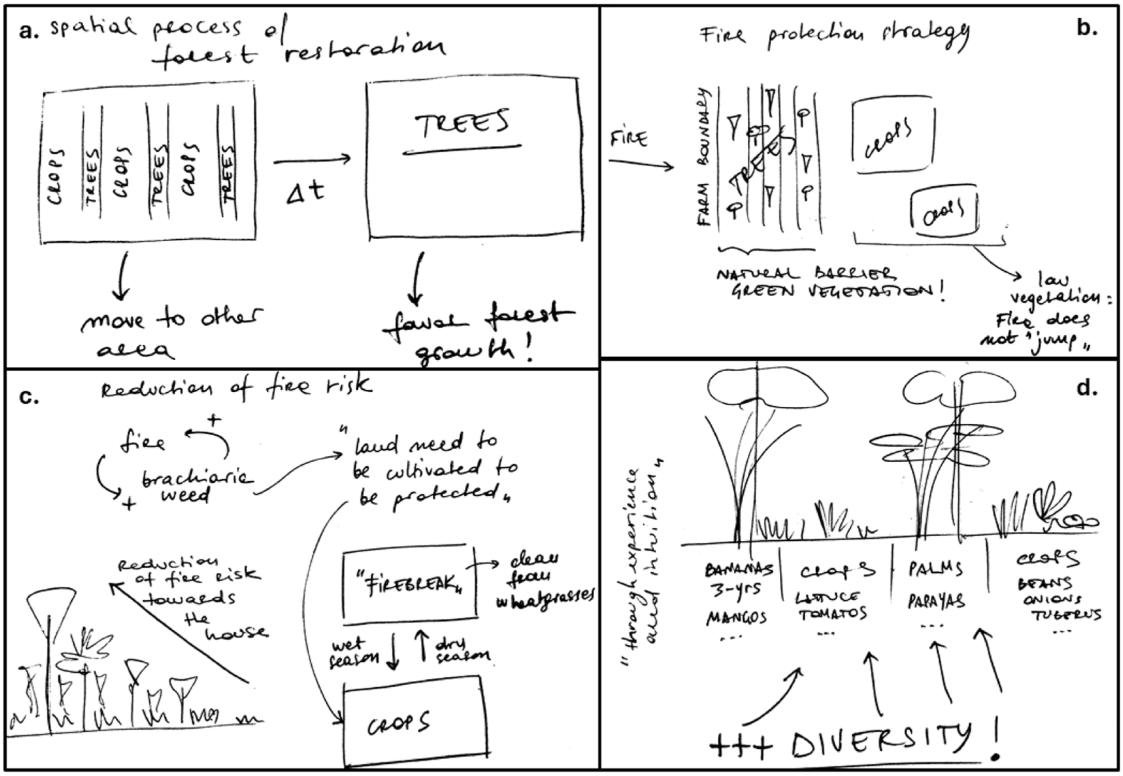

Fig. 4. Drawings and field notes from in-depth interviews with farmers' family members reporting their local knowledge on the topics of adaptive land management and agroecological practices: a.) to favor development of forest habitat by applying agroforestry practices, b.-c.) to protect land from fire spreading, d.) to increase biodiversity in the farm.

family members reporting land management strategies to favor forest habitat restoration, to protect land from fires, and to increase biodiversity at the farm scale. This information was merged with previous studies assessing the integrated sustainability of agricultural productions at Sitio Luciana (Comar, 2019) and was used to acquire new knowledge on the key ecological processes and feedback mechanisms mediated by farmers at this site, with a focus on modeling the long-term land-use dynamics. In Table 1 we summarized the key human factors contributing to the agroecosystem development at Sitio Luciana in terms of land use, economic strategies and goals at different stages of the project, clarifying its overall agroecological characteristics, spanning environmental, economic, social and cultural dimensions. Notably, in this study we only used a minimal set of information acquired through the process described, nevertheless, a deeper and nuanced understanding of the local farmers' perspectives can be learned beyond the modeling scope of this work, which is also intended to provide a scientific validation of Sitio Luciana's agroecological land-use model, contributing to the long-term goals of the project.

3. Model of agroecological land use dynamics

The system diagram of land use dynamics at Sitio Luciana is presented in Fig. 5. The system operates through three main processes of primary and agricultural productivity within three semi-natural land areas: semi-deciduous forest, agroforestry, and horticultural areas. The corresponding land stocks (respectively L_F, L_{AF}, L_H) take part in these processes, supported by land-specific biotic energy stocks (respectively B_F, B_{AF}, B_H) and human energy (H) in the form of diverse types of work. Agroforestry and horticulture produce useful resources for the farming household and its associated food network, with part of the yields flowing out of the system.

The growth of L_F, L_{AF}, L_H is constrained by the availability of total land (L), forming a self-limiting land cycle (Conte et al., 2023; Odum and Odum, 2000). Transitions between land stocks, including degraded land (L_D), occur through land conversion processes driven by human work, which is supplemented by auxiliary energy inputs from fossil-fuel-based technologies (FF), such as agricultural machinery for transport, tillage, and water management. The system dynamics is constrained by the availability of renewable resources (R).

The model in Fig. 5 is simplified into a minimal version shown in Fig. 6, keeping the core non-linear processes. This reduced model focuses solely on land stocks, measured in hectares, with the contribution of biotic and human energy stocks embedded in the parameters that govern land growth and conversion flows. These flows are shaped by the adaptive management practices of local farmers. In the model, we parametrize the following different transitions: the conversion of degraded land (L_D) into horticultural areas (L_H), the transition of horticultural land into agroforestry (L_{AF}), and the transformation of agroforestry land into forest (L_F). Each land stock has a characteristic lifetime determined by its vegetation cover, after which it reverts to the available land stock (L), enabling the continued development of the three key land uses.

The system of ordinary differential equation (ODE) governing the land use dynamics at Sitio Luciana, associated with diagram in Fig. 6, is

$$\begin{cases} \dfrac{dL_F}{dt} = k_F R L L_F - \dfrac{L_F}{\tau_F} + \dfrac{L_{AF}}{\tau_{AF-F}} \\ \dfrac{dL_{AF}}{dt} = k_{AF} R L L_{AF} - \dfrac{L_{AF}}{\tau_{AF}} - \dfrac{L_{AF}}{\tau_{AF-F}} + \dfrac{L_H}{\tau_{H-AF}} \\ \dfrac{dL_H}{dt} = k_H R L L_H - \dfrac{L_H}{\tau_H} - \dfrac{L_H}{\tau_{H-AF}} + \dfrac{L_D}{\tau_{D-H}} \\ \dfrac{dL_D}{dt} = -\dfrac{L_D}{\tau_D} - \dfrac{L_D}{\tau_{D-H}} \\ L = L_T - L_F - L_{AF} - L_H - L_D \end{cases} \tag{1}$$

In the ODE system, we define the growth rates per unit renewable resource and unit area: k_F (for forest), k_{AF} (for agroforestry), and k_H (for horticulture). The land inflows entail the non-linearities of the system, and for each stock depend on the total renewable input (R) and total available land (L_T). Each land stock has a characteristic lifetime: τ_F (for forest), τ_{AF} (for agroforestry), τ_H (for horticulture), and τ_D (for degraded land). Land conversion flows are linear terms in Eqs. 1 and occur on

Table 1
Farmers' adaptive management contributes to agroecosystem development at Sitio Luciana in terms of land use (addressing cropping and forestry systems), economy (addressing farmers' incomes, social network, and exchange with Indigenous Peoples), and goals (reflecting farmers' needs, values and beliefs) at different stages of the project (*source*: in-depth interviews with farmers family members and land workers at Sitio Luciana).

		Timing		
		until 2012	until 2021	since 2021
Goals		Establishing safe and accessible water stocks Protecting degraded fire-prone soil Moving from the urban area to establish a new agroecological production system Establishing a safe space for synergic interactions with Indigenous Peoples, and their food production practices, with a solidarity approach	Recovering from initial investment Experimenting the best solutions and practices for restoring native semi-deciduous forest within a landscape of agribusiness cropping systems (mainly corn and soybeans) Producing healthy food for local families Providing fair incomes for rural workers Building a local network and intercultural relations Experimenting natural ways for fire control and reduction of fire risk	Expanding semi-deciduous forest habitat areas Providing a sustainable alternative to the dominant agribusiness model in terms of environment, economy, and socio-cultural relations within the established network including farmers and indigenous groups of the area Disseminating the project results for reproduction
Adaptive management practices	**Land use**	Establishing a water management system Establishing a nursery Cultivating economically valuable plants Cultivating crops for self-consumption and subsistence	Reducing areas for nursery and cropping systems Establishing agroforestry systems for food production and forest recovery Planting native semi-deciduous forest species	Increasing semi-deciduous forest areas within a highly diversified agroecosystem
	Economy	Initial investment to purchase land and build structures Purchase and adapt machineries to agroecological practices requirements Selling seedlings and ornamental plants Self-consumption of horticultural products	Selling crops, horticultural and agroforestry products (including sugarcane products) in formal urban farmers markets	Direct selling through an informal self-managed economy with an affiliated purchase network Cooperating with Indigenous Peoples to increase subsistence food production

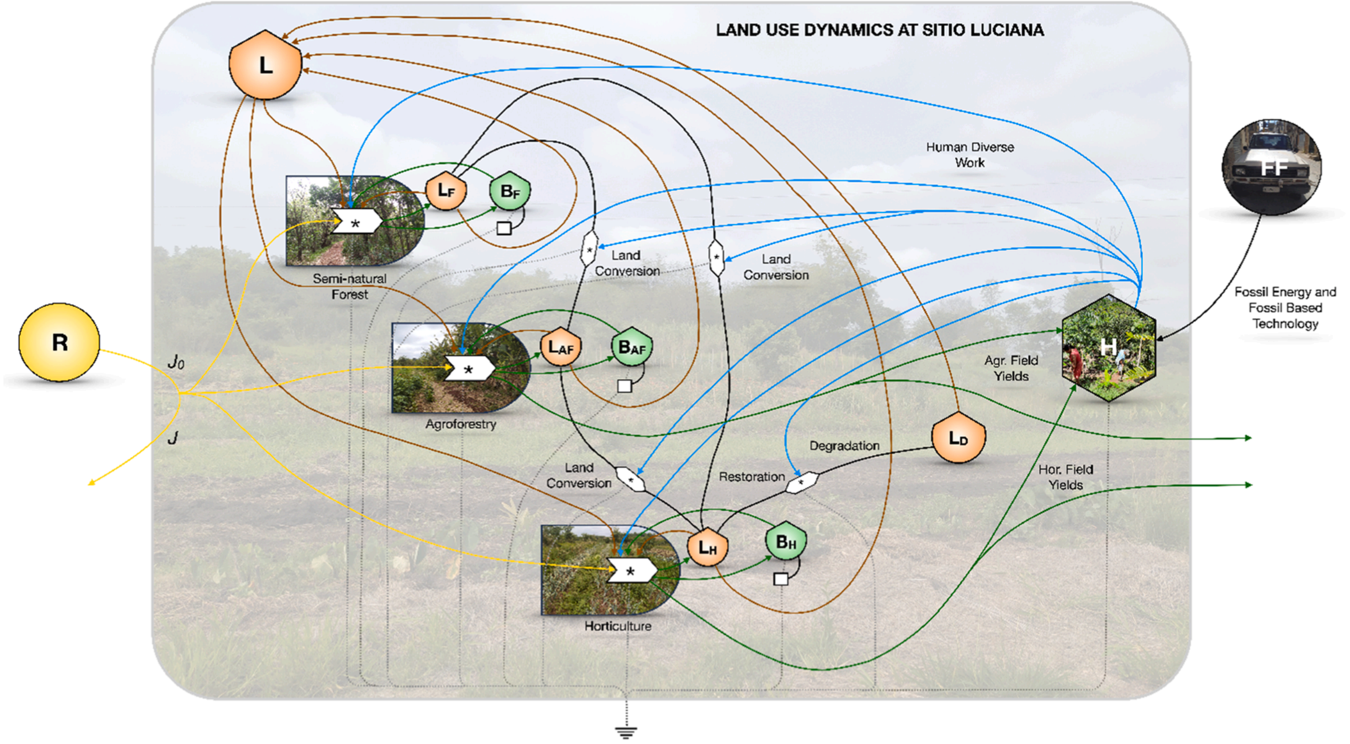

Fig. 5. System diagram of land use dynamics at Sitio Luciana (2009–2024), driven by primary productivity in semi-deciduous forest, agroforestry, and horticultural areas. Land stocks (L_F, L_{AF}, L_H) interact with biotic (B_F, B_{AF}, B_H) and human energy (H), constrained by total land (L) and renewable resources (R). Land conversions, including degraded land (L_D), occur through human work and fossil-fuel-based inputs (FF).

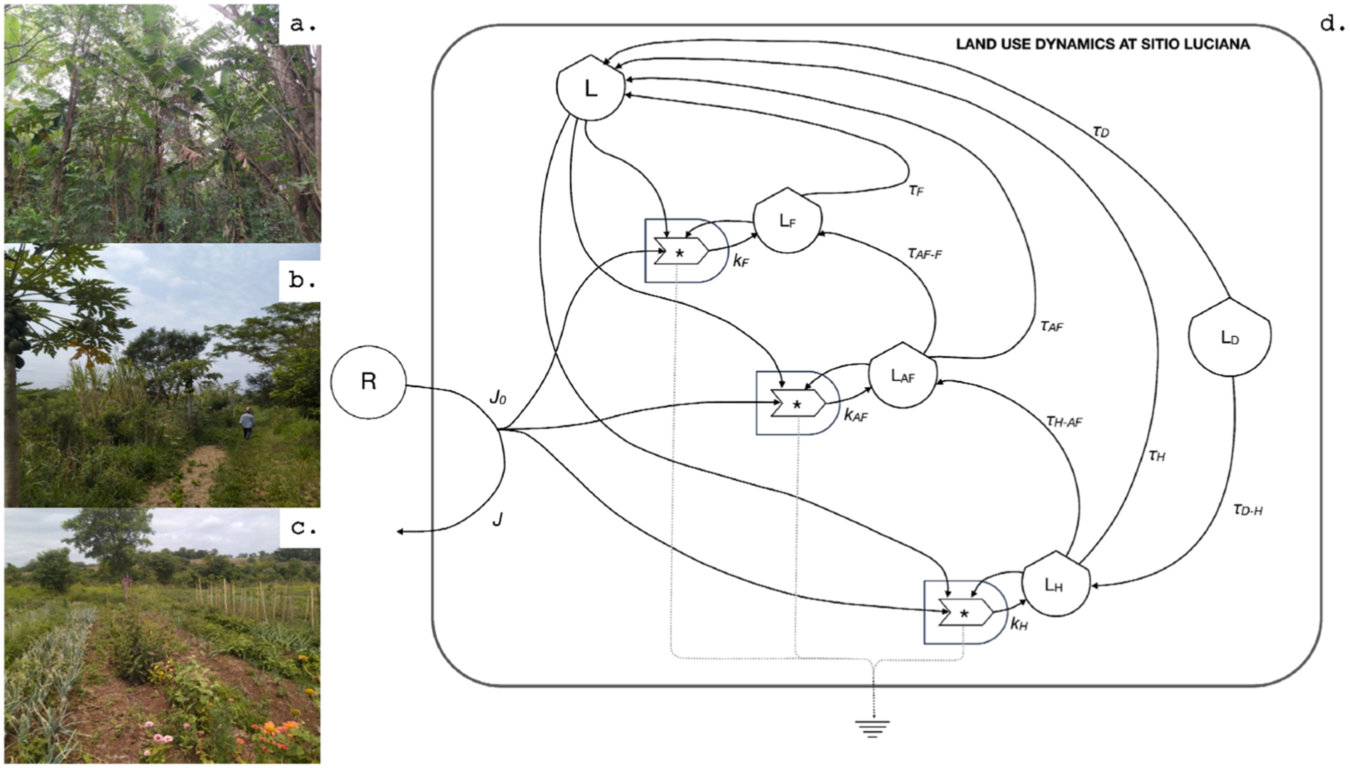

Fig. 6. (a.) Semi-deciduous forest (b.) Agroforestry (c.) Horticultural land at Sitio Luciana (in 2024) (d.) Land stock dynamics (in hectares) modeled with implicit biotic and human activity. Land conversions follow pathways determined by farmers' adaptive management which also defines transition times. Degraded land (L_D) is first converted to horticulture (L_H) with typical time τ_{D-H}, then from horticulture to agroforestry (L_{AF}) with typical time τ_{H-AF}, and eventually to forest (L_F) with typical time τ_{AF-F}. Each land type has a defined lifespan based on vegetation cover (τ_F, τ_{AF}, τ_H, τ_D), after which it returns to the stock of available land (L) for future use. Horticulture, agroforestry and forest land have their proper growth rate according to farmers' management (respectively k_F, k_{AF}, k_H). The system dynamics was defined per unit renewable resources (R).

timescales set by human management: degraded land converts to horticulture over time $\tau_{D\text{-}H}$, horticultural land converts to agroforestry in time $\tau_{H\text{-}AF}$, and agroforestry converts to forest land with time $\tau_{AF\text{-}F}$.

The model in Eqs. 1 was dimensioned to reproduce GIS-derived area estimates of different land cover classes: semi-natural forest, agroforestry, horticulture, and degraded land. Land areas are measured in hectares and have been converted into percentage of total area to show the model results. Table 2 summarizes the land area estimates from 2009 to 2024 to which we assigned a 5 % relative uncertainty to account for systematic errors in the GIS-based estimates. Q-GIS software was used to compute land areas on the basis of Landsat historical data.

In Table 3 there is a summary of the model parameters with the values used for setting up the simulator, the estimation method and the data source.

To estimate the growth rates of land stocks managed by farmers, we assumed that the productive processes of the system in Fig. 6 operate at the maximum power limit, according to a self-limiting cycle model for a single land stock constrained by total available land (L_T). It is defined as the thermodynamic limit of maximum power that can be obtained from a dissipative process or system at the steady state, given its physical constraints of energy, matter and information inputs. Notably, the maximum power state, or maximum power limit, describes one specific steady states of self-organizing systems with sufficiently high degrees of freedom (e.g., Kleidon, 2010, 2016; Conte et al., 2019). From the analytical expression for a single land stock in a steady state (L_{ss}) at maximum power, $L_{ss} = L_T/2$, and the differential equation governing a self-limiting cycle (Conte et al., 2023), we obtained the estimates for k_F, k_{AF}, and k_H coefficients reported in Table 3.

We obtained the best estimate for $\tau_{D\text{-}H}$, $\tau_{H\text{-}AF}$, and $\tau_{AF\text{-}F}$ applying an ordinary least squares (OLS) optimization method, regressing model simulation against land use observations reported in Table 2, with the goal to minimize the model's global root means square error (*RMSE*). We validate the model parameter setting by conducting a one-parameter-at-time (OPT) sensitivity analysis and varying the setup values of each parameter within 25 % relative uncertainty interval.

Simulations, parameter estimations and sensitivity analysis were all developed with a Python 3 code publicly available as computational notebook (Conte, 2025).

4. Results and discussion

The model simulation shown in Fig. 7 closely reproduced the land use dynamics at Sitio Luciana between 2009 and 2024. The observed patterns aligned with the model simulation with *global RMSE=2 %*. The model accurately matched the observations for each land stock, with slight differences among land classes. For each land stock fit statistics were respectively $RMSE_{forest}$=*2.1 %*, $RMSE_{agroforestry}$=*2.3 %*, $RMSE_{horticulture}$=*2.4 %*, $RMSE_{degraded}$=*2 %*. Horticultural and agroforestry land trajectories had a higher *RMSE* as estimated land cover follows slightly more irregular patterns due to the higher degree of interaction with the human energy stock through direct management of land, which is more affected by seasonality and unpredictable events.

Table 2

Land cover estimates at Sitio Luciana from 2009 to 2024, based on Landsat 4–5 TM and Landsat 8/9 OLI data. Categories include semi-natural forest, agroforestry, horticulture, buildings, and degraded land. Values are expressed in hectares and as percentages of total area.

LAND [%]					
year	forest	agroforestry	horticultural	degraded	available
2009	*6.9*	*4.7*	*8.0*	*22.4*	*58.0*
2012	*7.4*	*6.6*	*18.3*	*17.1*	*50.3*
2013	*8.1*	*7.8*	*17.3*	*17.1*	*49.4*
2014	*10.9*	*9.2*	*15.2*	*14.1*	*50.3*
2016	*12.4*	*10.7*	*14.5*	*12.0*	*50.2*
2017	*14.8*	*11.4*	*14.4*	*8.2*	*51.0*
2018	*15.2*	*13.0*	*16.1*	*8.0*	*48.5*
2019	*15.9*	*11.4*	*15.7*	*6.5*	*50.3*
2021	*20.6*	*15.0*	*9.4*	*6.3*	*48.4*
2022	*21.3*	*14.6*	*9.1*	*4.9*	*49.6*
2023	*22.9*	*15.6*	*9.8*	*4.5*	*46.6*
2024	*28.5*	*14.6*	*8.7*	*3.5*	*44.1*

Table 3

Summary of model parameters used to configure the land use simulator for Sitio Luciana, including parameter names, values, estimation methods, and data sources. Land cover values were based on GIS data and local knowledge from the landowner. Lifetimes and growth rates were drawn from literature or estimated in interviews with farmers. Transition times and forest growth rate were calibrated using simulation results and optimized to match observed land use data. All parameters reflect the specific context and management practices of the study site. MP stands for maximum power; OLS stands for ordinary least squares.

Parameter		Value	Method	Data source
R	Renewable resources	1	calibration per unit value	–
L_T	Total land area	14.3 *hect*	GIS estimation	Local farmer and landowner, Landsat 4–5 TM, Landsat 8/9 OLI
L_{F0}	Initial forest cover	1 *hect*	GIS estimation	Local farmer and landowner, Landsat 4–5 TM, Landsat 8/9 OLI
L_{AF0}	Initial agroforestry cover	0.7 *hect*	GIS estimation	Local farmer and landowner, Landsat 4–5 TM, Landsat 8/9 OLI
L_{H0}	Initial horticulture cover	1.15 *hect*	GIS estimation	Local farmer and landowner, Landsat 4–5 TM, Landsat 8/9 OLI
L_{D0}	Initial degraded land	3.2 *hect*	GIS estimation	Local farmer and landowner, Landsat 4–5 TM, Landsat 8/9 OLI
τ_F	Lifetime of semi-deciduous tropical forest	50 *years*	Literature review	(Blagitz et al., 2019)
τ_{AF}	Lifetime of agroforestry system	5 *years*	In-depth interview	Local farmer and landowner
τ_H	Lifetime of horticultural system	0.25 *years*	In-depth interview	Local farmer and landowner
τ_D	Time for degraded soil restoration	10 *years*	Literature review	(Souza-Alonso et al., 2022)
k_F	Growth rate of forest land stock	0.003 $hect^{-1}$ $years^{-1}$	$k_F = \frac{2}{L_T \cdot \tau_F}$ MP estimate (Conte et al., 2023)	(Blagitz et al., 2019)
k_{AF}	Growth rate of agroforestry land stock	0.03 $hect^{-1}$ $years^{-1}$	$k_{AF} = \frac{2}{L_T \cdot \tau_{AF}}$ MP estimate (Conte et al., 2023)	Local farmer and landowner
k_H	Growth rate of horticulture land stock	0.6 $hect^{-1}$ $years^{-1}$	$k_H = \frac{2}{L_T \cdot \tau_H}$ MP estimate (Conte et al., 2023)	Local farmer and landowner
$\tau_{D\text{-}H}$	Transition time from degraded to horticultural land	63 *years*	Inferred from simulation	OLS optimization
$\tau_{H\text{-}AF}$	Transition time from horticulture to agroforestry land	8 *years*	Inferred from simulation	OLS optimization
$\tau_{AF\text{-}F}$	Transition time from agroforestry to forest land	10 *years*	Inferred from simulation	OLS optimization

The system dynamics highlighted human-mediated ecological succession—targeted at restoring Atlantic Forest habitats—as key to agroecosystems development at Sitio Luciana. The first growth of a larger

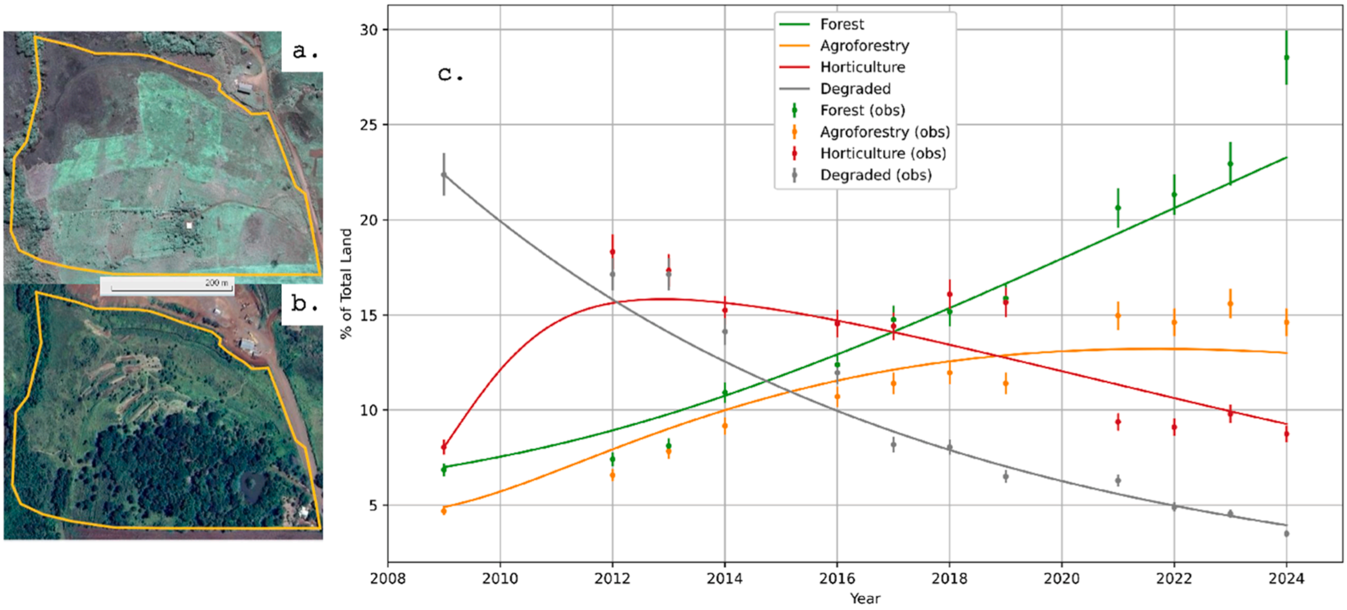

Fig. 7. (a.) Aeral view of Sitio Luciana in 2009 (b.) and in 2024 (c.) Comparison of simulated (solid curves) versus observed (dots with error bars) land-use at Sitio Luciana (2009–2024). The model reproduces the overall dynamics with a *global RMSE=2.0 %*. Fit statistics for each land category are forest (green, $RMSE = 2.1$ *%*), agroforestry (orange, *2.3 %*), horticulture (red, *2.4 %*), and degraded land (grey, *2.0 %*).

horticultural area peaks in 2012 to be later reduced – through local farmers' management – in favor of agroforestry and forest land areas. The forest area grew exponentially by reaching *~25 %* of the total land in 2024, with land cover projected to increase under present boundary conditions. Agroforestry land had a sigmoidal growth and occupied *~15 %* of the total land in 2024, with trajectory approaching a steady state. The degraded land area followed an exponential decay reaching <5 *%* of the total land in 2024.

The transition times – optimized to obtain the best agreement of model simulation and observations – were respectively $\tau_{D\text{-}H} = 63$ *years,* $\tau_{H\text{-}AF} = 8$ *years,* and $\tau_{AF\text{-}F} = 10$ *years*. These estimates indirectly reflected the amount of human work (also including auxiliary external fossil-

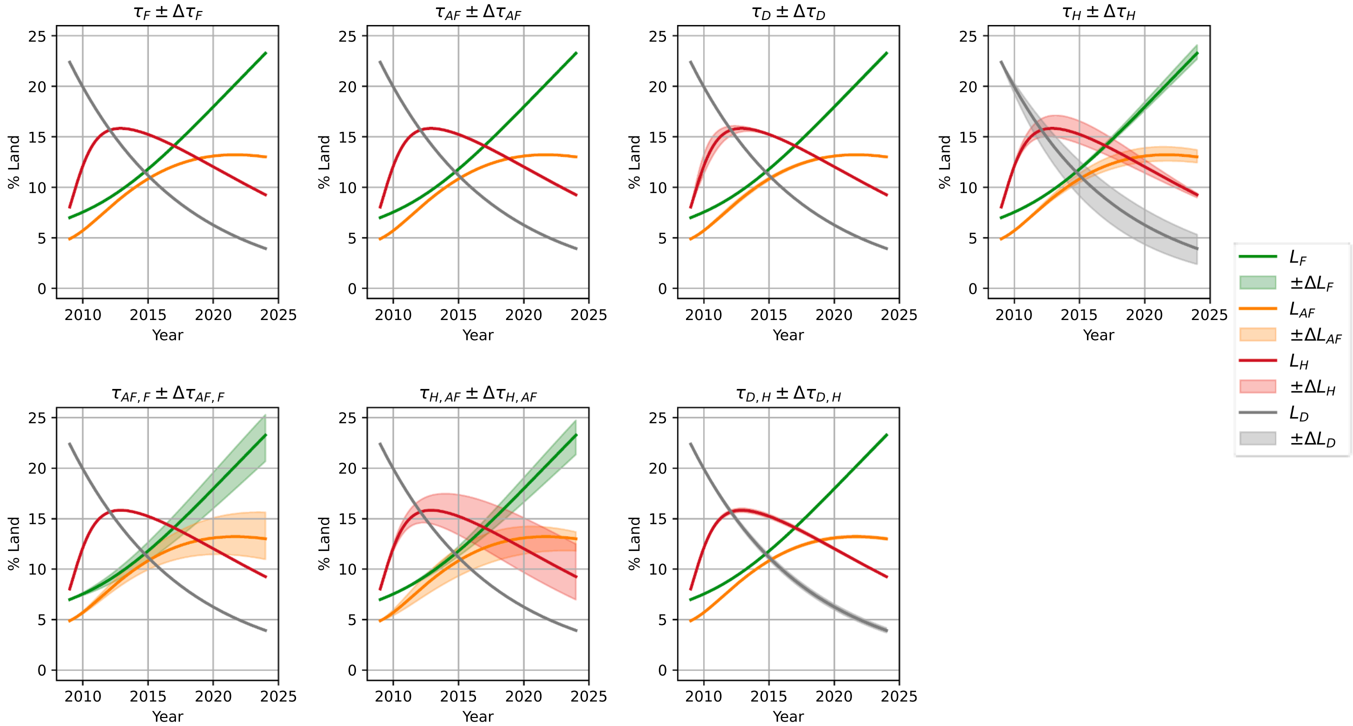

Fig. 8. Sensitivity analysis (one-parameter-at-time, OPT) of model parameters for Sitio Luciana land-use dynamics. Simulated trajectories for forest (green), agroforestry (orange), horticulture (red) and degraded (grey) land remain nearly unchanged under ±25 % change of model parameters, namely stock lifetimes (τ_F, τ_{AF}, τ_H, τ_D) and land conversion times ($\tau_{D\text{-}H}$, $\tau_{H\text{-}AF}$, and $\tau_{AF\text{-}F}$), validating the model calibration procedure. The trajectories with parameter setting defined in Table 2 are shown by the solid curves, while the uncertainty associated with the OPT parameter change are shown by the colored shaded regions of the graphs for each land stock. Varying conversion times—particularly the transitions from horticulture to agroforestry and from agroforestry to forest—induces larger uncertainty in the model outputs, although the overall system behavior is preserved under these perturbations.

based energies) that was invested by farmers for the land conversion processes. The transition from horticultural to agroforestry land was the fastest and was comparable in time with land conversion from agroforestry to forest land. The time for conversion of degraded land into productive horticultural land was from 6 to 7 times higher than the two. These results provide insight into farmers' management strategy under the pedo-climatic constraints of the area. As shown in Figs. 6 and 7, the pathways to achieve forest restoration were, from one hand, to transition from horticulture to agroforestry land ($\tau_{\text{H-AF}} = 8$ years), while, on the other hand, to favor the transition from agroforestry to forest land at a slight lower rate ($\tau_{\text{AF-}F} = 10$ years). Moreover, through land restoration, it was possible to intervene indirectly on the decay of degraded land, with only small direct interventions to convert degraded land areas into horticultural areas at a low rate ($\tau_{\text{D-}H} = 63$ years). The system diagram in Fig. 6 actually represents this complexity – which is highly site-specific – describing the co-existence and succession of different land cycles operated on diverse timescales, set by farmers adaptive management. These feedback mechanisms and the physical constraints, described in Fig. 5, are ultimately responsible for the emergent dynamics of the system and define the diverse timescales for transitioning between alternative land-uses, determining the overall agroecosystem development.

The results of the sensitivity analysis of model parameters are shown in Fig. 8. The model simulations for each land stock were robust to changes of ±25% in parameter values, validating the model parameter setting. The lifetime of the horticultural system was the most sensitive lifetime in the model, showing a typical greater variability in the entire system dynamics associated with horticultural management. The model was more sensitive to changes in land conversion times from horticulture to agroforestry, and from the latter to forest, however conserving the dynamical patterns. The change in $\tau_{AF\text{-}F}$ affected the variability of these two stocks, while a change in $\tau_{H\text{-}AF}$ had an impact on the variability of all the land stocks, showing horticultural production as a key process to manage the agroecosystem dynamics towards restoration of Atlantic Forest. In the model, the increase and decrease of degraded land lifetime (τ_D) is associated respectively to decrease and increase in horticultural land area.

The sensitivity analysis of model parameters showed the two processes of horticultural production and transition from horticultural to agroforestry land as key for the development of the semi-natural forest area. These results highlighted the essential role of farmers in the adaptive management of the agroecosystem at Sitio Luciana in cooperation with biotic activity to develop a complex agroecosystem. It reflected the role of local farmers in managing external inputs by developing internal feedback mechanisms through the diverse forms of human work (Odum, 1973), also shown in Fig. 5, which favored the development of complex semi-natural habitats while ensuring food production. In this perspective, it is interesting to note that farmers' management likely evolved to maximize useful power in the productive processes: on one hand, to boost forest restoration, and on the other, to support the co-existence of different land use areas to sustain both food production and biodiversity. This results are in line with findings and guidelines for restoring land through agroecological practices (Altieri, Nicholls, de Molina, et al., 2024; 2024; Dumont et al., 2021; Pashkevich et al., 2022; Vieira et al., 2009), aligning with the holistic view of agroecology (Garcia-Polo et al., 2021; Nicholls and Altieri, 2018), and suggesting a path to interpret development and evolution of agroecosystems through the lens of thermodynamic principles, addressing the speed and the effectiveness of energy transformation (Lotka, 1922; Odum and Pinkerton, 1955).

Thermodynamic principles offer a fundamental conceptual framework for studying and interpreting complex agroecosystems dynamics. The land-use at Sitio Luciana was likely to develop towards states of maximum power output, suggesting that the system evolved such as to maximize the rates of productive processes, while optimizing the rates for the land-use transitions through local farmers management and knowledge. In agreement with non-equilibrium Thermodynamics (e.g., Rico et al. (2013) and Marull et al. (2019)), this implies that a sufficiently complex and diverse agroecosystem including humans evolves – in the words of Odum and Pinkerton (1955) – to an 'optimum efficiency for maximum (useful) power output' in a way that is 'compatible with the constraints' acting on the system (Hall and McWhirter, 2023).

5. Conclusion

In this paper, we applied a physically grounded framework based on H.T. Odum's energy systems theory to model agroecological land systems, focusing on land use dynamics and human management. The modelling approach was validated against observed land-use patterns from a 15-year agroecological restoration initiative at Sitio Luciana, Brazil. The simulations closely reproduced the observed trajectories, underscoring the critical role of local farmers' adaptive management in mediating ecological succession and promoting the coexistence of diversified land uses, in synergy with food production. Our findings prove that incorporating local ecological knowledge within a stock-flow model is key to capturing the complex interplay between local land restoration and sustainable food production, providing a robust alternative to prevailing agribusiness models and offering valuable conceptual insights for guiding sustainable land-use strategies and policies.

Our results offer meaningful insight into the modelling of agroecological and land systems, particularly referring to land restoration processes. The model of land use dynamics at Sitio Luciana well balanced accuracy in reproducing historical changes in time of land areas and use of systems theory to uncover the core feedback and nonlinear mechanisms that drove land-use change at the site. The study gave a good example of the application of systems theory in land and agroecological systems modeling able to offer novel perspectives to build on existing knowledge in these field. The model not only accurately reproduced the temporal dynamics of observed land-use but also aided in identifying the key processes in agroecosystem development and the role of farmers in balancing productive needs and biodiversity, linking their adaptive management with Thermodynamics.

The energy system language and modelling tools – as originally formalized by H.T. Odum – proved their outstanding suitability to model agroecological land systems. As most models in land and agricultural sciences are still rooted in detailed biophysical, crop or economical mechanics, with only limited attention to higher-level system structure, thermodynamic principles and local knowledge forms, our modelling approach inherited from seminal works in ecosystems ecology and non-equilibrium thermodynamics is alternative to existing ones. It offers a physically grounded, stock-flow language that embeds biotic activity, human work, material and energetic constraints to build minimal nonlinear models that balance accuracy in reproducing observations, model complexity, ability to advance theoretical insight, and to include local knowledge in the modeling process. This work ultimately contributes to enlarging the range of applications of energy system theory besides the evaluation of the sustainability of agricultural productions, supply chains and food systems, thus opening a new path for the development of symbolic and computational models to study the temporal dynamics of agroecological and land systems. In this perspective, future works might address landscape, regional and global scale analysis of land systems focusing on modeling agroecological scenarios – including human work and local ecological knowledge – in the light of thermodynamic principles.

CRediT authorship contribution statement

Luigi Conte: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Federico Surra:** Writing – review & editing, Visualization, Formal analysis. **Sebastiano Favarin:** Writing – review & editing, Visualization, Data curation. **Vito Comar:** Writing –

review & editing, Supervision, Formal analysis. **Francesco Gonella:** Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

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

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Data availability

All data supporting the findings of this study are available within the article.

References

Abrantes, N., Pereira, R., Gonçalves, F., 2010. Occurrence of pesticides in water, sediments, and fish tissues in a lake surrounded by agricultural lands: concerning risks to humans and ecological receptors. Water Air. Soil. Pollut. 212 (1–4), 77–88. https://doi.org/10.1007/s11270-010-0323-2.

Albuquerque, A.F., Ribeiro, J.S., Kummrow, F., Nogueira, A.J.A., Montagner, C.C., Umbuzeiro, G.A., 2016. Pesticides in Brazilian freshwaters: a critical review. Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 18 (7), 779–787. https://doi.org/10.1039/c6em00268d.

Altieri, M.A., Nicholls, C.I., de Molina, M.G., Rojas, A.S., 2024a. Landscape agroecology: methodologies and applications for the design of sustainable agroecosystems. Land. (Basel) 13 (11), 1746. https://doi.org/10.3390/LAND13111746.

Altieri, M.A., Nicholls, C.I., Dinelli, G., Negri, L., 2024b. Towards an agroecological approach to crop health: reducing pest incidence through synergies between plant diversity and soil microbial ecology. Npj Sustain. Agricult. 2 (1), 1–6. https://doi.org/10.1038/s44264-024-00016-2.

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. In: Agronomy For Sustainable Development, 35. Springer-Verlag France, pp. 869–890. https://doi.org/10.1007/s13593-015-0285-2.

Altieri, M.A., Toledo, V.M., 2005. Natural resource management among small-scale farmers in semi-arid lands: building on traditional knowledge and agroecology. In Article in Annals of Arid Zone. https://www.researchgate.net/publication/267850766.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., de Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22 (6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Arneth, A., Olsson, L., Cowie, A., Erb, K.-H., Hurlbert, M., Kurz, W.A., Mirzabaev, A., Rounsevell, M.D.A., 2021. Restoring degraded lands. Ann. Rev. Environ. Resour. Restor. Degraded. Land. https://doi.org/10.1146/annurev-environ-012320.

Artuzo, F.D., Allegretti, G., Santos, O.I.B., da Silva, L.X., Talamini, E., 2021. Emergy unsustainability index for agricultural systems assessment: a proposal based on the laws of thermodynamics. Sci. Total Environ. 759. https://doi.org/10.1016/j.scitotenv.2020.143524.

Benítez, M., Rosell, J.A., Perfecto, I., 2022. Editorial: mathematical modeling and Complex systems in agroecology. Front. Sustain. Food Syst. 6, 829551. https://doi.org/10.3389/FSUFS.2022.829551/BIBTEX.

Berkes, F., Folke, C., Colding, J. (Eds.), 2000. Linking Social and Ecological systems: Management Practices and Social Mechanisms For Building Resilience. Cambridge University Press.

Bezner Kerr, R., Postigo, J.C., Smith, P., Cowie, A., Singh, P.K., Rivera-Ferre, M., Tirado-von der Pahlen, M.C., Campbell, D., Neufeldt, H., 2023. Agroecology as a transformative approach to tackle climatic, food, and ecosystemic crises. In: Current Opinion in Environmental Sustainability, 62. Elsevier B.V. https://doi.org/10.1016/j.cosust.2023.101275.

Blagitz, M., Botosso, P.C., Longhi-Santos, T., Bianchini, E., 2019. Tree rings in tree species of a seasonal semi-deciduous forest in southern Brazil: wood anatomical markers, annual formation and radial growth dynamic. Dendrochronologia (Verona) 55, 93–104. https://doi.org/10.1016/J.DENDRO.2019.04.006.

Bonini, I., Hur Marimon-Junior, B., Matricardi, E., Phillips, O., Petter, F., Oliveira, B., Marimon, B.S., 2018. Collapse of ecosystem carbon stocks due to forest conversion to soybean plantations at the Amazon-Cerrado transition. For. Ecol. Manage 414, 64–73. https://doi.org/10.1016/J.FORECO.2018.01.038.

Brainich, A., Erpul, G., Huang, Y., Roué, M., Guan Saw, L., Zabid Oglu Allahverdiyev, R., & Goodman Mketeni, F. (2018). *The assessment report on land degradation and restoration 2 summary for policymakers of THE Ipbes assessment report on land degradation and restoration*. www.ipbes.net.

Brown, M.T., Odum, H.T., Jorgensen, S.E., 2004. Energy hierarchy and transformity in the universe. Ecol. Modell. 178 (1–2), 17–28. https://doi.org/10.1016/j.ecolmodel.2003.12.002.

Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9.

Caporali, F., 2015. History and development of agroecology and theory of agroecosystems. Law Agroecol.: A Transdiscipl. Dialog. 3–29. https://doi.org/10.1007/978-3-662-46617-9_1.

Chen, M., Samat, N., Maghsoodi Tilaki, M.J., Duan, L., 2025. Land use/cover change simulation research: a system literature review based on bibliometric analyses. Ecol. Indic. 170, 112991. https://doi.org/10.1016/J.ECOLIND.2024.112991.

Comar, V., 2004. Applying HT Odum's concepts and principles in developing countries. Ecol. Modell. 178 (1–2), 171–175. https://doi.org/10.1016/j.ecolmodel.2003.12.011.

Comar, V., Ortega Rodriguez, E., Maria, J., & Ferraz, G. (2019). *Etnodesenvolvimento em terras indígenas: uma Abordagem Integradora*. https://www.ufgd.edu.br/setor/editora/catalogo.

Conte, L., Renner, M., Brando, P., Oliveira dos Santos, C., Silvério, D., Kolle, O., Kleidon, A., 2019. Effects of tropical deforestation on surface energy balance partitioning in southeastern Amazonia estimated from maximum convective power. Geophys. Res. Lett. 46 (8), 4396–4403. https://doi.org/10.1029/2018GL081625.

Conte, L., Gonella, F., Giansanti, A., Kleidon, A., Romano, A., 2023. Modeling cell populations metabolism and competition under maximum power constraints. PLoS. Comput. Biol. 19 (11), e1011607. https://doi.org/10.1371/JOURNAL.PCBI.1011607.

Conte, L., Prakofjewa, J., Floridia, T., Stocco, A., Comar, V., Gonella, F., Lo Cascio, M., 2024. Learning from farmers on potentials and limits for an agroecological transition: a participatory action research in Western Sicily. Front. Environ. Sci. 12, 1347915. https://doi.org/10.3389/FENVS.2024.1347915/BIBTEX.

Conte, L., 2025. Land use dynamics at Sitio Luciana (Dourados, Mato Grosso do Sul, Brazil). Zenodo. https://doi.org/10.5281/zenodo.15242328.

Cristiano, S., 2021. Organic vegetables from community-supported agriculture in Italy: emergy assessment and potential for sustainable, just, and resilient urban-rural local food production. J. Clean. Prod. 292. https://doi.org/10.1016/j.jclepro.2021.126015.

Di Paola, A., Valentini, R., Santini, M., 2016. An overview of available crop growth and yield models for studies and assessments in agriculture. J. Sci. Food Agric. 96 (3), 709–714. https://doi.org/10.1002/JSFA.7359.

Dittmer, K.M., Rose, S., Snapp, S.S., Kebede, Y., Brickman, S., Shelton, S., Egler, C., Stier, M., Wollenberg, E., 2023. Agroecology can promote climate change adaptation outcomes without compromising yield In smallholder systems. Environ. Manage 72 (2), 333–342. https://doi.org/10.1007/s00267-023-01816-x.

Dumont, A.M., Wartenberg, A.C., Baret, P.V., 2021. Bridging the gap between the agroecological ideal and its implementation into practice. A review. Agron. Sustain. Dev. 41 (3), 1–17. https://doi.org/10.1007/S13593-021-00666-3/FIGURES/4.

Ellis, E.C., Gauthier, N., Goldewijk, K.K., Bird, R.B., Boivin, N., Díaz, S., Fuller, D.Q., Gill, J.L., Kaplan, J.O., Kingston, N., Locke, H., McMichael, C.N.H., Ranco, D., Rick, T.C., Rebecca Shaw, M., Stephens, L., Svenning, J.C., Watson, J.E.M, 2021. People have shaped most of terrestrial nature for at least 12,000 years. Proc. Natl. Acad. Sci. U.S.A. 118 (17), e2023483118. https://doi.org/10.1073/PNAS.2023483118/SUPPL_FILE/PNAS.2023483118.SAPP.PDF.

Ellis, E.C., Goldewijk, K.K., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. Glob. Ecol. Biogeogr. 19 (5), 589–606. https://doi.org/10.1111/J.1466-8238.2010.00540.X.

Feng, S., Zhao, W., Zhan, T., Yan, Y., Pereira, P., 2022. Land degradation neutrality: a review of progress and perspectives. Ecol. Indic. 144, 109530. https://doi.org/10.1016/J.ECOLIND.2022.109530.

Filho, J.T., Barbosa, G.M., de, C., Ribon, A.A., 2010. Physical properties of dystrophic Red Latosol (Oxisol) under different agricultural uses. Revista Brasileira de Ciência Do Solo 34 (3), 925–933. https://doi.org/10.1590/S0100-06832010000300034.

Floridia, T., Prakofjewa, J., Conte, L., Mattalia, G., Kalle, R., Sõukand, R., 2024. Small farmers' Agricultural practices and adaptation strategies to perceived soil changes in the lagoon of Venice, Italy. Agriculture 14 (11), 2068. https://doi.org/10.3390/agriculture14112068.

Garcia-Polo, J., Falkowski, T.B., Mokashi, S.A., Law, E.P., Fix, A.J., Diemont, S.A.W., 2021. Restoring ecosystems and eating them too: guidance from agroecology for sustainability. Restor. Ecol. 29 (8). https://doi.org/10.1111/rec.13509.

Gavasso-Rita, Y.L., Papalexiou, S.M., Li, Y., Elshorbagy, A., Li, Z., Schuster-Wallace, C., 2024. Crop models and their use in assessing crop production and food security: a review. Food Energy Secur. 13 (1), e503. https://doi.org/10.1002/FES3.503.

Gliessman, S., 2016. Transforming food systems with agroecology. *Agroecology and Sustainable Food Systems* 40 (3), 187–189. https://doi.org/10.1080/21683565.2015.1130765.

Hall, C.A.S., McWhirter, T., 2023. Maximum power in evolution, ecology and economics. Phil. Trans. R. Soc. A 381. https://doi.org/10.1098/rsta.2022.0290.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu Rev. Ecol. Syst. 4 (1), 1–23. https://doi.org/10.1146/ANNUREV.ES.04.110173.000245.

Huang, S.L., Kao, W.C., Lee, C.L., 2007. Energetic mechanisms and development of an urban landscape system. Ecol. Modell. 201 (3–4), 495–506. https://doi.org/10.1016/J.ECOLMODEL.2006.10.019.

Jeanneret, P., Aviron, S., Alignier, A., Lavigne, C., Helfenstein, J., Herzog, F., Kay, S., Petit, S., 2021. Agroecology landscapes. Landsc. Ecol. 36 (8), 2235–2257. https://doi.org/10.1007/S10980-021-01248-0.

Kleidon, A., 2010. Life, hierarchy, and the thermodynamic machinery of planet Earth. Phys. Life Rev. 7 (4), 424–460. https://doi.org/10.1016/j.plrev.2010.10.002.

Kleidon, A., 2016. Thermodynamic Foundations of the Earth system. Cambridge University Press.

Kremen, C., Merenlender, A.M., 2018. Landscapes that work for biodiversity and people. Science (1979) 362 (6412). https://doi.org/10.1126/SCIENCE.AAU6020.

La Rosa, A.D., Siracusa, G., Cavallaro, R., 2008. Emergy evaluation of Sicilian red orange production. A comparison between organic and conventional farming. J. Clean. Prod. 16 (17), 1907–1914. https://doi.org/10.1016/j.jclepro.2008.01.003.

Lawrence, D.M., Hurtt, G.C., Arneth, A., Brovkin, V., Calvin, K.V., Jones, A.D., Jones, C. D., Lawrence, P.J., De Noblet-Ducoudré, N., Pongratz, J., Seneviratne, S.I., Shevliakova, E., 2016. The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design. Geosci. Model. Dev. 9, 2973–2998. https://doi.org/10.5194/gmd-9-2973-2016.

Leeprakton LI, T.P., Berger, F., van Aarde, R., World Alumina, A., Morris, J.P., Brainich, A., Erpul, G., Huang, Y., Roué, M., Guan Saw, L., Zabid Oglu Allahverdiyev, R., Andreas Baste, I., Goodman Mketeni, F., 2018. The assessment report on land degradation and restoration 2 THE Ipbes assessment report on land degradation and restoration. In: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 744. www.ipbes.net.

Levin, S.A., 1998. Ecosystems and the biosphere as complex adaptive systems. Ecosystems 1 (5), 431–436. https://doi.org/10.1007/S100219900037.

López-García, D., Cuéllar-Padilla, M., de Azevedo Olival, A., Laranjeira, N.P., Méndez, V. E., Peredo y Parada, S., Barbosa, C.A., Barrera Salas, C., Caswell, M., Cohen, R., Correro-Humanes, A., García-García, V., Gliessman, S.R., Pomar-León, A., Sastre-Morató, A., Tendero-Acín, G., 2021. Building agroecology with people. Challenges of participatory methods to deepen on the agroecological transition in different contexts. J. Rural. Stud. 83, 257–267. https://doi.org/10.1016/j.jrurstud.2021.02.003.

Lopez-Ridaura, S., 2022. Agroecology and systems analysis for Sustainable agriculture. J. Rur. Probl. 58 (1), 31–35. https://doi.org/10.7310/arfe.58.31.

Lotka, A.J., 1922. Contribution to the energetics of evolution. Proceed. Natl. Acad. Sci. 8 (6), 147–151. https://doi.org/10.1073/pnas.8.6.147.

Marull, J., Herrando, S., Brotons, L., Melero, Y., Pino, J., Cattaneo, C., Pons, M., Llobet, J., Tello, E., 2019. Building on Margalef: testing the links between landscape structure, energy and information flows driven by farming and biodiversity. Sci. Total Environ. 674, 603–614. https://doi.org/10.1016/J.SCITOTENV.2019.04.129.

Moreira, J.C., Peres, F., Simões, A.C., Pignati, W.A., Dores, E., de, C., Vieira, S.N., Strüssmann, C., Mott, T., 2012. Contaminação de águas superficiais e de chuva por agrotóxicos em uma região do estado do Mato Grosso. Ciência Saúde Coletiva 17 (6), 1557–1568. https://doi.org/10.1590/s1413-81232012000600019.

Nicholls, C.I., Altieri, M.A., 2018. Pathways for the amplification of agroecology. In: Agroecology and Sustainable Food Systems, 42. Taylor and Francis Inc, pp. 1170–1193. https://doi.org/10.1080/21683565.2018.1499578.

Nicholls, C.I., Parrella, M., Altieri, M.A., 2001. The effects of a vegetational corridor on the abundance and dispersal of insect biodiversity within a northern California organic vineyard. Landsc. Ecol. 16 (2), 133–146. https://doi.org/10.1023/A:1011128222867.

Noszczyk, T., 2019. A review of approaches to land use changes modeling. Hum. Ecolog. Risk Assessm.: Int. J. 25 (6), 1377–1405. https://doi.org/10.1080/10807039.2018.1468994.

Odum, H.T., Pinkerton, R.C., 1955. Time'S speed regulator: the optimum efficiency for maximum power output in physical and biological systems. Am. Sci. 43 (2). https://www.jstor.org/stable/27826618.

Odum, E.P., 1969. The strategy of ecosystem development. Science (1979) 164 (3877), 262–270. https://doi.org/10.1126/SCIENCE.164.3877.262.

Odum, H.T., 1971. Environment, Power, and Society for the Twenty-First Century: The Hierarchy of Energy. John Wiley & Sons.

Odum, H.T., 1973. Energy, ecology, and economics. Ambio 2 (6). *Energy in Society: A Special Issue*.

Odum, H.T., 1988. Self-organization, transformity, and information. Science (1979) 242 (4882), 1132–1139. https://doi.org/10.1126/SCIENCE.242.4882.1132.

Odum, H.T., Hall, C.A.S., 1995. Maximum power: the Ideas and Applications of H.T. Odum. University Press of Colorado.

Odum, H.T., 1996. Environmental Accounting: EMERGY and Environmental Decision Making. Wiley, New York.

Odum, H.T., Odum, E.C., 2000. Modeling For All Scales: An Introduction to System Simulation. Academic Press.

Ong, T.W.Y., Liao, W., 2020. Agroecological transitions: a mathematical perspective on a transdisciplinary problem. Front. Sustain. Food Syst. 4. https://doi.org/10.3389/FSUFS.2020.00091.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. Ann. Assoc. Am. Geogr. 93 (2), 314–337. https://doi.org/10.1111/1467-8306.9302004.

Pashkevich, M.D., d'Albertas, F., Aryawan, A.A.K., Buchori, D., Caliman, J.P., Chaves, A. D.G., Hidayat, P., Kreft, H., Naim, M., Razafimahatratra, A., Turner, E.C., Zemp, D. C., Luke, S.H., 2022. Nine actions to successfully restore tropical agroecosystems. Trend. Ecol. Evolut. 37 (11), 963–975. https://doi.org/10.1016/J.TREE.2022.07.007/ASSET/F2E138DE-3070-43F2-A9FC-B9164CBACB90/MAIN.ASSETS/B3.JPG.

Pengue, W.A., 2005. Transgenic crops in Argentina: the ecological and social debt. Bull. Sci. Technol. Soc. 25 (4), 314–322. https://doi.org/10.1177/0270467605277290.

Prăvălie, R., 2021. Exploring the multiple land degradation pathways across the planet. Earth. Sci. Rev. 220, 103689. https://doi.org/10.1016/J.EARSCIREV.2021.103689.

Priyadarshana, T.S., Martin, E.A., Sirami, C., Woodcock, B.A., Goodale, E., Martínez-Núñez, C., Lee, M.B., Pagani-Núñez, E., Raderschall, C.A., Brotons, L., Rege, A., Ouin, A., Tscharntke, T., Slade, E.M., 2024. Crop and landscape heterogeneity increase biodiversity in agricultural landscapes: a global review and meta-analysis. Ecol. Lett. 27 (3). https://doi.org/10.1111/ELE.14412.

Redlich, S., Martin, E.A., Steffan-Dewenter, I., 2018. Landscape-level crop diversity benefits biological pest control. J. Appl. Ecol. 55 (5), 2419–2428. https://doi.org/10.1111/1365-2664.13126.

Ribeiro, M.C., Metzger, J.P., Martensen, A.C., Ponzoni, F.J., Hirota, M.M., 2009. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biol. Conserv. 142 (6), 1141–1153. https://doi.org/10.1016/J.BIOCON.2009.02.021.

Rico, P., Harris, N.L., Hall, C.A.S., Lugo, A.E., 2013. A test of the maximum power hypothesis along an elevational gradient in the Luquillo Mountains of Puerto Rico. Bulletins 54, 233–244. https://doi.org/10.2307/26796817.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.

Rosset, P.M., Barbosa, L.P., Val, V., McCune, N., 2022. Critical Latin American agroecology as a regionalism from below. Globalizations 19 (4), 635–652. https://doi.org/10.1080/14747731.2021.1923353.

Rounsevell, M.D.A., Pedroli, B., Erb, K.H., Gramberger, M., Busck, A.G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M., Lotze-Campen, H., Metzger, M.J., Murray-Rust, D., Popp, A., Pérez-Soba, M., Reenberg, A., Vadineanu, A., Verburg, P.H., Wolfslehner, B., 2012. Challenges for land system science. Land. Use Policy 29 (4), 899–910. https://doi.org/10.1016/J.LANDUSEPOL.2012.01.007.

Shah, S.M., Liu, G., Yang, Q., Wang, X., Casazza, M., Agostinho, F., Lombardi, G.V., Giannetti, B.F., 2019. Emergy-based valuation of agriculture ecosystem services and dis-services. J. Clean. Prod. 239, 118019. https://doi.org/10.1016/J.JCLEPRO.2019.118019.

Song, X.P., Hansen, M.C., Potapov, P., Adusei, B., Pickering, J., Adami, M., Lima, A., Zalles, V., Stehman, S.V., Di Bella, C.M., Conde, M.C., Copati, E.J., Fernandes, L.B., Hernandez-Serna, A., Jantz, S.M., Pickens, A.H., Turubanova, S., Tyukavina, A., 2021. Massive soybean expansion in South America since 2000 and implications for conservation. Nat. Sustain. 4 (9), 784–792. https://doi.org/10.1038/s41893-021-00729-z.

Souza-Alonso, P., Saiz, G., García, R.A., Pauchard, A., Ferreira, A., Merino, A., 2022. Post-fire ecological restoration in Latin American forest ecosystems: insights and lessons from the last two decades. For. Ecol. Manage 509, 120083. https://doi.org/10.1016/J.FORECO.2022.120083.

Spagnolo, S., Chinellato, G., Cristiano, S., Zucaro, A., Gonella, F., 2020. Sustainability assessment of bioenergy at different scales: an emergy analysis of biogas power production. J. Clean. Prod. 277. https://doi.org/10.1016/j.jclepro.2020.124038.

Steward, C., 2007. From colonization to "environmental soy": a case study of environmental and socio-economic valuation in the Amazon soy frontier. Agric. Human. Value. 24 (1), 107–122. https://doi.org/10.1007/S10460-006-9030-4/METRICS.

Šūmane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., des Ios Rios, I., Rivera, M., Chebach, T., Ashkenazy, A., 2018. Local and farmers' knowledge matters! how integrating informal and formal knowledge enhances sustainable and resilient agriculture. J. Rural. Stud. 59, 232–241. https://doi.org/10.1016/j.jrurstud.2017.01.020.

Taylor, C.A., Rising, J., 2021. Tipping point dynamics in global land use. Environ. Res. Lett. 16 (12). https://doi.org/10.1088/1748-9326/ac3c6d.

Tilley, D., 2015. Transformity dynamics related to maximum power for improved emergy yield estimations. Ecol. Modell. 315, 96–107. https://doi.org/10.1016/j.ecolmodel.2014.10.035.

Tixier, P., Duyck, P.F., Côte, F.X., Caron-Lormier, G., Malézieux, E., 2013. Food web-based simulation for agroecology. Agron. Sustain. Dev. 33 (4), 663–670. https://doi.org/10.1007/S13593-013-0139-8/FIGURES/3.

Vandermeer, J., 2020. Confronting complexity in agroecology: simple models from Turing to Simon. Front. Sustain. Food Syst. 4. https://doi.org/10.3389/FSUFS.2020.00095/FULL.

Verburg, P.H., Alexander, P., Evans, T., Magliocca, N.R., Malek, Z., Rounsevell, M.D.A, van Vliet, J., 2019. Beyond land cover change: towards a new generation of land use models. Curr. Opin. Environ. Sustain. 38, 77–85. https://doi.org/10.1016/J.COSUST.2019.05.002.

Verburg, P.H., Crossman, N., Ellis, E.C., Heinimann, A., Hostert, P., Mertz, O., Nagendra, H., Sikor, T., Erb, K.H., Golubiewski, N., Grau, R., Grove, M., Konaté, S., Meyfroidt, P., Parker, D.C., Chowdhury, R.R., Shibata, H., Thomson, A., Zhen, L., 2015. Land system science and sustainable development of the earth system: a global land project perspective. Anthropocene 12, 29–41. https://doi.org/10.1016/J.ANCENE.2015.09.004.

Vieira, D.L.M., Holl, K.D., Peneireiro, F.M., 2009. Agro-successional restoration as a strategy to facilitate tropical forest recovery. Restor. Ecol. 17 (4), 451–459. https://doi.org/10.1111/J.1526-100X.2009.00570.X.

Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, Adaptability and Transformability in Social-ecological Systems, 9. https://about.jstor.org/terms.

Walters, J.P., Archer, D.W., Sassenrath, G.F., Hendrickson, J.R., Hanson, J.D., Halloran, J.M., Vadas, P., Alarcon, V.J., 2016. Exploring agricultural production systems and their fundamental components with system dynamics modelling. Ecol. Modell. 333, 51–65. https://doi.org/10.1016/j.ecolmodel.2016.04.015.

Watanabe, M.D.B., Ortega, E., 2014. Dynamic emergy accounting of water and carbon ecosystem services: a model to simulate the impacts of land-use change. Ecol. Modell. 271, 113–131. https://doi.org/10.1016/j.ecolmodel.2013.03.006.

Wolford, W., 2008. Environmental justice and the construction of scale in Brazilian agriculture. Soc. Nat. Resour. 21 (7), 641–655. https://doi.org/10.1080/08941920802096432.

Wright, C., Ostergård, H., 2016. Renewability and emergy footprint at different spatial scales for innovative food systems in Europe. Ecol. Indic. 62, 220–227. https://doi.org/10.1016/J.ECOLIND.2015.10.042.

Zhang, L.X., Song, B., Chen, B., 2012. Emergy-based analysis of four farming systems: insight into agricultural diversification in rural China. J. Clean. Prod. 28, 33–44. https://doi.org/10.1016/J.JCLEPRO.2011.10.042.