Some slide-cascades in social-ecological systems viewed by spatially explicit and multi-scale models

Authors

- Maxime Leloup, MPI EVA, HBEC Dept., Leipzig, Germany, maximeleloup61@gmail.com, https://orcid.org/0000-0003-0462-6505
- Maximilien Cosme, CIRAD, UMR AMAP, Montpellier, France, maximilien.cosme@cirad.fr, https://orcid.org/0000-0001-8353-5104
- Franck Pommereau, Université Paris-Saclay, Univ Evry, IBISC, 91020, Evry-Courcouronnes, France,franck.pommereau@univ-evry.fr, https://orcid.org/0000-0002-9959-3699
- Cédric Gaucherel, INRAE, UMR AMAP, Montpellier, France, cedric.gaucherel@inrae.fr, https://orcid.org/0000-0002-4521-8914

Keywords: Burkina Faso; discrete-event system; Petri nets; food security; slide-cascade; decision maker; foresight; process-based model.

Abstract

Food security is a key aspect of a sustainable society, and some threats as climate change and food riots may unsettle any social-ecological system such as the Dano's region in Burkina Faso. Some facets of food security such as food production and food distribution are inherently spatial, and taking space into account may refine our region understanding. We developed both spatialized and non-spatialized discrete event models to address food security dynamics in the Dano social-ecological system. The comparison of these two models allowed estimating the influence of spatialization in modelling dynamics. Results showed that water cycle and soil components are critical features of the landscape's food security. Space refined the region's understanding in highlighting unexpected slide-cascades the system is exposed to and revealing high sensitivity of the region's food security to dam water presence. As food security spreading in space, to explicit spatial processes in models appears critical to get a proper understanding of most processes in social ecological systems.

Declarations

Funding

- SESASA project, fund n°727715 ERA-Net Cofund LEAP-Agri

- Max Planck Institute for Evolutionnary Anthropology, Human Behavior, Ecology and Culture department hosted and provided office and computer for Maxime Leloup's 2019 internship.

Conflict of interest / Competing interest

The authors declare no conflict of interest or competing interest.

Availability of data & material

Data & material that would be lacking in the article is fully available on request.

Code availability

Maxime Leloup's code that would be lacking in the article is fully available on request.

Author's contributions

- Maxime Leloup is the main contributor of this work. He developped reflexions, models, analysis, figures and wrote the article.

- Maximilien Cosme supervised the whole work and contributed to reflexions and writing.

- Franck Pommereau contributed to Deer semantic development, and designed & developped Python / Jupyter server.

- Cédric Gaucherel supervised the whole project to stay on course, and contributed to reflexions, Python / Jupyter server design and article writing.

Acknowledgment

We want to specially thank Natalie Dubus, Richard McElreath and Julia Cissewski for the particular commitment they showed to make Maxime Leloup's 2019 internship possible. We also want to thank Christine Fürst, Martin Schultze and their German and African colleagues. Maxime Leloup thanks Cédric Gaucherel for the research freedom he've been offered, Franck Pommereau for guiding his Python vagrancy and getting ahead of Deer needs, Maximilien Cosme for being so enthusiastic, Richard McElreath for science insights and department hospitality, intern colleagues for their conviviality, Philippe, Olivia & Malo for hosting some wanderings, Nathalie & Miléna for co-organizing them, Lucie Benoit & his supportive Lpz friends who will recognize themselves, his parents & sisters for granting him unconditional support and comprehension. They all made this work possible.

Some slide-cascades in social-ecological systems viewed by spatially explicit and multi-scale models

Abstract

Food security is a key aspect of a sustainable society, and some threats as climate change and food riots may unsettle any social-ecological system such as the Dano's region in Burkina Faso. Some facets of food security such as food production and food distribution are inherently spatial, and taking space into account may refine our region understanding. We developed both spatialized and non-spatialized discrete event models to address food security dynamics in the Dano social-ecological system. The comparison of these two models allowed estimating the influence of spatialization in modelling dynamics. Results showed that water cycle and soil components are critical features of the landscape's food security. Space refined the region's understanding in highlighting unexpected slide-cascades the system is exposed to and revealing high sensitivity of the region's food security to dam water presence. As food security spreading in space, to explicit spatial processes in models appears critical to get a proper understanding of most processes in social ecological systems.

1) Introduction

Food system is a critical criterion for a sustainable society, and food security evaluates how sensitive and robust are different food systems. The food security framework has been developed long time ago (United Nations, 1975 ; Peng, Berry 2019 ; Anderson 2019), and requires at least a viable food production and food distribution network (Peng, Berry 2019). Food security spreads in space, and both food production and food distribution are today and will become increasingly sensitive to climate change, such as rainfall pattern change, as well as to human activities. For example, livestock herding is impacted by higher occurrence of extreme events (Mbow et al. 2020), while human conflicts combine with climate change to create extreme hunger hotspots, as in West African Sahel (OXFAM 2021). Lastly, these observations are spatially distributed and mediated, and thus require an explicit consideration of their spatial aspects, as all these concepts and threats spread out in definite landscape (Mbow et al. 2014). In this study, we investigated how spatialized modelling can grasp the influence of climate change on food security in a social-ecological system (SES).

The SES framework establishes an integrated approach able to investigate how climate change and human conflicts may combine for disturbing food security (Cherkasskii 1988 ; Colding, Barthel 2019 ; Wittman et al. 2017). In this context, climate modelling already raise awareness answers about future climate change (Mbow et al. 2020), while other models raise awareness for both social ecological systems and food security, including in a climate change scenario (Fujimori et al. 2019). Hence, environmental sciences use various formal model types for understanding their studied systems and anticipate their fates (Goulart et al. 2013 ; Ortiz et al. 2013 ; Magliocca et al. 2013 ; Motesharrei et al. 2014 ; Gaucherel, Pommereau 2019). Here, we will consider *models* defined as formal models, and *systems* defined as the field reality they represent, perceived through a systemic approach (Garbolino et al. 2019).

The studied SES is the Dano catchment (126 km^2) in the South West region of Burkina Faso, West Africa. This landscape is a densely populated and impacted West African Sudanian savanna, next to Sahel (Op de Hipt et al. 2017). This region summarizes global stakes: climate change, land and soil degradation, forecasted water shortage, decreasing agricultural productivity, and increased potential food insecurity (Yaro, Hesselberg 2016 ; Eze et al. 2014 ; Sandwidi 2007 ; Callo-Concha et al. 2012). This region provides the relevant context to study food security at stake, due to it is low adaptive capacity to climate change (Yira et al. 2017).

We aim at modelling the Dano SES to understand and anticipate its possible fates. Ecology has long used models, such as the Lokta-Volterra predator prey model representing the population system with quantitative differential equations (Volterra 1926 ; Motesharrei et al. 2014). Ecology also adopted agent-based models (ABM), and Social-ecological research went further in adopting them (Colon et al. 2015 ; Dou et al. 2020). ABM disaggregates system components in populations of interacting lower level entities (e.g. individuals or households). In doing so, ABMs aim to explain large scale, emergent phenomena from local interactions (Grimm, Railsback 2005). Other ABMs represent human-environment interaction such as the pasture-forest-shepherds one, managing to illustrate an individual–society retro-action loop in which the constraint on individuals is spatial and multi-scale (Bonnefoy et al. 2001).

As any process distributes in space, some of them may be ignored or poorly represented by a non-spatial model, missing some key resulting patterns. Various models have been developed in environmental sciences to address how and when spatial configuration can be of significant influence. The first approach is pattern oriented, focusing on display of land uses and land covers in space (Inkoom et al. 2018 ; Koo et al. 2018 ; 2019 ; Verburg et al. 2002 ; Gaucherel et al. 2012). The second approach is process oriented, focusing on individual's behaviors and their potentially emergent effects (Bonnefoy et al. 2001 ; Kniveton et al. 2011). Finally, some approaches try to combine both previous ones (Castella, Verburg 2007).

Discrete event models provide a complementary point of view to model such complex social ecological systems. They allow a qualitative and integrated approach (Mao et al. 2021), more intuitive to the modeler than differential equations. Unlike ABMs, they also allow exploring all potential trajectories of a system (i.e. successions of states) and are sometimes called possibilistic models (Mao et al. 2021 ; Gaucherel et al. 2012). Discrete event models thus complement traditional models and can be a preliminary heuristic step before focusing on quantitative and fine grain differential equations. In addition, discrete event models can also cope with space although some difficulties may arise here too due to upscaling model inputs (Verburg et al. 2002 ; Gaucherel et al. 2012).

The objective of this work is to address social-ecological questions using discrete event, process oriented and spatially explicit models. Our main question focuses on food security issues in Southwest Burkina Faso, where climate change is expected to threaten food security (Yaro, Hesselberg 2016). We will address the following questions: (Q1) Does climate change (here, drought and violent rainfall events) impact food security, and how? And (Q2) How does space mediate these impacts? We hypothesize that: (H1) Food security is threatened by social and ecological processes: mainly violent events, soil fertility loss and water supply (Callo-Concha et al. 2012 ; Peng, Berry 2019 ; Anderson 2019), and (H2) Spatial structure affects food security through functional complementarity between spatial units. In particular some landscape effects will occur, in which food security can deconstruct or reconstruct step by step. Finally, we discuss the importance of considering space in anticipating food security issues.

2) Materials and Methods

2.1) Study site

The study focuses on a subpart of the Dano's watershed around the Moutori Dam (11° 08′ 38″ N, 3° 03′ 43″ W), located in Burkina Faso, West Africa (Fig. 1a-b). This area is a climate change hotspot subject to the African Monsoon (Yaro, Hesselberg 2016 ; Callo-Concha et al. 2012). Rainfall patterns are already subject to high intra- and inter-annual variabilities, varying from droughts to high intensity rains (Yira et al. 2017). Some dams have been built in the country to mitigate induced seasonal low water availability (Kabe Kagne 2009 ; Dreyer Stiftung 2019). Groundwater potentials have been evaluated as moderate to good, but groundwater in similar nearby regions is already at risk in the near future (2030) (Martin 2006 ; Sandwidi 2007). The region is hilly with 295m mean elevation and 3.1% mean slope (Op de Hipt et al. 2017). Soil fertility is generally low, soils are sensitive to erosion and compaction (Callo-Concha et al. 2012), and uphill soils can degrade up to the formation of petroplinthite, an infertile iron-rich rock (Eze et al. 2014). Local potential vegetation mixes forests and savannas, which tend to shrink, gradually replaced by agricultural land uses such as rainfed crops and irrigated crops (Arbonnier 2004 ; Callo-Concha et al. 2012). Multi-functional trees are kept in the well-known African agroforestry park (Arbonnier 2004). The Dano landscape is a stopover in seasonal livestock migrations further north and further south (Callo-Concha et al. 2012 ; Pale 2018 ; Greenhough 2016).

Local population mainly includes sedentary farmers (90%), urban people (10%) and seasonal nomads with herds (Pale 2018). This population is growing at a fast pace, inducing reduced fallow and increasing conversion of forest and savannah to croplands (Pale 2018 ; Op de Hipt et al. 2017). Monetary economy entered deeply in people's life recently, including through agricultural loans and supply chain, supervised by NGOs such as Dreyer Stiftung and extension officers. Local markets provide foods produced in the region, the country or abroad (Kabe Kagne 2009 ; OEC 2017 ; Cosme 2019). These markets are still highly commodity dependent and thus sensitive to commodity price variations (OEC 2017 ; FAO 2019). In extreme cases, excessive food price inflation can lead to food riots (Bush 2010 ; Berazneva, Lee 2013). Livestock can also trigger conflicts, due to misconduct and/or water shortage (Pale et al. 2016 ; Abroulaye et al. 2015). And threatening terrorism in the north of Burkina Faso coming south could highly disturb local food security (Benedikter, Ouedraogo 2019 ; Cosme 2019).

We chose to divide the Dano landscape into five patches (Fig. 1b) according to several criteria such as the food security research questions and the specificities of existing activities. Water cycle, the main limiting factor in this SES, drove the intention to work at the watershed level. The need to develop the spatial model on a simplified landscape suggested limiting the number of patches to five. To shape food security (e.g. food production places, local market) and ecologically sounded patches (e.g. water resources, vegetation), the landscape has been divided into hills *h1* and *h2*, the Moutori Dam *d*, the downslope valley bottom *v* and the neighboring Dano city *c* (Fig. 1b). The time scale chosen in this model is long term (about 30 years), which allowed enough significant changes in the qualitative and discrete model to be represented, but intentionally avoided drastic transformations difficult to model such as humans and non-humans adaptive processes. To focus on long term dynamics, only inter-annual climate variations have been modeled. For example, occurrence of drought in the model represented recurrent droughts having a significant impact in the Dano SES.

2.2) Methods

2.2.1) The EDEN modeling framework

A model from the EDEN framework (Gaucherel, Pommereau 2019 ; Cosme et al. 2021) describing any SES uses a set of Boolean variables, an initial state, and a set of if-then rules describing successive changes in system state (Table S1). We represented the Dano landscape as an interaction graph, in which nodes and edges represent variables and their interactions, respectively (Fig. 1c, 2a-c). The model represents dynamics as sequences of discrete states and transitions. A state is a combination of all Boolean variables V_i, whether they are present V_i+ (sometimes written V_i in figures), or absent V_i- (often not written). Rules consist in two parts: the condition (if) and the realization (then). A condition specifies the value of some variables (e.g. if resources are present) triggering the realization (e.g. then humans are present, i.e. supposedly functionally present and potentially impacting the rest of the modeled SES). The model also includes priority rules (called constraints) to represent fast processes that *must* realize, whereas a rule *may* realize (Tables S1-4). Hence, a system state fulfilling the condition of a constraint is unrealistic from the model's point of view. From a given initial state and based on chosen rules, the model computes *all* reachable states (or state space). The resulting social-ecological dynamics are then represented by a state-transition graph (STG) made up of the system states (vertices) and transitions (edges) linking states through one process, unique or one among several possible. For interpretation purpose, the STG can be simplified into a realistic state transition graph displaying only realistic states and transitions (Fig. 2 d-e) (Cosme et al. 2021), after application of all constraints (the case of most STGs here, if unspecified).

2.2.1.1) The Deer spatial modeling

A Deer (Discrete Ecosystemic Evolution Rules) model lean on the EDEN model to build a spatially explicit version of the studied landscape in a twofold way: the generic part and the specific part of the SES. The generic part described how *any* considered landscape is functioning, while the specific part described *the* specific landscape studied, including this landscape's initial state. Firstly, the generic part of the model consisted in locations, considered as generic spatial units. Each location was considered as a sub-system with variables (e.g. resources in any local unit), rules and constraints (e.g. humans in the global region can deplete local resources). Secondly, each location was associated to specific spatial units (e.g. "any local region" becomes "this local region"). Specific spatial units then form a spatial graph (called specific landscape) whose edges correspond to their spatial relations (contiguity, slope and/or scale) (Fig. 1b, 2b). Each specific spatial unit is thus described by its neighboring relations and the initial values of its variables (Table S2-5). Thirdly, processes written in a given location use variables from his own location or from another location according to spatial (contiguity, slope or scale) and logical criteria (« there exists » or « for all »).

Deer generic processes were also translated in processes formulated with the specific part of the model (e.g. *this* given human population in *this* global region can deplete *this* local region resources). Hence, the Deer model translated in a complete EDEN model with specific variables, initial state and rules and constraints (Table S3). In this spatially explicit framework, system dynamics were still represented as a STG. However, in contrast with the non-spatial framework, events (i.e. process transitions) have a definite spatial extent.

Through an illustrating example, we presented and compared spatial and non-spatial models (Fig. 2, Tables S1-2). These toy-models represented a theoretical SES system highlighting the human-environment interaction, with the environment being perceived as resources to sustain the human population. This model was thus a simplified population - resource model, comparable to the Lotka-Volterra predator prey model. Both models described the same relations between humans (Hu) and environmental resources (E), first in a non-spatial model (Fig. 2a, Table S1). The spatial model introduced a landscape containing two locations, local and global locations. The spatial graph contained three spatial units, two local regions (r1 and r2) and a global one (g) (Fig. 2b). The non-spatial model variables were then attributed to the spatial model locations (S2). The environment (E) is located in each local region (r1 and r2), while humans (Hu) populate the global region (g) due to possible migrations between units (S2-3). In the non-spatial model, there was only one resource pool (E) (Table S1, Fig. 2a), while the spatial model included two localized distinct resource pools (ER1 and ER2) (Table S2, Fig. 2b-c). Then, each process was written in chosen locations, keeping separated inter- and intra-unit processes (S2). The models were built with a unique identifier (*ID*) for each process to link their meaning in both model outputs (S1-2-3, Fig. 2d-e). Some new spatially related processes may occur here, such as migrations of environmental resources between local regions (e.g. colonizing forest) or local niche constructions (S2). Both spatial and non-spatial model outputs had a common property: they form a set of mutually reachable states (Fig. 2d-e).

2.2.2) The Dano models and scenarios

For the Dano study site, pairs of models have been developed to then be compared: the non-spatial one and spatial one. The non-spatial model includes 19 variables, 26 constraints and 71 rules (S4). Variables were chosen to represent *a priori* key elements of the studied SES. They represented local climate, soils, water, flora, fauna and human society (Table 1). Some (control) variables cannot be influenced by others and are fixed, such as drought *Dr*, violent rainfall events *Rv*, rain randomization *Rr*, and external food commodity *Ec* coming from abroad. All models in this study focused on the poorest urban quintile of local population who are the most and first exposed to food insecurity (Peng, Berry 2019 ; Anderson 2019), thus food distribution and city market. Following the same workflow as for the toy-models, the non-spatial model was spatialized. The resulting spatial model has 31 variables, 163 rules and 47 constraints (S5). They were allocated to one (*e.g.* livestock *Li* in the global one) or several (*e.g.* Soil degradation *Sd* in hills or valley bottom) locations. Some variables, such as pest outbreaks or trees, were thus present in several specific spatial units (Fig. 1c), S5).

In parallel, two scenarii for the Dano site were developed to then be compared: a reference and a climate change scenario. The reference scenario displayed an initial state free of climate change and no external food commodity shortage (Callo-Concha et al. 2012). It describes the current situation of the studied SES (in 2019) without major disturbance (Table 1) (Callo-Concha et al. 2012 ; Cosme 2019). The climate change scenario simulated major climatic disturbances, with significant recurrence of both droughts and violent rains over the years. It represented a plausible forecasted evolution of the regional climate (Yira et al. 2017 ; Op de Hipt et al. 2017 ; Yaro, Hesselberg 2016 ; Pachauri et al. 2015) (Table 1). Consequently, four combinations of scenarii and spatial versions were investigated to address our questions: a reference scenario non-spatial model, a reference scenario spatial model, a climate change scenario non-spatial model, and a climate change scenario spatial model.

2.2.3) The Dano model analyses

The model outputs (STG) tend to have a high number (often millions) of SES states. Hence, interpreting them required using several techniques to summarize their information content, such as grouping states according to their composition (i.e. which variables are present/absent?) or dynamic relations (e.g. are they connected to each other?). An example of dynamically related states is a Strongly Connected Component (SCC, hereafter called “a stability”) is a set of mutually reachable states (Cosme et al. 2021 ; Gaucherel, Pommereau 2019). One such stability is represented in Fig.

2d-e. Also, a set of states leading to the same stabilities was called "a basin" (Bérenguier et al. 2013 ; Cosme et al. 2021). Based on stabilities and basins, the STG can be summarized into a hierarchical transition graph (HTG) whose nodes are basins and SCCs (Bérenguier et al. 2013). The HTG enables identifying irreversible transitions in system dynamics, which may be crucial events for ecosystem management. Social-ecological properties can be further examined in both STG and HTG (summarized in Suppl. Mat. S6). Food production *Prod* is one of these properties. A system state is labelled with food production when two among three food variables are present (rainfed crops *Rc*+, irrigated crops *Ic*+ and external commodities *Ec*+). Labels differed when studying a stability in a given STG, or when analyzing a diamond-shape HTG due to connected basins (S6).

We recall that a stability was a set of mutually reachable states, i.e. any change can be reversed, which is comparable to the definition of resilience (Gunderson, Holling 2002). Here, we say that a stability was food security compatible if *some* state in this stability simultaneously produced (labelled *Prod*) and distributed (labelled *Distr*) food (labelled *ProdDistr*, S6). Labels and model variables will always be written in *italics*. Labels used for STG stabilities used the Boolean operation "or" to point variables affecting food security *presence*. Presence of any reversible degradation was thus labelled *Degr1* (S6). System characteristic can then be directly read from the labels in STGs or extracted STG stabilities. To keep this labelled text simpler, the absence of a label will be crossed out (e.g. no food production is noted ~~*Prod*~~), and the Boolean « and » operation between two labels will be written by concatenation (e.g. *ProdDistr*). Clean food security was thus *ProdDistr*, degraded food security was *ProdDistrDegr1*, and food insecurity grouped all the other labels, written (~~*Prod*~~ or ~~*Distr*~~). The eight possible combinations of the labels presence or absence allowed displaying a summarized (Diop et al. 2019) and standardized representation of a stability named a « canonical graph ». Hence, reading the food security dynamics in a stability became systematic and made comparisons of stabilities easier. This food security dynamics can then be summarized according to different steps and drivers in potential trajectories in what we called the « monitoring scheme table » (Table S7). This table was thus highlighting food security early warning signals and early regenerating signals.

The analysis of diamond shape HTG focused on ecosystemic components affecting food security by a systematic *absence* in each stability or basin (using Boolean « and » operation), such as *no* food production *NoProd*, *no* food distribution *NoDistr* and reversible/irreversible degradations *Degr1* / *Ip*, *Aq* and their combination *Degr2* (S6). Hence, the focus differed from a single stability analysis, as labels featured only stabilities and basins in which food security is possible ~~*NoProdNoDistr*~~, or impossible: *NoProd*, *NoDistr* or *NoProdNoDistr*. They allowed displaying a standardized HTG representation, standardizing the reading of food security dynamics. These labels also allowed interpreting the beginning, intermediate, ending and largest stabilities of the whole state space, as well as focusing on key transitions and processes linking them.

2.2.4) Overall methodology

Finally, to highlight differences between spatial and non-spatial models, we compared the reference scenario and the climate change scenario with canonical graphs, monitoring scheme table and standardized HTG. Canonical graph allowed comparing food security dynamics between scenarios displaying a single stability with the largest stability found in a diamond-shape HTG scenario. The monitoring scheme table gave more details about food security dynamics in the canonical graphs of different scenarii, and spatial / non-spatial models (S7). This table highlighted key early warning and regeneration signals among processes and drivers involved in food insecurity (Peng, Berry 2019 ; Anderson 2019 ; Callo-Concha et al. 2012). Standardized HTG investigated both non-spatial model and spatial model diamond-shape HTG scenarios.

3) Results

3.1) Reference scenario

In the non-spatial model of the reference scenario (Fig. 3a), dynamics are reversible, i.e. all states form a single stability. This stability includes food insecure (~~*Prod*~~ or ~~*Distr*~~) as well as food secure (*ProdDistr* and *ProdDistrDegr1*) states. Although some states exhibited reversible land degradation (Degr1), the system was never irreversibly degraded (i.e. petroplinthite soils (*Ip+*) or dry aquifers (*Aq*-)). The model predicted a constantly full dam (Dw+) and no pest outbreak (Ps-) (Table S7). Other variables vary and system characterization such as degraded food security presents *a priori* unexpected recurring components combinations. For example, reversible degradation (*Degr1*) in degraded food security states was always associated with a systematic combination of soil degradation, excessive livestock, excessive fire, or NGOs and technical services absence (*Sd+* or *Li+* or *Fi+* or *Ng*- states, S6-7). Hence, violent events and banks absence (*Ve+* and *Bk*-) which were also labelled *Degr1* were not compatible with food security in this scenario, even in degraded food security (Table S7).

Food security may be directly reached from several states of the modeled system, but can only be lost when already combined to reversible degradation. Hence, the global food security disturbing scheme was linear in this reference scenario. Trajectories from clean food security to degraded food security and then food insecurity relied on a few rules and system states. The associated processes and components can be considered as early warning signals in the system (Table S7). For example, degrading clean food security started with abundant trees and rainfed crops bringing excessive livestock herds (*ID 17*), which can then collapse crops (*ID 15, 39*) and bring conflicts (*ID 61, 62*), leading later on to food insecurity. On the other side, food security may resettle through early regenerating signals. Banks play a central role in settling food security, sometimes clean food security, by restoring distribution networks (*ID 73*), irrigated crops (*ID 76*), and rainfed crops (*ID 89*). Irrigated crops may restart on their own in appropriate contexts (*ID 77*), and enough available food can stop price inflation (*ID 82, 83, 84*). Food security can then be cleaned through absence of fodder pushing out livestock excesses (*ID 69*), Banks restoring NGOs (*ID 81*), NGOs restoring fire situation (*ID 75*), or both restoring soils (ID 91) (Table S7).

The spatial model of the reference scenario displayed roughly the same dynamics (Fig. 3a), with the notable exception that livestock excess, which may locally remove trees (*ID 58*), will lead to the collapse of the global distribution network (constraint *ID 66*) through a violence outbreak (constraint *ID 63*) along a cascade of events (Table S7). On the other hand, accounting for spatial structure allowed retrofitting the system, one spatial unit at a time, up to a clean food security, with fallow practices for example (*ID 90*).

3.2) Climate change scenario

The non-spatial model of the climate change scenario displayed a globally unstable and irreversible dynamic (diamond shape HTG, Fig. 5a). Unlike the non-spatial model of the reference scenario, dam water, aquifer and petroplinthite vary now following the climatic disturbances of drought and violent rains. These three transitions are irreversible (Table S4, Fig. 5a). In this scenario, the overall system dynamics contain basins and stabilities (Fig. 5b-c-d). The initial stability, the largest one, contains no systematic annoyance (i.e. *NoProd*, *NoDistr*, *Degr1*, *Ip+*, *Aq*- etc.), making it similar to the reference scenario model (Fig. 5a-b, 3b). And the terminal stability (Fig. 5a-e) is a collapse in which food production (*resp*. food distribution) is impossible (*NoProd*, resp. *NoDistr*), dam (resp. aquifer) is empty (*Dw-*, resp. *Aq-*), and reversible degradation (resp. petroplinthite presence) is systematic (*Degr1*, resp. *Ip+*). Intermediate food security compatible stabilities displayed various combinations, such as one small stability with reversible degradation (*Degr1*) and dam water loss (*Dw-*) only (Fig. 5a-b), and four tiny stabilities with reversible degradation, dam water loss and petroplinthite presence (Fig. 5a-c).

The overall cascading dynamics proceeded from a few transitions (i.e. aquifer emptying (*ID 1)*, and petroplinthite formation (*ID 16)* (Fig. 5a)). Transitions emptying dam water were more numerous (S12), the most obvious ones being direct effects of drought that may combine with excessive livestock (*ID 3*, *4*), and direct sedimentation after violent rains on degraded soils (*ID 96*, S12, Fig. 5a). Other indirect processes all implied a constraint leading to a combination of violent rains, soil degradation and livestock excesses (constraint *ID 98*). Soil degradation or livestock excesses in this last constraint may be triggered by abundant trees and rainfed crops (*ID 17*) or rainfed and irrigated crops (*ID 45*, *46*, S12, Fig. 5a).

3.2.1) Largest stability

The transitions in the main (largest) stability differed from the main stability of the non-spatial model of the reference scenario: two new transitions may leave food security states, including one starting directly from clean food security to food insecurity (Fig. 3b). The transition involved was the detrimental effect of droughts on rainfed crops (*ID 31*, Table S7). Hence, unlike in the reference scenario, food security disturbing scheme under climate change was no longer linear. Transitions between degraded food security and food insecurity varied in their combination. Some may no longer operate (*ID 15*, *39*), as combination of their condition with violent rains constrained the system by emptying the dam (constraint *ID 98*), thus leaving the initial and main stability. Yet, new transitions may operate and collapse irrigated (*resp*. rainfed) crops through pest outbreak (*ID13*, *resp*. *ID 40*), or rainfed crops through drought, sometimes in combination with excessive fires and tree absence (*ID 31*, *42*).

Early regenerating signals in the main stability also differed compared to the non-spatial model of the reference scenario. Crop restoration processes may no longer operate as they were drought-free dependent (*ID 76*, *77*, *89*, Table S7). They were replaced by processes with more restrictive conditions. Irrigated crops restored from bank helped as in the reference scenario, but only when pests and soil degradation were absent (*ID 79*). Rainfed crops restored with even more restrictive conditions, requiring in addition NGOs and absence of excessive fires or livestock (*ID 88*). Hence, cleaning food security implied the same processes as in the non-spatial model of the reference scenario, but it added a new process specific to the climate change scenario: shutting down pest outbreak with helps of banks and NGOs (*ID 85*).

3.2.2) Spatial model

The spatial model of the climate change scenario displayed the same overall unstable and irreversible system dynamics (diamond shape HTG), yet in more details as petroplinthite is now spatialized (*Ip1*, *Ip2*, Fig. 6a). The system dynamic contained no more basins but only stabilities (Fig. 6b...f). Intermediate stabilities displayed various combinations of processes, such as allowing food security and dam water presence when one among the two hill plots contained petroplinthite

(*Ip*, Fig. 6c-d). These stabilities displayed larger sizes and more diverse trajectories than the two empty-dam-water stabilities free of petroplinthite and of systematic reversible degradation (Fig. 6b-c-d). The main stability differed from the non-spatial model one by some transitions (Table S7). Early warning signals of degraded food security were the same, adding rainfed crop collapse from excessive livestock (*ID 39*, Table S7). Here, dam emptying conditions required soil degradation everywhere upslope. Yet, new cascading effects threaten degraded food security. As in the spatial model of the reference scenario, violent event emergence (constraint *ID 63*) implied cascades triggered by either local fire excess (*ID 6*) or by local trees collapse due to pests (*ID 59*). These cascades exhibited many steps, up to four successive constraints (S8). Differences in the early regenerating signals compared to the spatial model of the reference scenario lied in the absence of fallow due to violent rainfalls (*ID 90*), as well as in local cascading collapse of degradations due to pests and fires (*ID 13, 31, 40, 42*).

4) Discussion

In this study, we compared a spatial and a non-spatial model of a complex West-African social-ecological system (SES). This comparison highlighted the complementary role played by the various spatial units of the studied landscape for maintaining food security at the watershed scale.

4.1) The effect of space in SES dynamics

Spatialization allowed phenomena to cross geographical scales, known as a transcalar effect. Unlike a multiscalar phenomenon, acting at several scales at once (Gaucherel et al. 2008 ; S. Fowler 2016), a transcalar phenomenon crosses geographic scales when some local processes imply a global process or the reverse (Djament-Tran 2015). In our study, the reference scenario highlighted cascading processes which made a local event triggering a global disturbance putting the whole system's food security at risk (Table S7). We propose to call them *slide cascade*, and they are expected to be faster than other trajectories as they only involve constraints representing fast events. Once lost, food security recovered progressively (i.e. one spatial unit a time), thus scaling up from local to global yet without cascading processes (Table S7). These transcalar phenomena illustrated how food security instability is at its margin and may disturb the whole system. In this case, food security may « break at once », while it may gradually rebuild « step by step », which has deep influence on the way we manage our SES (Pasqualino et al. 2019).

Spatial heterogeneity enabled accounting for functional complementarity between spatial units of the modeled landscape. For example, hills *h1* and *h2* (Fig. 1b) may stabilize food security in intermediate (local) states along the general cascading collapse of the system (Fig. 5-6). This is due to the fact that when one hill is degraded with petroplinthitic soils and cannot support food production, the other still can, thus maintain global food security. In this context, dam water can still maintain as dam sedimentation threshold from uphill soil degradation have not been reached (S12). Twenty-two different stabilities show this property, unlike in the non-spatial model (Fig. 5b-c, 6b-c-d). Two stabilities among these displayed big sizes (i.e. with more diverse trajectories) than the two empty-dam-water ones free of petroplinthite soils with systematic reversible degradation (Fig. 6b-c-d). Hence, spatialization showed that food security is sensitive to dam water absence compared to local irreversible soil degradation of a plot in the modeled climate change scenario.

Climate change induced irreversible social-ecological transitions. Droughts, violent rains and pests were able to induce food insecurity at the whole stability level (Showler 2002 ; Poisot et al. 2018 ; Fujimori et al. 2019). Due to violent rains, the system no longer relied on fallow to recover, and dam water became a key component to save the SES food security (Fig. 5-6, Tables S4-5). Dam water also became a sensitive component of the SES, as it can no longer refill correctly due to recurrent droughts (Fig. 5-6, Tables S4-5). As expected and confirmed by the literature (Turral et al. 2011 ; Callo-Concha et al. 2012 ; Eze et al. 2014), water shortage and soil degradation (more precisely, aquifer drying up and soil hardening) were able to induce irreversible transformations of the SES. Other ones related to the dam water appears to be less obvious for local authorities and management. Besides obvious threats, our models revealed interesting *slide cascade* that would be highly difficult to anticipate without such a qualitative and possibilistic model. For example, a local process locally degrading soil may trigger drying up dam water downslope and place the whole SES at risk (Fig. 6).

4.2) Pros and cons of qualitative and discrete models

The EDEN spatially implicit models allow integrated, discrete and qualitative modelling of SESs, in a wide range of situations. Hence, they help thinking these complex systems, in a different way than quantitative and traditional models (Volterra 1926 ; Motesharrei et al. 2014). They also allow focusing on processes that are critical in the SES dynamics and may then be investigated in more details with quantitative approaches (Bisson et al. 2019 ; Fujimori et al. 2019).

The Deer models extend the EDEN models with spatialized processes into a powerful yet perfectible framework. This extends the previous thinking with spatial considerations, handling a multi- and trans-scalar spirit on already complex SES systems. Unlike raster-based approach (Inkoom et al. 2018 ; Koo et al. 2018 ; Bisson et al. 2019), the vector-oriented and topological view as chosen in Deer opens a new way in considering space. This approach is often less resource intensive and is complementary to other traditional approaches (Verburg et al. 2002 ; Bonnefoy et al. 2001 ; Bisson et al. 2019). Similarly, to use the same topological spirit to model the whole SES functioning (Gaucherel et al. 2012), as represented in the SES network (Fig. 1), appears quite efficient and parsimonious. By this way, system trajectories can be represented with simplified GIS maps at intermediate computed states, without the need to compute the whole dynamics in a GIS environment (Verburg et al. 2002 ; Inkoom et al. 2018). This functional approach of geography can thus merge with ecological understanding to build a greater comprehension of SESs and their dynamics.

Despite their inherent inability to answer quantitative questions, EDEN and Deer models provide an integrated and complementary tool to quantitative ones. They explore causality (Pearl, Mackenzie 2018) in their own way (Fig. 3-5-6), and can help to focus on key variables to quantify in differential equations as causal models do in determining *a priori* if running a linear model is worth it or not (Pearl, Mackenzie 2018 ; McElreath 2020). These qualitative models will likely fail in upscaling with highly realistic representations, containing up to hundred spatial units for example, as the possibilistic output (computed state space) grows exponentially with the input size (i.e. the number of processes and variables). But the spirit of the Deer model is not to faithfully represent space, rather than to more faithfully represent the whole SES functioning and dynamics without neglecting the landscape structure (Gaucherel et al. 2012) (Figs 1-3-5-6).

In our study, the topology of spatial units is static. The mean patch borders in the modeled landscape are not static, but their neighborhoods are (Fig. 1b). This may occasionally limit the modelling capacities of Deer models, but seems to be a reasonable constraint for the 30 year foresights of this study. As in any other model, Deer and EDEN frameworks keep the same variables and rules during the whole computation. Hence, our models also fail in grasping innovative or adaptive aspects of the studied systems. Can we imagine that Dano people will let all the hills covered with petroplinthite without some innovative attempts to change this inevitable fate (Fig. 6)? This is an option which would suggest changing the model’s rules and running again EDEN and Deer models. Modelling innovation and adaptation is a huge stake/issue and is probably the next major challenge for SES models, as it may open the door out of irreversibility, be it climatic, social or ecological.

References

ABROULAYE, Sanfo, ISSA, Savadogo, ABALO, Kulo E et NOUHOUN, Zampaligre, 2015. Climate Change: A Driver of Crop Farmers-Agro Pastoralists Conflicts in Burkina Faso. In : *International Journal of Applied*. 2015. Vol. 5, n° 3.

ANDERSON, Jock R., 2019. Concepts of Stability in Food Security. In : *Encyclopedia of Food Security and Sustainability* [en ligne]. S.l. : Elsevier. pp. 8-15. [Consulté le 19 juillet 2019]. ISBN 978-0-12-812688-2. Disponible à l'adresse : https://linkinghub.elsevier.com/retrieve/pii/B9780081005965223159.

ARBONNIER, Michel, 2004. *Trees, shrubs and lianas of West African dry zones* [en ligne]. S.l. : Quae. Disponible à l'adresse : https://books.google.fr/books?hl=fr&lr=&id=U4JTDwAAQBAJ&oi=fnd&pg=PA5&dq=Arbonnier++M.++2004.++Trees,++shrubs++and++lianas++of++West++African++dry++zones.++CIRAD+Margraf,+GMBH,+MNHN,+Paris,+France.&ots=YglHKI9xr6&sig=vIlrmzy8IzWmsjgN95s2RrRXlc0#v=onepage&q&f=false.

BENEDIKTER, Roland et OUEDRAOGO, Ismaila, 2019. Saving West Africa from the rise of terrorism: Burkina Faso's 'Emergency Program for the Sahel' and the need for a multidimensional strategy. In : *Global Change, Peace & Security*. 2 janvier 2019. Vol. 31, n° 1, pp. 113-119. DOI 10/gmb4bm.

BERAZNEVA, Julia et LEE, David R., 2013. Explaining the African food riots of 2007–2008: An empirical analysis. In : *Food Policy*. avril 2013. Vol. 39, pp. 28-39. DOI 10/gk9phx.

BÉRENGUIER, D., CHAOUIYA, C., MONTEIRO, P. T., NALDI, A., REMY, E., THIEFFRY, D. et TICHIT, L., 2013. Dynamical modeling and analysis of large cellular regulatory networks. In : *Chaos: An Interdisciplinary Journal of Nonlinear Science*. juin 2013. Vol. 23, n° 2, pp. 025114. DOI 10/gmb547.

BISSON, Anne, BOUDSOCQ, Simon, CASENAVE, Céline, BAROT, Sébastien, MANLAY, Raphaël J., VAYSSIÈRES, Jonathan, MASSE, Dominique et DAUFRESNE, Tanguy, 2019. West African mixed farming systems as meta-ecosystems: A source-sink modelling approach. In : *Ecological Modelling*. novembre 2019. Vol. 412, pp. 108803. DOI 10/gmcnnw.

BONNEFOY, Jean-Luc, BOUSQUET, François et ROUCHIER, Juliette, 2001. Modélisation d'une interaction individus, espace et société par les systèmes multi-agents : pâture en forêt virtuelle. In : *L'Espace géographique*. 2001. Vol. 30, n° 1, pp. 13-25. DOI 10/gg29m8. Cairn.info

BUSH, Ray, 2010. Food Riots: Poverty, Power and Protest. In : *Journal of Agrarian Change*. janvier 2010. Vol. 10, n° 1, pp. 119-129. DOI 10.1111/j.1471-0366.2009.00253.x.

CALLO-CONCHA, Daniel, GAISER, Thomas et EWERT, Frank, 2012. 100 : *Farming and cropping systems in the West African Sudanian Savanna. WASCAL research area: Northern Ghana, Southwest Burkina Faso and Northern Benin* [en ligne]. Working Paper. S.l. ZEF Working Paper Series. [Consulté le 19 juillet 2019]. Disponible à l'adresse : https://www.econstor.eu/handle/10419/88290.

CASTELLA, Jean-Christophe et VERBURG, Peter H., 2007. Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam. In : *Ecological Modelling*. avril 2007. Vol. 202, n° 3-4, pp. 410-420. DOI 10/dqf5c8.

CHERKASSKII, BL, 1988. The system of the epidemic process. In : *Journal of hygiene, epidemiology, microbiology, and immunology*. 1988. Vol. 32, n° 3, pp. 321-328.

COLDING, Johan et BARTHEL, Stephan, 2019. Exploring the social-ecological systems discourse 20 years later. In : *Ecology and Society*. 2019. Vol. 24, n° 1, pp. art2. DOI 10.5751/ES-10598-240102.

COLON, C., CLAESSEN, D. et GHIL, M., 2015. Bifurcation analysis of an agent-based model for predator–prey interactions. In : *Ecological Modelling*. décembre 2015. Vol. 317, pp. 93-106. DOI 10/f72b8g.

COSME, Maximilien, 2019. *Interviews in Dano's region, Chapter 2 of PhD thesis*. 2019. S.l. : Montpellier University.

COSME, Maximilien, HÉLY, Christelle, POMMEREAU, Franck, PASQUARIELLO, Paolo, TIBERI, Christel, TREYDTE, Anna et GAUCHEREL, Cédric, 2021. *East-African savanna dynamics: from a knowledge-based model to the possible futures of a social-ecological system* [en ligne]. preprint. S.l. Ecology. [Consulté le 8 juillet 2021]. Disponible à l'adresse : http://biorxiv.org/lookup/doi/10.1101/2021.04.05.438440.

DIOP, Ousmane, TOURNIEL, Laurent et FROMION, Vincent, 2019. Summarizing complex asynchronous Boolean attractors, application to the analysis of a mammalian cell cycle model. In : *2019 18th European Control Conference (ECC)* [en ligne]. Naples, Italy : IEEE. juin 2019. pp. 1677-1682. [Consulté le 28 juillet 2021]. ISBN 978-3-907144-00-8. Disponible à l'adresse : 10/gmb6bf.

DJAMENT-TRAN, G, 2015. La résilience, une question d'échelles. In : *Reghezza-Zitt M., Rufat S., Résiliences: sociétés et territoires face à l'incertitude, aux risques et aux catastrophes, Londres, ISTE*. 2015. pp. 61-79.

DOU, Yue, DEADMAN, Peter J., BERBÉS-BLÁZQUEZ, Marta, VOGT, Nathan D. et ALMEIDA, Oriana, 2020. Pathways out of poverty through the lens of development resilience: an agent-based simulation. In : *Ecology and Society*. 2020. Vol. 25, n° 4, pp. art3. DOI 10/gmb336.

DREYER STIFTUNG, 2019. Water. In : *Dreyer Stiftung* [en ligne]. 2019. [Consulté le 9 janvier 2020]. Disponible à l'adresse : http://www.dreyerstiftung.de/index.php/en/projects/water.

EZE, PN, UDEIGWE, TK et MEADOWS, ME, 2014. Plinthite and its associated evolutionary forms in soils and landscapes: a review. In : *Pedosphere*. 2014. Vol. 24, n° 2, pp. 153-166.

FAO, 2019. *STATE OF FOOD SECURITY AND NUTRITION IN THE WORLD 2019: safeguarding against economic slowdowns... and downturns.* S.l. : FOOD & AGRICULTURE ORG. ISBN 978-92-5-131570-5.

FUJIMORI, Shinichiro, HASEGAWA, Tomoko, KREY, Volker, RIAHI, Keywan, BERTRAM, Christoph, BODIRSKY, Benjamin Leon, BOSETTI, Valentina, CALLEN, Jessica, DESPRÉS, Jacques, DOELMAN, Jonathan, DROUET, Laurent, EMMERLING, Johannes, FRANK, Stefan, FRICKO, Oliver, HAVLIK, Petr, HUMPENÖDER, Florian, KOOPMAN, Jason F. L., VAN MEIJL, Hans, OCHI, Yuki, POPP, Alexander, SCHMITZ, Andreas, TAKAHASHI, Kiyoshi et VAN VUUREN, Detlef, 2019. A multi-model assessment of food security implications of climate change mitigation. In : *Nature Sustainability*. mai 2019. Vol. 2, n° 5, pp. 386-396. DOI 10/gh275n.

GARBOLINO, Emmanuel, CHÉRY, Jean-Pierre et GUARNIERI, Franck, 2019. The Systemic Approach: Concepts, Method and Tools. In : GUARNIERI, Franck et GARBOLINO, Emmanuel (éd.), *Safety Dynamics* [en ligne]. Cham : Springer International Publishing. Advanced Sciences and Technologies for Security Applications. pp. 1-30. [Consulté le 5 juillet 2021]. ISBN 978-3-319-96258-0. Disponible à l'adresse : http://link.springer.com/10.1007/978-3-319-96259-7_1.

GAUCHEREL, CÉdric, ALLEAUME, Samuel et HELY, Christelle, 2008. The Comparison Map Profile Method: A Strategy for Multiscale Comparison of Quantitative and Qualitative Images. In : *IEEE Transactions on Geoscience and Remote Sensing*. septembre 2008. Vol. 46, n° 9, pp. 2708-2719. DOI 10/dsv5p2.

GAUCHEREL, Cédric, BOUDON, Frédéric, HOUET, Thomas, CASTETS, Mathieu et GODIN, Christophe, 2012. Understanding Patchy Landscape Dynamics: Towards a Landscape Language. In : MARTENS, Lennart (éd.), *PLoS ONE*. 25 septembre 2012. Vol. 7, n° 9, pp. e46064. DOI 10.1371/journal.pone.0046064.

GAUCHEREL, Cédric et POMMEREAU, Franck, 2019. Using discrete systems to exhaustively characterize the dynamics of an integrated ecosystem. In : CHISHOLM, Ryan (éd.), *Methods in Ecology and Evolution*. septembre 2019. Vol. 10, n° 9, pp. 1615-1627. DOI 10.1111/2041-210X.13242.

GOULART, Fernando F., SALLES, Paulo, SAITO, Carlos H. et MACHADO, Ricardo B., 2013. How do different agricultural management strategies affect bird communities inhabiting a savanna-forest mosaic? A qualitative reasoning approach. In : *Agriculture, Ecosystems & Environment*. janvier 2013. Vol. 164, pp. 114-130. DOI 10/f4q3b5.

GREENHOUGH, Karen, 2016. *Pastoralists and Change in Burkina Faso*. S.l. WASCAL.

GRIMM, Volker et RAILSBACK, Steven F., 2005. *Individual-based Modeling and Ecology:* [en ligne]. S.l. : Princeton University Press. [Consulté le 30 juillet 2021]. ISBN 978-1-4008-5062-4. Disponible à l'adresse : https://www.degruyter.com/document/doi/10.1515/9781400850624/html.

GUNDERSON, Lance H. et HOLLING, Crawford S. (éd.), 2002. *Panarchy: understanding transformations in human and natural systems*. Washington, DC : Island Press. ISBN 978-1-55963-857-9.

INKOOM, Justice Nana, FRANK, Susanne, GREVE, Klaus et FÜRST, Christine, 2018. A framework to assess landscape structural capacity to provide regulating ecosystem services in West Africa. In : *Journal of Environmental Management*. mars 2018. Vol. 209, pp. 393-408. DOI 10.1016/j.jenvman.2017.12.027.

KABE KAGNE, Désiré, 2009. *Evaluation des performances d'irrigation du périmètre de Moutori* [en ligne]. Master's Thesis. S.l. : Institut international d'ingénierie de l'eau et de l'environnement. Disponible à l'adresse : http://documentation.2ie-edu.org/cdi2ie/opac_css/doc_num.php?explnum_id=1665.

KNIVETON, Dominic, SMITH, Christopher et WOOD, Sharon, 2011. Agent-based model simulations of future changes in migration flows for Burkina Faso. In : *Global Environmental Change*. décembre 2011. Vol. 21, pp. S34-S40. DOI 10/bwrmrt.

KOO, Hongmi, KLEEMANN, Janina et FÜRST, Christine, 2018. Land Use Scenario Modeling Based on Local Knowledge for the Provision of Ecosystem Services in Northern Ghana. In : *Land*. 4 mai 2018. Vol. 7, n° 2, pp. 59. DOI 10.3390/land7020059.

KOO, Hongmi, KLEEMANN, Janina et FÜRST, Christine, 2019. Impact assessment of land use changes using local knowledge for the provision of ecosystem services in northern Ghana, West Africa. In : *Ecological Indicators*. août 2019. Vol. 103, pp. 156-172. DOI 10.1016/j.ecolind.2019.04.002.

MAGLIOCCA, Nicholas R., BROWN, Daniel G. et ELLIS, Erle C., 2013. Exploring Agricultural Livelihood Transitions with an Agent-Based Virtual Laboratory: Global Forces to Local Decision-Making. In : JIANG, Bin (éd.), *PLoS ONE*. 5 septembre 2013. Vol. 8, n° 9, pp. e73241. DOI 10/gmb3w9.

MAO, Zhun, CENTANNI, Julia, POMMEREAU, Franck, STOKES, Alexia et GAUCHEREL, Cédric, 2021. Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system. In : *Ecosystem Services*. février 2021. Vol. 47, pp. 101220. DOI 10/gmb353.

MARTIN, Nicola, 2006. 41 : *Development of a water balance for the Atankwidi catchment, West Africa – A case study of groundwater recharge in a semi-arid climate*. S.l.

MBOW, Cheikh, ROSENZWEIG, Cynthia E, BARIONI, Luis G, BENTON, Tim G, HERRERO, Mario, KRISHNAPILLAI, Murukesan, RUANE, Alexander C, LIWENGA, Emma, PRADHAN, Prajal, RIVERA-FERRE, Marta G, et OTHERS, 2020. Food security. In : *IPCC* [en ligne]. 2020. Disponible à l'adresse : https://www.ipcc.ch/site/assets/uploads/sites/4/2021/02/08_Chapter-5_3.pdf.

MBOW, Cheikh, VAN NOORDWIJK, Meine, LUEDELING, Eike, NEUFELDT, Henry, MINANG, Peter A et KOWERO, Godwin, 2014. Agroforestry solutions to address food security and climate change challenges in Africa. In : *Current Opinion in Environmental Sustainability*. février 2014. Vol. 6, pp. 61-67. DOI 10/f5w9xj.

MCELREATH, Richard, 2020. *Statistical rethinking: a Bayesian course with examples in R and Stan*. 2. Boca Raton : Taylor and Francis, CRC Press. CRC texts in statistical science. ISBN 978-0-367-13991-9.

MOTESHARREI, Safa, RIVAS, Jorge et KALNAY, Eugenia, 2014. Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. In : *Ecological Economics*. mai 2014. Vol. 101, pp. 90-102. DOI 10/f54wzd.

OEC, 2017. Burkina Faso (BFA) Exports, Imports, and Trade Partners. In : *The Observatory of Economic Complexity* [en ligne]. 2017. [Consulté le 11 mars 2020]. Disponible à l'adresse : https://oec.world/en/profile/country/bfa/.

OP DE HIPT, Felix, DIEKKRÜGER, Bernd, STEUP, Gero, YIRA, Yacouba, HOFFMANN, Thomas et RODE, Michael, 2017. Applying SHETRAN in a Tropical West African Catchment (Dano, Burkina Faso)—Calibration, Validation, Uncertainty Assessment. In : *Water*. 9 février 2017. Vol. 9, n° 2, pp. 101. DOI 10.3390/w9020101.

ORTIZ, Marco, LEVINS, Richard, CAMPOS, Leonardo, BERRIOS, Fernando, CAMPOS, Fernando, JORDÁN, Ferenc, HERMOSILLO, Brenda, GONZALEZ, Jorge et RODRIGUEZ, Fabián, 2013. Identifying keystone trophic groups in benthic ecosystems: Implications for fisheries management. In : *Ecological Indicators*. février 2013. Vol. 25, pp. 133-140. DOI 10/f4m7c4.

OXFAM, 2021. *The hunger virus multiplies: deadly recipe of conflict, covid-19 and climate accelerate world hunger* [en ligne]. S.l. OXFAM. [Consulté le 9 juillet 2021]. Disponible à l'adresse : https://oi-files-d8-prod.s3.eu-west-2.amazonaws.com/s3fs-public/2021-07/The%20Hunger%20Virus%202.0_media%20brief_EN.pdf.

PACHAURI, R. K., MAYER, Leo et INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (éd.), 2015. *Climate change 2014: synthesis report*. Geneva, Switzerland : Intergovernmental Panel on Climate Change. ISBN 978-92-9169-143-2.

PALE, Sié, 2018. Apport de la géomatique dans l'aménagement des flancs de collines du sous-bassin versant de Moutori à Dano, au Burkina Faso. In : [en ligne]. 2018. [Consulté le 26 février 2020]. DOI 10.13140/RG.2.2.19673.57440. Disponible à l'adresse : http://rgdoi.net/10.13140/RG.2.2.19673.57440.

PALE, Sié, KIEMDE, Bienvenue Joséphine et CONSTANT DA, Dapola Evariste, 2016. Pratiques traditionnelles paysannes dans les bas-fonds agricoles au Burkina Faso. In : *Rev. Sc. Env. Univ., Lomé (Togo)*. 2016. Vol. n° 13, pp. 119-136.

PASQUALINO, Roberto, MONASTEROLO, Irene et JONES, Aled, 2019. An Integrated Global Food and Energy Security System Dynamics Model for Addressing Systemic Risk. In : *Sustainability*. 23 juillet 2019. Vol. 11, n° 14, pp. 3995. DOI 10/gmcnj3.

PEARL, Judea et MACKENZIE, Dana, 2018. *The book of why: the new science of cause and effect*. First edition. New York : Basic Books. ISBN 978-0-465-09761-6.

PENG, Wen et BERRY, Elliot M., 2019. The Concept of Food Security. In : *Encyclopedia of Food Security and Sustainability* [en ligne]. S.l. : Elsevier. pp. 1-7. [Consulté le 19 juillet 2019]. ISBN 978-0-12-812688-2. Disponible à l'adresse : https://linkinghub.elsevier.com/retrieve/pii/B9780081005965223147.

POISOT, Anne-Sophie, HRUSKA, Allan, FREDRIX, Marjon et NZEZA, Koko, 2018. *Gestion intégrée de la chenille légionnaire d'automne sur le maïs* [en ligne]. S.l. FAO. [Consulté le 27 novembre 2019]. Disponible à l'adresse : http://www.fao.org/3/I9124FR/i9124fr.pdf.

S. FOWLER, Christopher, 2016. Segregation as a multiscalar phenomenon and its implications for neighborhood-scale research: the case of South Seattle 1990–2010. In : *Urban Geography*. 2 janvier 2016. Vol. 37, n° 1, pp. 1-25. DOI 10/gh2gtx.

SANDWIDI, Wennegouda Jean Pierre, 2007. *Groundwater potential to supply population demand within the Kompienga dam basin in Burkina Faso*. PhD Thesis. S.l. : Universitäts-und Landesbibliothek Bonn.

SHOWLER, Allan T., 2002. A summary of control strategies for the desert locust, Schistocerca gregaria (Forskål). In : *Agriculture, Ecosystems & Environment*. juin 2002. Vol. 90, n° 1, pp. 97-103. DOI 10.1016/s0167-8809(01)00167-0.

TURRAL, Hugh, BURKE, Jacob J. et FAURÈS, Jean-Marc, 2011. *Climate change, water and food security*. Rome : Food and Agriculture Organization of the United Nations. FAO water reports, 36. ISBN 978-92-5-106795-6. S494.5.W3 T88 2011

UNITED NATIONS, 1975. *Report of the World Food Conference, Rome, 5–16 November 1974* [en ligne]. New York. United Nations,. Disponible à l'adresse : https://digitallibrary.un.org/record/701143.

VERBURG, Peter H., SOEPBOER, Welmoed, VELDKAMP, A., LIMPIADA, Ramil, ESPALDON, Victoria et MASTURA, Sharifah S.A., 2002. Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. In : *Environmental Management*. septembre 2002. Vol. 30, n° 3, pp. 391-405. DOI 10/d67h7p.

VOLTERRA, Vito, 1926. Variazioni e fluttuazioni del numero d'individui in specie animali conviventi. In : . 1926.

WITTMAN, Hannah, CHAPPELL, Michael Jahi, ABSON, David James, KERR, Rachel Bezner, BLESH, Jennifer, HANSPACH, Jan, PERFECTO, Ivette et FISCHER, Joern, 2017. A social–ecological perspective on harmonizing food security and biodiversity conservation. In : *Regional Environmental Change*. juin 2017. Vol. 17, n° 5, pp. 1291-1301. DOI 10/gbhpwm.

YARO, Joseph A. et HESSELBERG, Jan (éd.), 2016. *Adaptation to Climate Change and Variability in Rural West Africa* [en ligne]. Cham : Springer International Publishing. [Consulté le 15 novembre 2019]. ISBN 978-3-319-31497-6. Disponible à l'adresse : http://link.springer.com/10.1007/978-3-319-31499-0.

YIRA, Yacouba, DIEKKRÜGER, Bernd, STEUP, Gero et BOSSA, Aymar Yaovi, 2017. Impact of climate change on hydrological conditions in a tropical West African catchment using an ensemble of climate simulations. In : *Hydrology and Earth System Sciences*. 20 avril 2017. Vol. 21, n° 4, pp. 2143-2161. DOI 10.5194/hess-21-2143-2017.

Tables

Model variables and scenarii

Acronym	Description	Initial state Reference scenario	Initial state Climatic scenario
Atmosphere			
Dr	Drought	-	+
Rv	Violent rains	-	+
Rr	Rain randomisation	-	-
Soil			
Ip	Iron Pebble (petroplinthite)	-	-
Sd	Soil, degraded	+	+
Water			
Dw	Dam water (focused on Moutori dam)	+	+
Aq	Aquifer	+	+
Fauna			
Li	Livestock (in excess)	-	-
Ps	Crop pests	-	-
Flora			
Tr	Lignous plants (includes food & fodder trees)	+	+
Ic	Irrigated crops	+	+
Rc	Rainfed crops	+	+
Fi	Fire (in excess)	-	-
Human			
Ve	Violent events	-	-
Bk	Banks	+	+
Dn	Food distribution network	+	+
Pi	Food price inflation	-	-
Ng	NGOs & technical services (extension officers)	+	+
Ec	External commodities (food commerce)	+	+

Table n°1) Model variables and their initial values (+ or -) for each scenario in non-spatial models. “+” (resp. “-”) means that the corresponding variable is initially present (resp. absent). Full model references, comments, rules, constraints, and spatially explicit version available in the supplementary material (S4-5). Scenarii fixed parameters include Dr, Rv, Rr and Ec. In spatial models multi-localised ecosystemic components include Ip, Sd, Ps, Tr, Rc, and Fi.

Figure captions

Study site & spatialization

Figure 1. The study site and its spatialization. The Dano site (a), in Burkina Faso, West Africa, is displayed with the Dano social ecological system (b, SES) and the ecosystem graph (c). The SES is displayed with its corresponding spatial graph, the modeled spatial units with their topology and slopes. The ecosystem graph is displayed for the spatial model, with vertice colors that fit the ecosystem component colors to be found in table S11. Images sources: Open Street Map & Sentinel 2.

Toy models

Figure 2. Spatial and non-spatial toy models of human-environment interactions. The interaction graph of the Dano non-spatial model (a), displaying linked variables if they are connected by a rule or a constraint. The spatial graph (b) shows dotted lines for global contiguity and plain line for local contiguity. The interaction graph of the Dano spatial model (c) is displayed too. The state-transition graph of the spatial model (d) is displayed with vertices and edges representing the system structure (states) and transitions linking them, respectively. Transition labels are assembled as follows: the rule unique identifier (ID), type of event (r: regeneration or d: degradation), variable affected (Hu: humans, E: environment). For instance, 2.dE indicates that the transition is caused by rule 2 and induces an environmental degradation (i.e. E-). Finally, the state-transition graph of the spatial model (e) shows a different structure than the non-spatial model (d), two additional types of events (mi: migration and n: niche construction) are introduced. They are allowed by dividing space into two local regions.

Canonical graphs

Figure 3. Canonical graphs of food security for the biggest stabilities of reference and climate change scenarios. Canonical graphs represents the various food security statuses the system can exhibit and the transitions between them in the reference scenario (a), and climate change scenario (b). Climate change canonical graph bold arrows indicate transitions that were absent in the reference scenario. Initial scenarii states belong to "*ProdDistrDegr1*" vertice. Spatial and non-spatial models don't vary canonical graph transitions topology. Differences lie in the content of transitions (cf monitoring scheme table S7 and biggest stabilities raw data S10). Climate change scenario adds transitions removing food security, including a new food security removing transition starting directly from clean food security "*ProdDistr*".

Raw hierarchical transition graphs, climate change scenario, spatial model

Figure 4. Raw HTG, climate change scenario, spatial model, colored with number of states of the 1829 stabilities. Diamond shape HTG displays a global irreversibility, leading from the initial stability to the terminal one through different trajectories. Nothing else can be said about stabilities content as only their size appear.

Summarized hierarchical transition graph, climate change scenario, non-spatial model

Figure 5. Hierarchical transition graph, climate change scenario, non-spatial model. The HTG, labelled using irreversible degradations *Ip* & *Aq* as a criteria have been summarized (a). Zooming in different (a) vertices, allowed to summarize at an intermediate level (b...e), grouping irreversible degradation free vertices (b), *Ip* present vertices (c), *Aq* present vertices (d), and both Ip & Aq present vertices (e). These zoomed graphs used systematic absences of food production *NoProd* or food distribution *NoDistr*, presence of reversible degradation *Degr1* and topological nature of HTG vertices as a criteria (e.g. stabilities in **bold** and basins in *italic*) to summarize at an intermediate level (b...e). In the climate change scenario water drives the global dynamic (a), leading irreversibly from initial, biggest, food security compatible, dam water present and free of systematic degradation stability (483 states), to a completely collapsed end stability. Intermediary steps keeps some food security possible when losing dam water in one stability (b) (16 states), and then when petroplinthitic soils *Ip* adds in 4 extremely small dam water dried stabilities (2 states maximum). Basins and their irreversibility can be present in trajectories, and in (b) and (c) losing food production is definitive whereas losing food distribution can sometimes reverse. Several processes lead to dam water loss at the top of (a-b) (linked to excessive livestock, drought, violent rain, fire and crops), but all other transitions in (a) contain one process among two: petroplinthitic soils formation or aquifer emptying.

Summarized hierarchical transition graph, climate change scenario, spatial model

Figure 6. Hierarchical transition graph, climate change scenario, spatial model. The HTG, labelled using irreversible degradations *Ip1*, *Ip2* & *Aq* as a criteria have been summarized (a). Zooming in different (a) vertices, allowed to summarize at an intermediate level (b...f), grouping irreversible degradation free vertices (b), *Ip1* present vertices (c), *Ip2* present vertices (d), *Ipsat* present vertices (e). All other vertices in (a) are similar (f). These zoomed graphs used systematic absences of food production *NoProd* or food distribution *NoDistr*, presence of reversible degradation *Degr1* and topological nature of HTG vertices as a criteria (e.g. stabilities in **bold**, no basins present) to summarize at an intermediate level (b...f). In the climate change scenario water drives the global dynamic (a), leading irreversibly from initial, biggest, food security compatible, dam water present and free of systematic degradation stability (339774 states), to a completely collapsed end stability. Intermediary steps keeps some food security possible when losing dam water in two stability (b) (1544 & 1600 states). Local petroplinthic soils development allows two kinds of food secure compatible intermediate stabilities. The first one keeps dam water in one (resp. 21) stability (c) (resp. (d)) with 12338 states (resp. 35 to 5562 states). The second one losed dam water in 11 (resp. 45) stabilities (c) (resp. (d)) with 4 to 80 states (resp. 2 to 24 states). Petroplinthic soils saturation in hills allowed extremely small food security compatible dam water dried stabilities (20 with 1 to 4 states). Several processes lead to dam water loss at the top of (a-d) (linked to excessive livestock, drought, violent rain, fire and rainfed crops), but all other transitions in (a) contain one process among two: petroplinthitic soils formation or aquifer emptying. Results are very close to non-spatial model of the climate change scenario (Fig. 5) in a more detailed way as space is explicited and there is now 2 *Ip*s. Except that: no more basins are present, irrigated crops cannot be a dam emptying factor as they are downslope, spatializing allow food security & dam water presence when one among two *Ip* is present (c-d), with bigger stabilities sizes than the two dam-water-off ones in (b).

Figure1

Click here to access/download;Figure;Fig1.eps

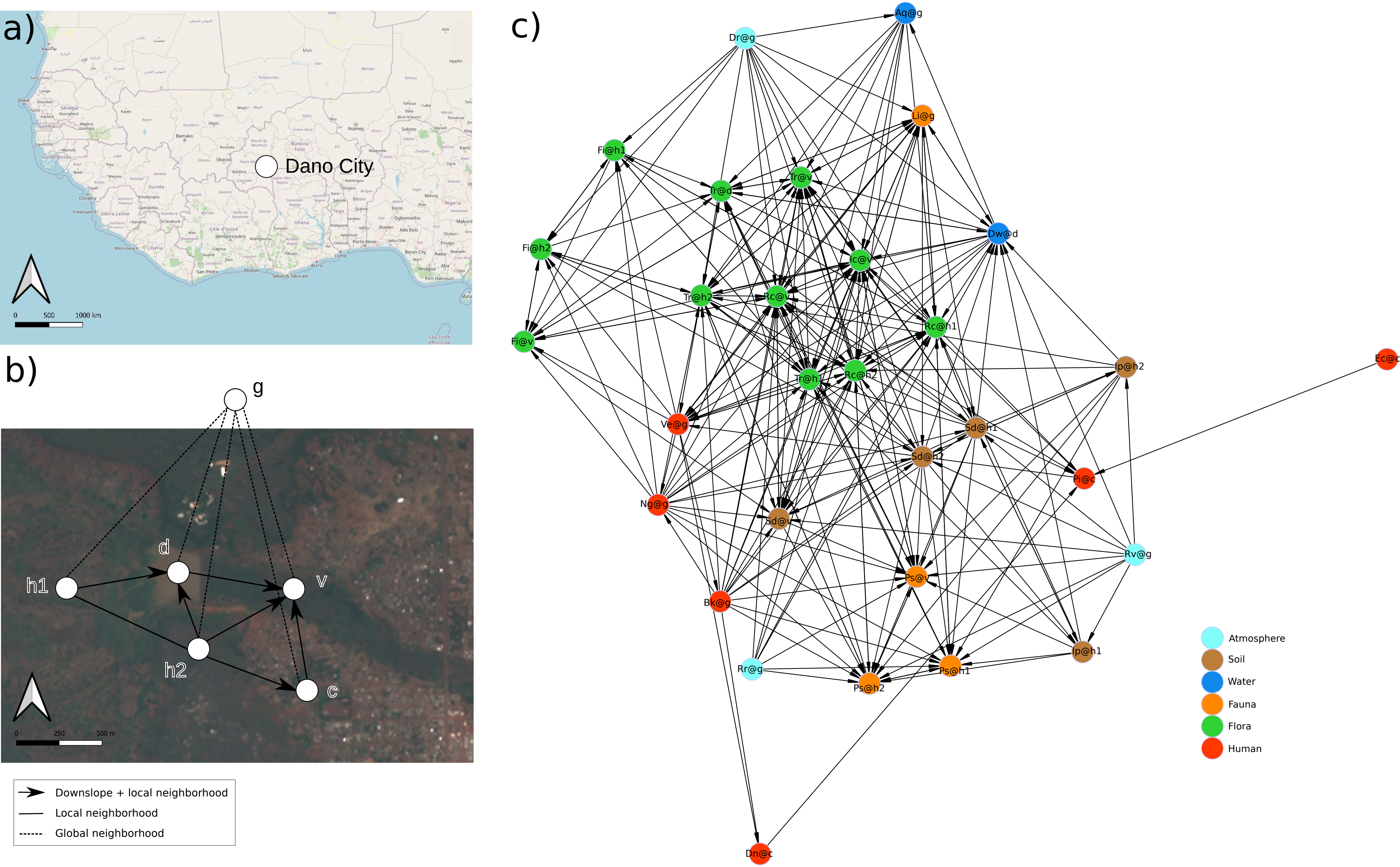
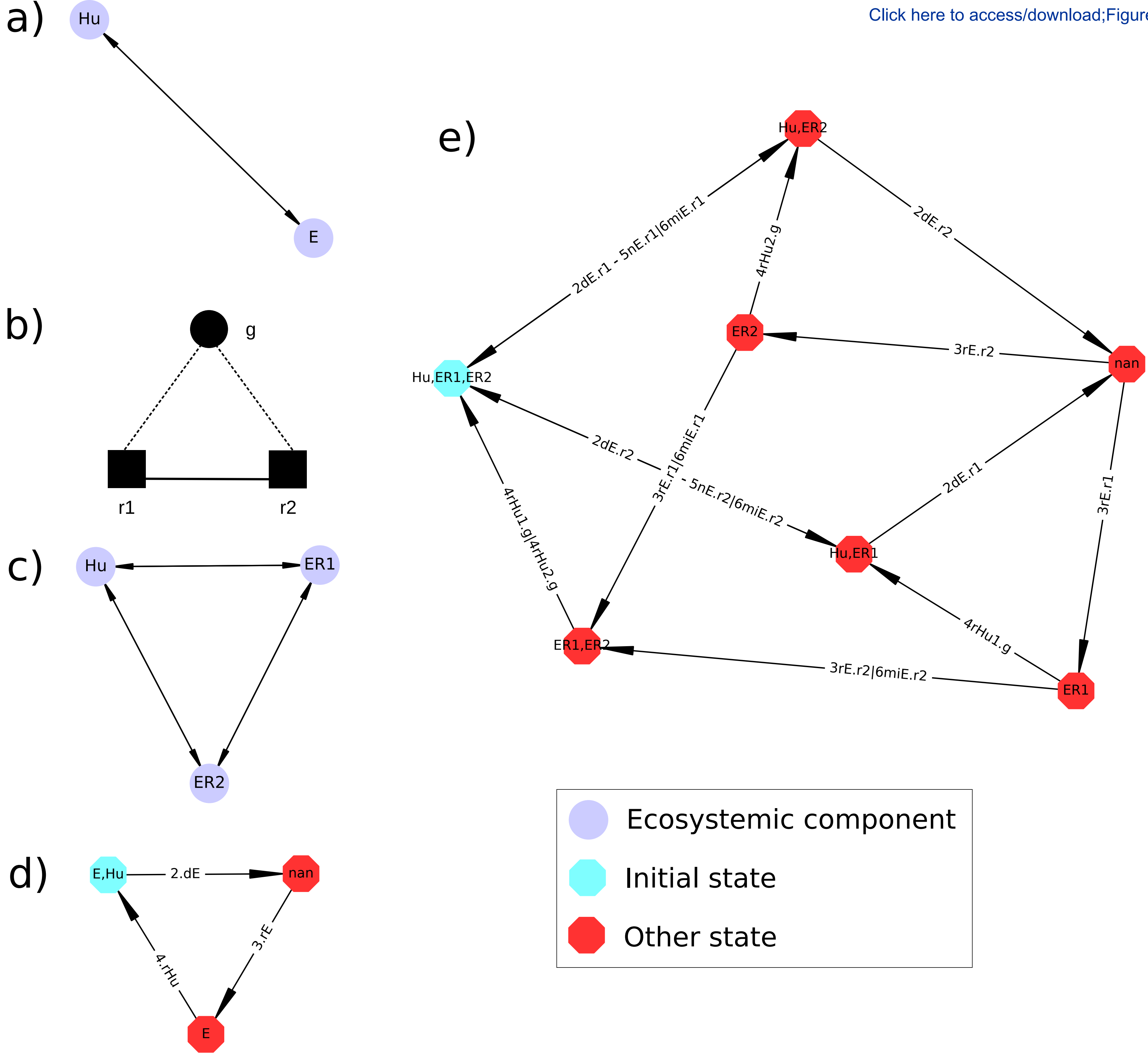


Figure2



a)
Hu
E
b)
g
r1
r2
c)
Hu
ER1
ER2
d)
E,Hu
2.dE
nan
3.rE
4.rHu
E
e)
Hu,ER2
2dE.r1 - 5nE.r1|6miE.r1
4rHu2.g
2dE.r2
ER2
3rE.r2
nan
Hu,ER1,ER2
2dE.r2 - 5nE.r2|6miE.r2
3rE.r1|6miE.r1
2dE.r1
3rE.r1
4rHu1.g|4rHu2.g
Hu,ER1
4rHu1.g
ER1,ER2
3rE.r2|6miE.r2
ER1
Ecosystemic component
Initial state
Other state

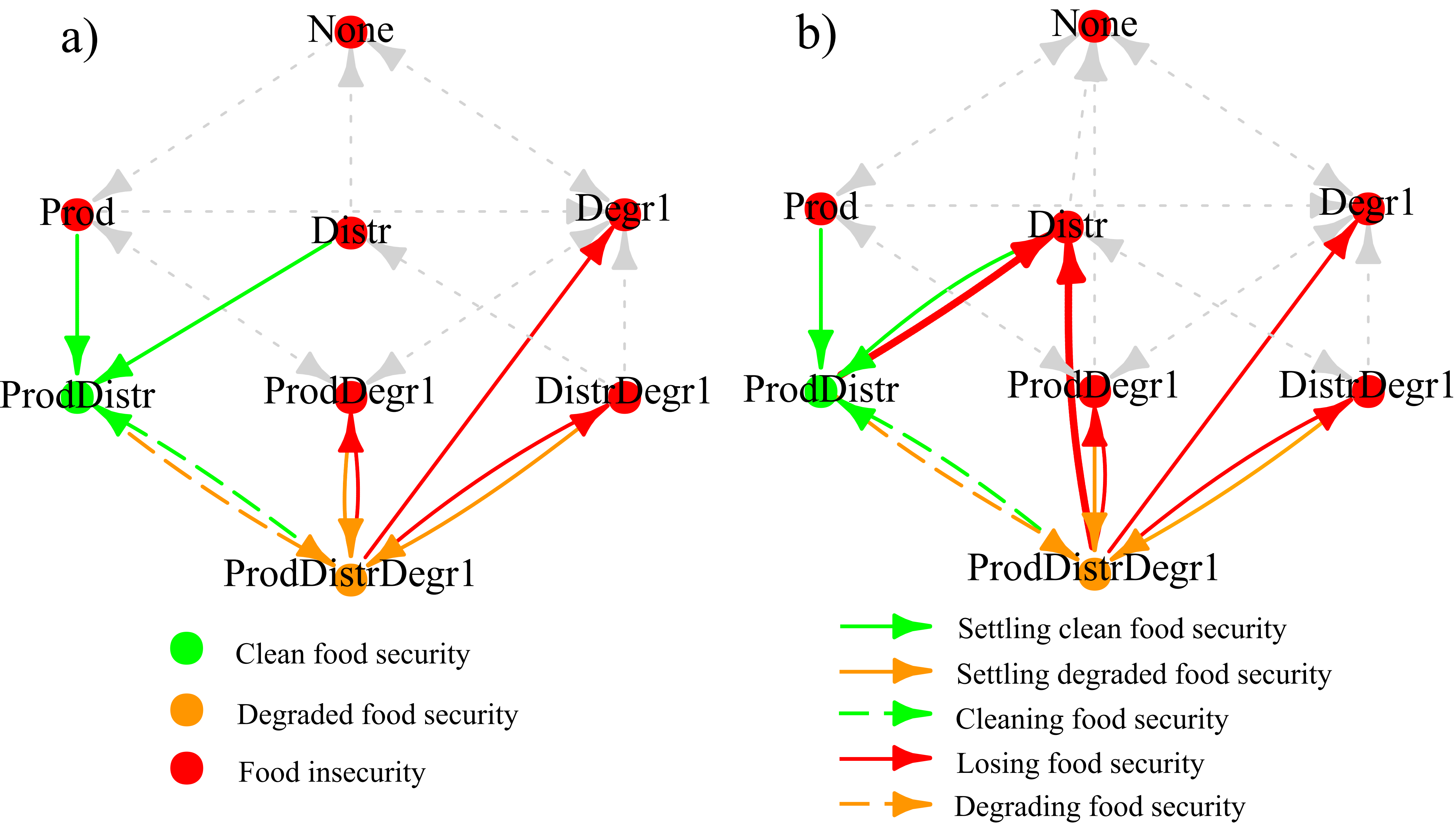

a)
None
Prod
Distr
Degr1
ProdDistr
ProdDegr1
DistrDegr1
ProdDistrDegr1
Clean food security
Degraded food security
Food insecurity
b)
None
Prod
Distr
Degr1
ProdDistr
ProdDegr1
DistrDegr1
ProdDistrDegr1
Settling clean food security
Settling degraded food security
Cleaning food security
Losing food security
Degrading food security

Figure4

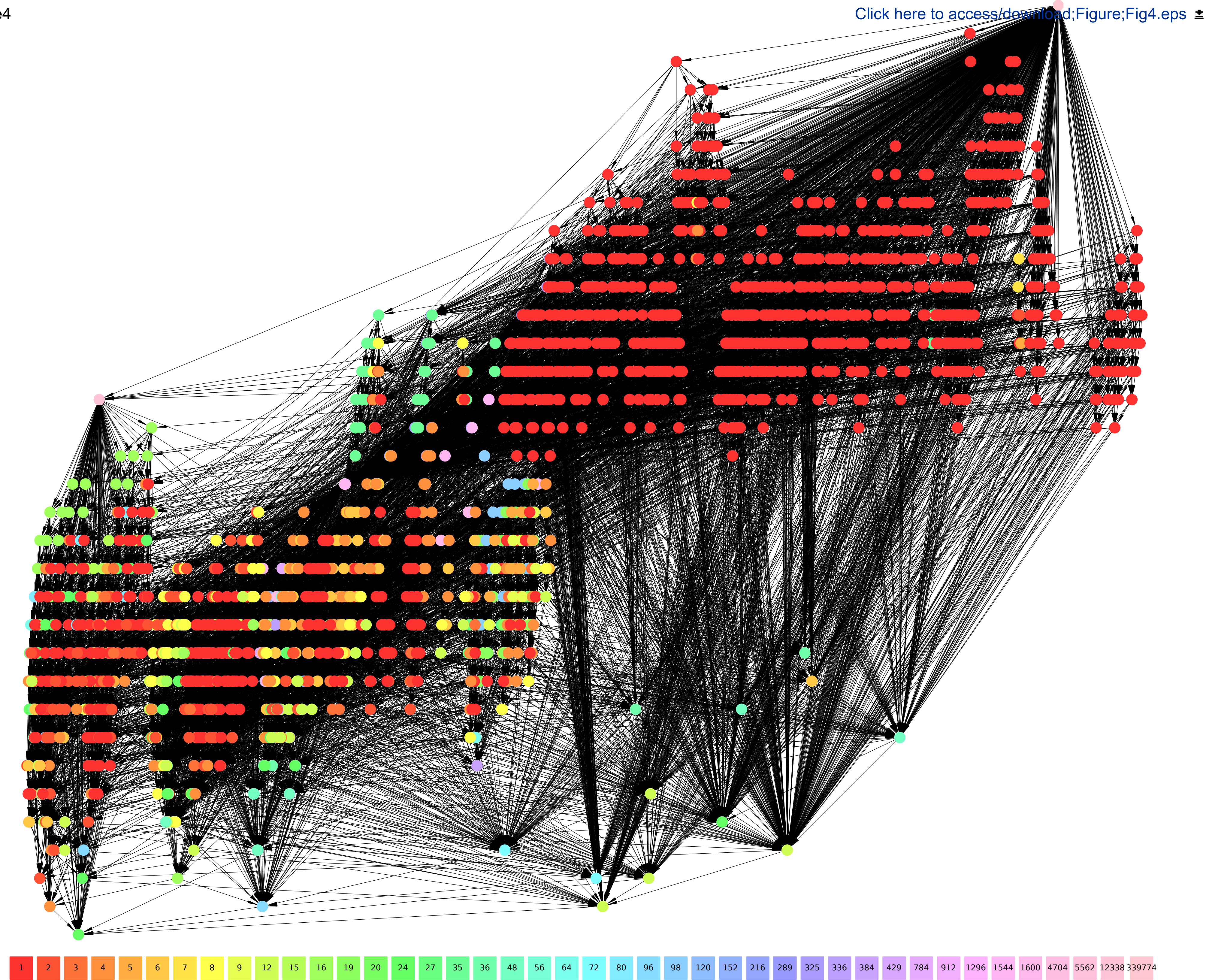

1
2
3
4
5
6
7
8
9
12
15
16
19
20
24
27
35
36
48
56
64
72
80
96
98
120
152
216
289
325
336
384
429
784
912
1296
1544
1600
4704
5562
12338
339774

Figure5

Click here to access/download;Figure;Fig5.eps

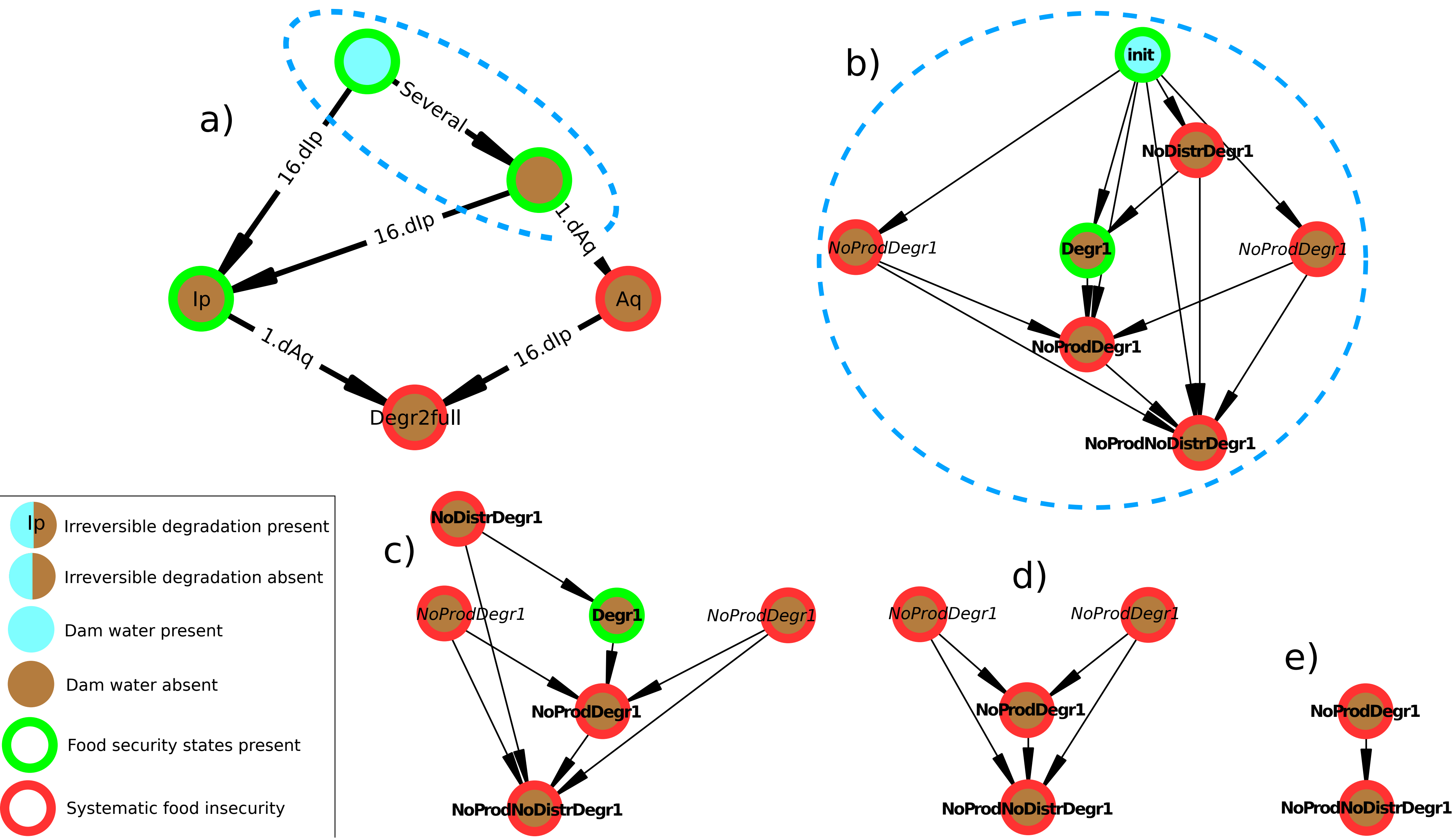


Figure6

Click here to access/download;Figure;Fig6.eps