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Anticipatory action and resilience in the Sahel pastoral region: Geoethical considerations in exploring the potential of coupling a regional early warning system with simulation modelling as a semi-qualitative case study in the development sector

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Abstract

Artificial Intelligence (AI) and machine learning have been taking an increasing role in analysing and monitoring socioeconomic vulnerability, especially regarding food systems in relation to geohazards. These methods require a large amount of data that are not always available at the field level, nor are they exempt from bias. Instead, more empirical qualitative approaches, such as case studies, seem more appropriate when analysing human-geosphere intersections. Therefore, efforts need to be made to establish how a case study approach can better inform AI and machine learning, what is the added value, and how do decision makers avoid missing important developments in anticipatory action.

The case study approach may help current AI methods to make them more reliable and *better; hence, there is interest in benefitting from them. Case studies are suitable for explaining complexity through data triangulation. At the same time, they allow a quick rate of return in terms of understanding complex interrelations between humans and nature, particularly when related to climate change and conflict risk assessments. Furthermore, they can be used together with machine learning methods to calibrate the validity of results and can, especially, be used as training data in machine learning. Finally, and perhaps most importantly, case studies bring transparency to scientific methods because they are not an extractive method, but apply iterative heuristics recognising the users' experience and giving legitimacy to results; in turn, it is necessary to ensure impact and durability of decisions in the humanitarian and development sector. However, case studies are labour intensive and, therefore, it is only possible to have a limited number of case studies that serve to inform extrapolation methods using AI and machine learning techniques.*

This paper makes a conceptual review of the, as yet, unresolved inter-linkages of risk, vulnerability, resilience, and adaptation concepts, suggesting a georisks adaptive governance framework considering geoethical principles. Furthermore, it provides an example of how to apply this framework by coupling an early warning system in the Sahel region with systems dynamic modelling under a case study approach in order to observe the impact of adaptation strategies in relation to cultural resilience in food systems in the development and humanitarian sector.

Keywords: Geosphere; Early warning system; Simulation modelling; Case study; Geoethics

1. Introduction

Broadly defined, georisks [Bobrowsky, 2013] are the result of human-geosphere intersections[1]. Human-geosphere intersections [Bohle, 2016] are characterised by reciprocal effects and feedbacks, emergent properties, non-linearity, thresholds, time lags, heterogeneity, and couplings across spatial and time scales. The increasing complexity, irreversibility, and uncertainty of human-geosphere intersections in the Anthropocene demand for more anticipatory action in supporting decision making in

[1] A complete reasoning of the use of the term geosphere can be found in Bellaubi [2024b].

humanitarian and development sectors. This need is in line with increasing scholarly literature on concepts such as vulnerability, adaptation, and resilience in relation to the above-mentioned risks. Different scholars [among them: Cutter, 1996; Birkmann, 2006; Soares et al., 2012; Wisner et al., 2012; Wolf et al., 2013; Lei et al., 2014; and Moret, 2014], have tried to provide a comprehensive approach to these risk-related concepts, but definitions are continuously commented and reviewed by scholars and international organisations [Estoque et al., 2023; Ishtiaque, 2022]. Hereby, it is important to highlight that "the study of the Earth, its history and how it works provides essential knowledge, experience, and guidance on how to meet many of society's most acute planetary challenges in the Anthropocene." [Stewart and Gill, 2016].

Risk management is associated with decision support systems to analyse: (a) the current level of risk, (b) the best risk reduction alternative, (c) changing risk due to possible future scenarios[2], and (d) the best "change-proof" alternative, the alternative that behaves best under possible future scenarios [van Westen and Greiving, 2017]. Hence, analysis of future alternatives through forecasting allows anticipatory action as a set of actions taken to prevent or mitigate potential disaster impacts before a shock or acute impacts are felt [IFRC, 2022].

Vulnerability is a major component in risk assessments. van Westen et al. [2011], as many geoscientists, considers vulnerability related to spatial and geostatistical analysis in relation geohazards' probability exposure. In the last decade, Artificial Intelligence (AI) and machine learning have been taking an increasing role in analysing and monitoring vulnerability, especially regarding food systems, at the global and national levels using an indicators-based approach [Vuppalapati, 2022] to extrapolate data [Yousefzadeh and Cao, 2022]. These methods rely on optimisation [Sadeghi et al., 2022] as unsupervised clustering data (K-means clustering, Self Organising Maps and Principal Component Analysis). "However, such index-based approaches have three significant drawbacks: 1) Index-based approaches do not account for complex interdependencies (feedbacks and cascading effects) among urban social, physical, institutional, and natural components during the disaster recovery process. 2) They do not account for the dynamic process of resilience, which could result in neglecting potential critical thresholds of urban systems. 3) They are difficult to validate and test." [Yabe et al., 2022, p.3].

Therefore, it would be interesting to look for other approaches to better understand the "why" of vulnerability, how it relates to exposure of geohazards, and what the triggers are of adaptation processes toward hazards in order for territories to become more resilient in reducing environmental degradation [Depietri, 2020]. Bellaubi [2024]

[2] According to Godet [1994], a scenario is a totality made up of the description of a future situation and of the sequence of events which facilitates evolution from the original situation to this future situation (the set of events must demonstrate a certain coherence).

presents the concept of georisks adaptive governance at the core of anticipatory action considering human-geosphere intersections, bringing together the knowledge from the social geosciences [Cendrero et al., 1992; Panizza, 1996], human ecology framework using systems thinking [Dyball et al., 2020] and geoethics [Peppoloni and Di Capua, 2022]. The concept of human-geosphere intersections enlarges that of socioecological systems and Coupled Human And Nature Systems (CHANS). The CHANS framework emphasizes consideration of all aspects of nature including not only environmental processes in the term of "human-environmental systems" but also other dimensions (e.g., hydrological, climatic). CHANS includes not only social dimensions but also many other human dimensions (e.g., economic, cultural) that are not emphasized in the term of "social-ecological systems" [Liu et al., 2021, p.1178]. Human-geosphere intersections are founded on the human impact on biogeochemical and geodynamics processes that affect resources' allocation and distribution, exposing vulnerable populations, in relation with human rights [Watts and Bohle, 1993; Cutter, 1996; Bellaubi, 2024a] and spatial justice [Soja, 2010]. Human-geosphere intersections occur through technocratic artifacts and integrity of governance mechanism, grounded in epistemologies of power that relate to cultural values, beliefs, and worldviews [Bellaubi, 2024b]. Consequently, wrong adaptation strategies of vulnerable populations to cope with the disruption of biogeochemical and geodynamics processes may end up with environmental degradation and resource depletion, increasing the devastating effects of geohazards and decreasing the resilience of the system. This idea is at the core of the concept of the noosphere, or the energy of human culture as defined by Vernadsky [1938].

Human-geosphere intersections encompass the concept of territory. "The territory is not simply the place where one was born or lives by chance, but it is the physical, cultural, and valuable support of one's life, a valuable resource, and, above all, one of the founding values of human identity, thus a good to be preserved. Furthermore, rediscovering the identity value of the territories can lead to cultural change and a growth in responsibility in most of societies, thus understanding the importance of developing policies for land protection and prevention of risks". [Peppoloni, 2023]. This makes the point that to improve territorial resilience, it is necessary to consider the geoethical and cultural value dimension [Mehta and Chamberlain, 2023].

Therefore, anticipatory action relates to georisks adaptive governance on three aspects (Figure 1): 1) risk knowledge geohazards forecasting, monitoring tools and information dissemination, 2) governance mechanisms articulated through decision support systems considering cultural values, and 3) social learning through appropriation that allows moving effectively from anticipation to action fostering response capacities of vulnerable populations to increase territorial resilience. As human-geosphere intersections unfold in complex systems, simulation modelling coupling forecasting and vulnerability analysis that consider cultural values and geoethics may be of special interest. Accordingly, geosprospective modelling has been proved to be useful by looking at territorial resilience regarding climate change and other geohazards, evaluating its spatial impacts using simulation [Garbolino and Baudry, 2021]. Geoprospective modelling stresses the fact that: i) its purpose is not finding the best prediction or the best solution to a problem, but aims at better understanding the future changes to enrich the decision-making process; ii) the spatial dimension takes a major role in the modelling; the goal is to detect how the spatial system reacts to an event, a natural or human change, a national policy or an increasing practice; and iii) generally, there is a strong relationship between the model and the field [Voiron-Canicio, 2012]. Geosprospective modelling goes hand in hand with geogovernance, which is "an approach that leads to a shared knowledge to co-construct the territories of the future. The particularity of geogovernance is to use spatial analysis as a vector of territorial knowledge. In this way, the acquisition, modelling, representation and transfer of complex territorial knowledge will be possible under conditions that promote interaction and articulation between expert knowledge and the know-how of civil society" [Masson Vincent et al., 2012].

The geoethics of georisks adaptive governance unfolds in two principles of prevention and responsibility. Prevention, which is implemented by considering adaptation strategies that improve the resilience of human communities, and reduce the extent of economic and environmental effects of hazards to restore and improve environmental health and human well-being, is an ethical duty [Peppoloni and Di Capua 2022]. The responsibility principle refers to the implications of geosciences' research to produce and implement valid and tailored scientific results according to societal needs, to develop educational and dissemination tools, and to cooperate and support decisions-making processes with key social actors in relation to prevention [Peppoloni, 2023]. This means developing, reviewing, and critically questioning the variety of models attempting to represent a specific reality, assuring the following: models must be built so that processes and analytical procedures are transparent and accountable to the broader society; modelers must be ethically committed to the principle of responsibility and prevention; models must reflect the diversity of cultural values of the vulnerable populations at risk; and models must be clear in their purpose and use. In the same way, Houet [2022] suggests four principles, namely: 1) relevance to justify the choice of a model; 2) transparency or the ability of the user to understand and explain the functioning of the model use; 3) plausibility by carrying out a simulation on a past period and comparing it with an observed situation; and 4) coherence must demonstrate that new spatio-temporal processes can be simulated in coherence with other existing or new processes.

This extends to good geoethical practices in modelling human-geosphere intersections such as:

1. Stakeholders' participation in setting objectives, processes, and results seeking for legitimacy.
2. Recognition of diversity of knowledge, values, and nature agency.
3. Spatial representation of unequal allocation and distribution to georesources environmental degradation and geohazards.
4. Ensure transparent methodology and results using modelling protocols.
5. Due accountability of results through open peer-reviewed evaluation.
6. Ensure governance capacities for effective "localized"[4] decision making through institutional integration.

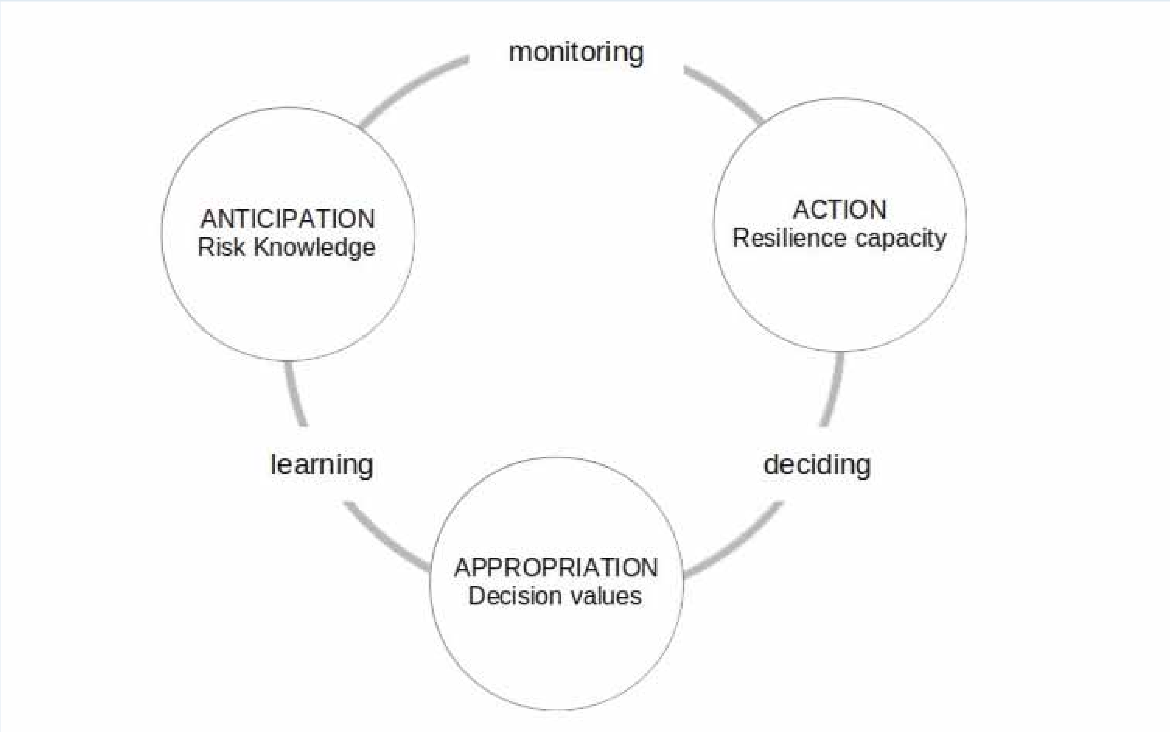

Figure 1. *The "3As" of the Georisks Adaptive Governance Cycle.*[3]

[3] https://voiceeu.org/publications/voice-out-loud-37-anticipatory-action-shaping-the-future-of-humanitarian-response.pdf (accessed 23 December 2024).
[4] https://www.humanitarianlibrary.org/sites/default/files/2021/07/Localization-external-policy-brief-4-April-2.pdf (accessed 23 December 2024).

2. The case of the Pastoralism Early Warning System in the Sahel

Sahelian pastoralist populations face environmental fragility, limited capacity to cope with climate change shocks, seasonal climatic conditions, and regional conflicts. To overcome this situation, a better understanding of the exposure-adaptation cycle of vulnerable populations at risk is necessary to develop anticipatory action. The Pastoralist Early Warning System (PEWS)[5] in Sahel, financed by different interational development donors and launched in 2007 by Action Against Hunger, is based on satellite analysis to forecast seasonal biomass production anomalies. Information analysis is made through a dual system based on remote sensing and data collected from sentinel posts, providing two independent layers of information. The analysis of Dry Matter Productivity (DMP), or biomass anomalies, from satellite imagery is also used to derive surface water availability. The analysis of DMP is helpful as a measure of vulnerability for pastoralist communities.

PEWS relies on the monitoring of socioecological vulnerability quantitative indicators through a network of field collectors called pastoral sentinels distributed all along the Sahel region in a geo-localised analysis of livestock seasonal maps, quantity of water resources and their status, animal health and health facilities, and, lastly, the occurrence of conflict events.[6] This analysis draws on bimonthly surveys distributed through SMS/mobile phones across a set of sentinel sites in Burkina Faso, Mali, Niger, Mauritania, and Senegal. A regional pastoral network, Réseau Billital Maroobé (RBM), also takes part in the data collection process. This analysis is distributed through a website in bulletins every three months. However both components, quantitative forecasting of biomass anomalies related to geohazards (drought and flooding periods due to rainfall variation) and qualitative socioecological vulnerability (monitoring of local food prices, animal health, security conflicts, and access to water and food for cattle) are not currently coupled in order to produce a risk cartography.[7]

Risk is a dynamic concept meaning it is important to understand how vulnerable populations in a territory adapt when they become exposed to climate and conflict-related geohazards. Therefore, forecasting is not enough to assess risk. It is essential to also understand the pastoralist adaptation strategies that shape territorial dynamics when exposed to geohazards. At present PEWS does not have a simulation model that relates how territorial dynamics of exposure-adaptation of

[5] https://sigsahel.info/en/ (accessed 23 December 2024).

[6] Although relative long data records of sentinels are available, sentinel data are very limited in terms of spatial outreach (several kilometers from the sentinel).

[7] Sahel pastoral surveillance system-phase 2. ACH internal document. Author: Padonou F., February [2023].

different vulnerable groups happen in relation to geohazards forecasting. As such, information on pastoral sentinels remains very locally limited, without dismissing their added value in terms of worthy information, in understanding the dynamics and evolution of the territorial system. Instead, system dynamics modelling that couples forecasting climate change data with that provided by the sentinels would allow simulation of possible future risk scenarios and may empower herders to take informed actions to improve access and management of seasonal pastures. As a result, to move from an early warning system based on forecasting to anticipatory action, it is is necessary to develop a risk-resilience dynamic simulation model informing decision support system for a better georisks adaptive governance; coupling satellite biomass production anomalies with data provided by sentinels related to socioecological indicators. The risk-resilience dynamic model may be calibrated and adjusted according to data provided by the sentinels. Hereby, there are two main points to consider in the development of the dynamic simulation model. First, the model does not search for a statistical representation or correlation, extrapolating climate conditions that determine biomass anomalies with socioeconomic conditions reported by the sentinels. Rather, it seeks comparative aggregation, meaning the model only reflects the specific reality of a location and is refined and fined tuned by comparing and aggregating knowledge of other sentinels' locations and following a case study approach. Second, the advantage of the above apparent limitation is that it is possible to have a discrete overview of a large region with different climate, conflict, and socioeconomic spatially distributed conditions in accordance with sentinels' locations.

3. Methodological proposal

3.1. Conceptual framework

There is extensive literature in the development sector relating to conflict, climatic change, and economic crisis affecting human well-being and environmental health, which consequently affects vulnerability in terms of unequal access and distribution of water, energy, food, and health services resulting in hunger and malnutrition (The Lancet[8]; ICRC[9]); [Adger, 1999; Scherr, 2002; Gray and Moseley, 2005; Gregory et al., 2005; Abbott et al., 2017; Ridoutt et al., 2019; Brown et al.,

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[8] https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(18)32822-8/fulltext (accessed 23 December 2024).

[9] https://www.icrc.org/sites/default/files/topic/file_plus_list/double_vulnerability_0.pdf (accessed 23 December 2024).

2020; Friel et al., 2020; Maurya et al., 2020; Subramaniam and Masron, 2021; Nuwayhid and Mohtar, 2022]. Equally, changes in the water, energy, food and health systems can mitigate climate change and reduce all forms of malnutrition [Dietz, 2020].

Food security [Ericksen, 2008a; 2008b] in relation to water, energy and health is a concept that demands a better understanding in the scope of these relationships considering the resilience of human-geosphere intersections. Blanchet et al. [2017] and Lebel et al. [2006] define resilience as a measure of the amount of change a system can undergo and still retain the same controls on structure and function or remain in the same domain of attraction. In a similar vein, Blanchet et al. [2017] associate resilience with absorptive, adaptive, and transformative capacities. Adaptiveness is the capacity of the (vulnerable) actors in a system to respond to stresses and shocks [Blanchet et al., 2017]. For Adger and Brown [2009, p.110], adaptation, as an attribute of vulnerability together with exposure and sensibility, "is the ability of a system to evolve in order to accommodate environmental perturbations or to expand the range of variability with which it can cope." The same authors define sensibility as "the extent to which a human or natural system can absorb the impacts without suffering long-term harm or some significant state change." For Blanchet et al. [2017], absorption relates to the capacity of a system to continue to deliver the same level (quantity, quality, and equity) of services. According to Gallopín [2006] and Jozaei et al. [2022], it is possible to relate resilience to adaptation capacity and vulnerability. For Gallopín [2006], exposure, sensibility, and capacity of response define vulnerability.

The concept of vulnerability relates to that of resilience [Adger, 2000; Miller et al., 2010]. According to Chambers [1989], the most vulnerable individuals, groups, classes, and regions are those most exposed to perturbations; they possess the most limited coping capability, suffer the most from crisis impact, and are endowed with the most circumscribed capacity for recovery. In other words, vulnerability can be defined in terms of exposure, capacity, and potentiality. Paloviita et al. [2017] relates vulnerability to exposure, coping capacity, and adaptive capacity. van Westen and Greiving [2017] give a more quantitative approach to vulnerability. Vulnerability is the degree of damage to a specific element-at-risk given the local intensity caused due to the occurrence of a hazard scenario and risk is conceptually presented as the following basic equation: Risk = Hazard × Vulnerability x Amount of elements at risk [van Westen and Greiving, 2017]. Depietri [2020], following Turner et al. [2003], defines social-ecological vulnerability as the extent to which environmental degradation and climate change cause negative changes in exposure and susceptibility, and in the capacity of the social–ecological system, to anticipate, cope, and recover from the hazard.

This is a very interesting turn in the definition of vulnerability because it acknowledges that adaptation strategies may have negative impacts on the social-ecosystems, thus increasing the impact of hazards on vulnerable populations. This double aspect of vulnerability in relation to the environment depends on the active or passive role of humans and is presented by Panizza's [1996] seminal work; in such a way that impacts are the consequences of human activity on an environment (induced hazards) and risks are the consequences of hazards on a situation of vulnerability. Canseco and Bellaubi [2022] relate impact and vulnerability to territorial risk and resilience. In line with this, the contribution of the human ecology systems thinking framework is significant, especially when related to food systems.

Because of the lack of conceptual consensus between scholars in analysing the complexity of these relationships, Bellaubi [2024a] proposes the framework of Figure 2 (adapted from Fu et al. [2022]; Nuwayhid and Mohtar [2022]).

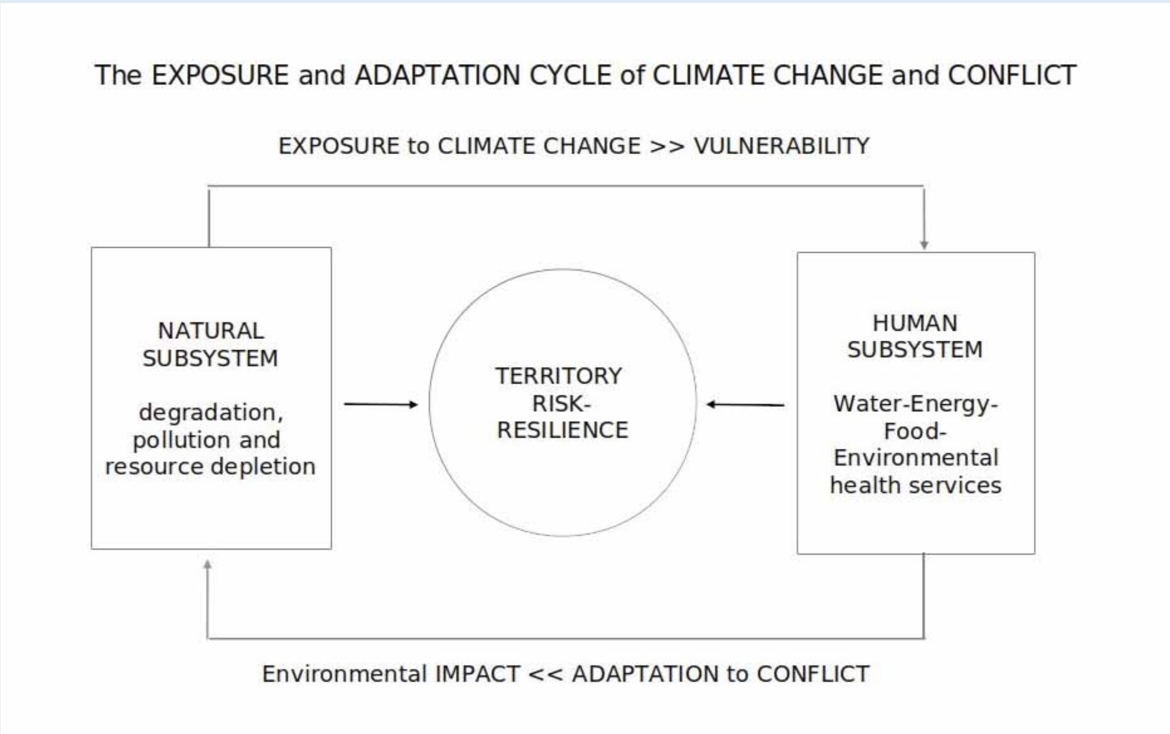

Figure 2. *The exposure-adaptation cycle in human-geosphere intersection.*

The exposure-adaptation cycle (Figure 2) describes human-geosphere intersections, where humans impact biogeochemical cycles that, in turn, modify geodynamic processes affecting human vulnerability. This implies that a vulnerable population exposed to climate change seeks to adapt because of governance conflicts arising in allocation and distribution of water, energy, food, and environmental health services. In turn, adaptation has an impact on environmental services and natural resources (water, soil, and air pollution, degradation and depletion), which in turn increases exposure. Both vulnerability and impact determine the resilience of the system under risk. Resilience happens when vulnerable populations at risk adapt by using different coping strategies over time. The feedback loop of the cycle can be positive or negative. The focus of the analytic framework is to measure the evolution of system resilience in an exposure-adaptation cycle in terms of water, energy, food, and environmental health services in relation to pollution and degradation as necessary (but unknown if sufficient) to achieve food security. Hereby and in line with some scholars [Panter-Brick, 2015; Holtorf, 2018; Cutter, 2019; Mehta and Chamberlain, 2023], resilience within a territory is defined as the processes of rebuilding community bonds through innovative adaptation, reducing socioeconomic vulnerability exposure considering the cultural land use value [Canseco and Bellaubi, 2022], and ensuring access to water, energy, food, and a healthy environment in line with the Universal Declaration of Human Rights (UDHR)[10]. However, it is important to highlight that vulnerability do not result of exposition to geohazards but rather the opposite, meaning vulnerable groups become exposed because neither represented nor recognized and their lack of capacities in coping with socioeconomic and cultural exploitation and exclusion, resulting in unequal allocation and distribution to georesources, environmental degradation and geohazards [Bellaubi, 2024b]. Therefore, adaptation strategies mimic agency asymmetries of power (domain), or abuse of power for the benefit of individuals or groups, and show the absence of effective accountable governance mechanism. This geopolitical[11] approach to vulnerability has considerable implications in terms spatial justice [Soja, 2010] and human rights, pointing out the underlying values of the technocratic artifacts that determine the human-geosphere intersections.

The conceptual framework, representing the described human-geosphere intersections in terms of the risk-resilience relations, can be expressed considering

[10] https://www.un.org/en/about-us/universal-declaration-of-human-rights (accessed 23 December 2024) and UN Resolution A/RES/76/300 on the human right to a clean, healthy, and sustainable environment.

[11] "Geopolitics refers to the fact that politics have become international in scope, but rather that geology today lies at the center of political concerns, whether the issue is climate change, endangered species, natural resources, or the siting of roads and landfills". Frodeman [2003].

the work of Panizza [1996] and Cendrero and Panizza [1999], according to the simplified set of equations:

*Risk = geohazards * (vulnerability exposure)* (1)

*Impact = georesources * (vulnerability adaptation)* (2)

Based on empirical generalisations of Vernadsky [1938] [in Korobova and Romanov, 2014] and the postulate that the biogeochemical situation observed in any point of space could be interpreted quantitatively as a result of a combined impact of natural and technogenic factors, risk may be derived:

Risk to geohazard = f (environmental impact of adaptation, socioeconomic vulnerability exposure) (3)

where resilience is expressed as a variation on time of the socioeconomic vulnerability.
In the context of food security and land evaluation associated to climate change geohazards (drought flooding and landslides), socioeconomic vulnerability exposure of different social groups, communities or household types may be calculated according to different adaptation strategies of land use types following Lagorge [2001] and van der Zee et al. [2001]. Thus, cultural resilience of a territory shows the ability to cope when faced with different exposition levels through adaptation strategies considering users' experience and knowledge [Heijboer, 2020]:

socioeconomic vulnerability (days) = (household cash-flow) ÷ (basic needs costs) (4)

3.2 Method

Case studies are a suitable research method because of the explanatory nature and the necessary holistic approach to human-geosphere interactions in a specific territory. Case studies are a bottom-up research method focusing on field evidence of a specific location. They use data triangulation that allows building narratives and contributing to find solutions to current challenges with a quick rate of return involving key stakeholders in advocacy initiatives. Case studies are useful when analysing complex systems because of triangulation, combining quantitative and qualitative data, observation, and information from different sources [Bans-Akutey and Tiimub, 2021]; searching for data stops when information becomes redundant. Case studies do not seek a statistical representation, but the understanding of a specific situation of system patterns over time and space, which means focusing on specific vulnerable sectors of a population (considered as statistical anomaly). Case studies are based on comparative aggregation [Levi-Faur, 2006]; therefore, it is possible to have a better understanding of the complex system in terms of structure, agents, and relationships between them [Yin, 2014].

Based on similar research, Bellaubi and Visscher [2016], show that a few case studies covering rural areas and periurban-urban locations at country level can be representative enough to establish the exposition of vulnerable populations to different hazards, in such a way that allows comparative aggregation. The resulting empirical generalisations allow building a simulation model to represent hazard and environmental relationships observed in different case studies affecting different or specific vulnerable groups within a territory.

Case studies may be enriched with simulation modelling such as system dynamics coupled with geospatial analysis resulting in georisk cartographies (maps) showing different scenarios. A System Dynamics (SD) model "consists in a set of ordinary differential equations that makes a stock-and-flow representation of the studied system. SD models are conceived as a structure made up of causal feedback loops including nonlinear relationships and delays" [Martínez-Valderrama et al., 2020, p.2]. SD modelling of case studies has been selected as a simulation modelling method to couple geohazards and conflicts with socioeconomic vulnerability because it allows capturing emergent patterns that can be observed using large-scale observations [Yabe et al., 2022]. Furthermore, SD modelling has been used to display the complex interplay between climate change and food security through a number of relevant academic works [Phalkey et al., 2015; Pongsiri et al., 2021] as well as in relation to land use and food security [Cleaves et al., 2015; Turner et al., 2016]. Another important point is that SD also considers the ethical dimension in informing ethical and sustainable decision making and integrity in governance mechanisms [Kunsch et al., 2007]. Dynamics system modelling relies on participatory systems thinking as a key previous element to build a reliable model applied to food systems [Davila, 2020]. Similar works have been conducted by Cleaves et al. [2015] and Oyo and Kalema [2016] in the scope of food security, Khairulbahri [2020] and Wen et al. [2022] on water-energy-food nexus, Xu and Coors [2012] and Bassi and Gallagher [2020] in showing different geospatial scenarios, and especially the research of Herrera and Kopainsky [2020] on agricultural farmers' resilience, and Martínez-Valderrama [2020] in applying an early warning system to desertification and pasturage.

According to Martín García [2003, p.24], "The viewpoint of Systems Dynamics is radically different from that of other techniques applied to the construction of models based on a behaviourist approach. Empirical data are used as the basis for statistical calculations to determine the direction and correlation between the different factors. The evolution of the model is carried out on the basis of the past evolution of the variables called independent, and statistics are applied to determine the parameters of the system of equations that relate them to the other variables called dependent. These techniques aim to determine the behaviour of the system without entering into the knowledge of its internal mechanisms. On the other hand, the basic objective of Systems Dynamics is to understand the structural causes that provoke the behaviour of the system. This implies increasing knowledge about the role of each element of the system, and seeing how different actions, carried out on parts of the system, accentuate or attenuate the behavioural tendencies implicit in it. As a distinguishing characteristic from other methodologies, it can be said that it is not intended to predict future behaviour in detail. Studying the system and testing different policies on the model will enrich our knowledge of the real world, verifying the consistency of our hypotheses and the effectiveness of the different policies."

4. Application of the methodology to PEWS

Based on the work of Fillol et al. [2020], the methodology unfolds in two steps: an impact-vulnerability mapping of pastoralist populations exposed to climate change events and conflicts, defining a territory case study. This is coupled with a territorial SD modelling to evaluate the environmental impacts of the possible adaption strategies in a specific location of exposed herders' communities.

The case study builds around a sentinel or group of sentinels in the territory of Selibaby. The most important role of sentinels' networks at field level is to collect quantitative information. This should allow to calibrate the model as well as to help interpret the results. The area of Selibaby (7083 km^2) in the department of Guidimaka in the south eastern border of Mauritania with Mali and Senegal has been chosen as a case study. This is because of the boundary cattle movements and concentration of animals (around 54000 cattle, goats, sheep, and camelids between February and March 2024). It is also a large area of biomass production (Dry Matter Productivity) that ranges from 1.5 M Tn in 2021 to 2.0 M Tn in 2023, with relatively stable food prices through the season according to data provided by International Organisation for Migration (IOM), Réseau Billital Maroobe (RBM), and PEWS (2023)[12].

[12] https://dtm.iom.int/sites/g/files/tmzbdl1461/files/reports/GUIDIMAGHAA%20-%20EVALUATION%20DE%20LA%20MOBILITE%20ET%20DU%20CHANGEMENT%20CLIMATIQUE%20ECHO%20R2%20Fevrier%20mars%202024.pdf (accessed 23 December 2024). https://www.inter-reseaux.org/wp-content/uploads/BULLETIN-DE-VEILLE-MAI-JUIN-2024.pdf (accessed 23 December 2024). https://geosahel.info/Viewer.aspx?map=Biomass_Production. https://sigsahel.info/wp-content/uploads/2023/04/ACF_bulletin_prix_marches_N7_Mauritanie_fevrier_mars_2023.pdf (accessed 23 December 2024).

According to Fillol et al. [2020], only a part of biomass (30%) is used as rangeland pasture.

4.1. Impact-Vulnerability mapping and definition of the case study area

The impact-vulnerability mapping relates to environmental degradation and resources depletion impacts associated to adaptation strategies when vulnerable pastoralists exposure to climate change related geohazard (drought and flooding due to rainfall probability variation) and reported armed conflicts. As mentioned, an important point is that exposure is intrinsic to vulnerability as a manifestation of asymmetries of power in a specific territory, expressed through governance mechanism and technocratic artifacts as adaptation, that define allocation and distribution to georesources and geohazards:
Definitions of cartographic zones overlapping (1) spatial probability of climate change related geohazards (flooding, drought, and landslides), (2) environmental degradation (soil, water, and atmospheric pollution) associated to land use-cover resulting of vulnerable types adaptation strategies, and (3) violent conflicts (migration arrivals and confinement areas). The geospatial analysis is done using satellite data and geoecological maps at medium scale and field reconnaissance. In the case of PEWS, soil degradation due to overgrazing in specific transhumance corridors, resulting from traditional governance mechanisms to access pastures, is crossed with conflict events and biomass seasonal production anomalies as showed in Figure 3 [Fillol et al., 2008].
Characterisation of the zones by socioeconomic vulnerability types is according to: (1) economic capability aiming to define cash flows at the household level as production units (income, capital, employment stability, socioeconomic structure, housing, illness and disabilities, gender, and consumption of basic goods and environmental services, and (2) integrity in allocation rights and distribution of georesources, basic goods and environmental services, and geohazards[13]. Primary data (household surveys, semi-structured interviews, and focus groups), as well as secondary data, define the vulnerability types or profiles. In the case of PEWS, sentinel networks provide indicators about access water and pastures (biomass), animal health, security, and food market prices, but not on the governance mechanisms of whom, how, and when determine the allocation and distribution to georesources and environmental services (Figure 4).

[13] Drinking water, cooking and heating energy, basic food basket, primary healthcare, housing, primary education, cultural and recreational facilities, and commuting transport.

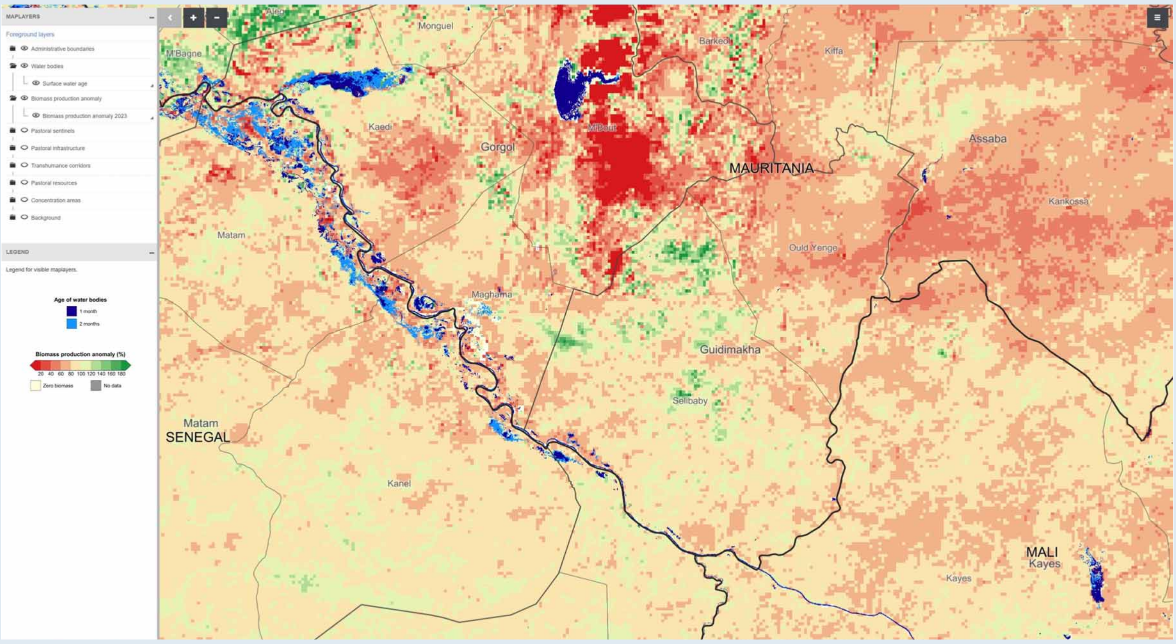

Figure 3. *Biomass production season anomalies 2023 (source: PEWS).*

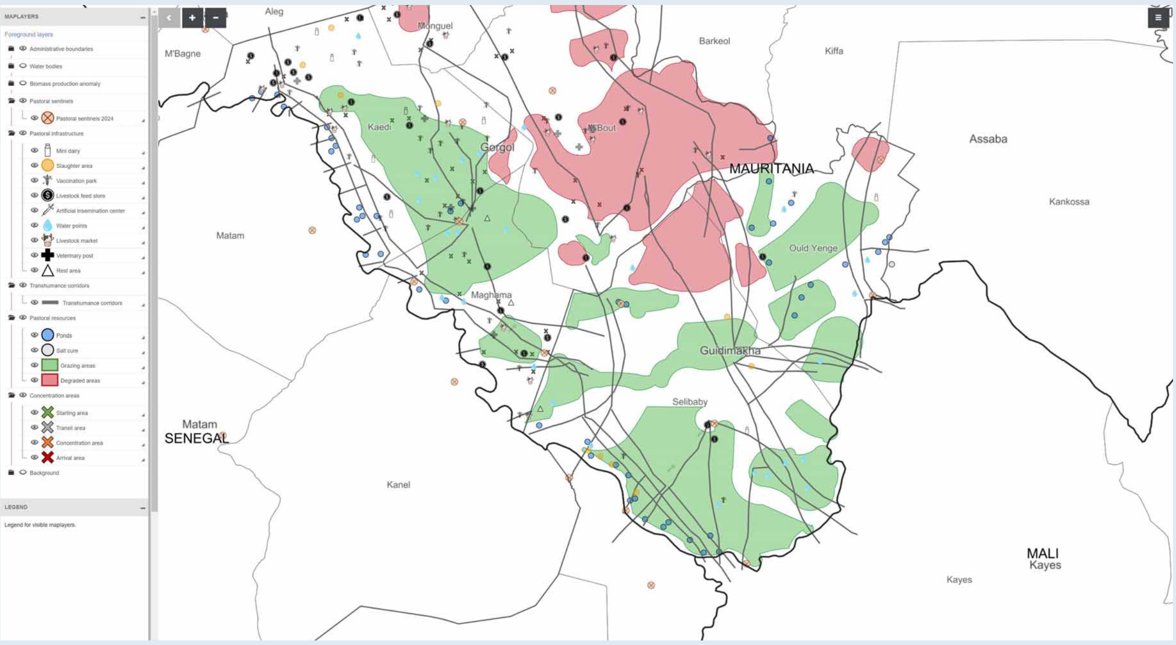

Figure 4. *Impact-vulnerability mapping (source: PEWS).*

4.2. Case study dynamic simulation modelling[14]

As mentioned, the SD model should build on the comparative aggregation of territorial case studies representing similar vulnerable groups or typologies in different impact-vulnerability zones. The model uses macro quantitative data at the regional level such as the biomass production anomalies and field quantitative data and observations provided by the sentinels. The construction of the model may be co-produced and validated with the participation of main regional stakeholders, sentinels' networks using companion modelling [Etienne, 2010] or collaborative conceptual modelling [Newell and Proust, 2012; Neely et al., 2019]. Because of time limitations of the current research, the current SD model is developed using the only data available for the Selibaby location with 20 sentinels. However, this does not diminish the interest of the research in showing the viability and advantages of simulation modelling of possible adaptation strategies of vulnerable types. The PEWS' sentinels do not provide information about income and expenditure at the household level. Therefore, socioeconomic vulnerability in terms of food security (Eq. 3) could not be calculated. Figure 5 presents the stocks, flows and variables of the simulation model. The model simulates the evolution of the price of rangeland pastures in the Selibaby location. The main feed resources for grazing ruminants are pastures and crop residues [Bayala et al., 2014; Amole et al., 2022]. Therefore, anomalies on biomass production and animals' demand affect animal food prices and, consequently, household expenditure over cash-flows in order to feed animals when pastures face a shortage by the end of the rainy season. Hereby, the adaptation strategies to biomass anomalies are mainly migration and overgrazing [Ouédraogo, 2021]. Residual biomass or pasture is represented in the model as a stock that changes through the year according to animal consumption (flow). Because of the heterogeneity of herds (cattle, goats, sheep, and camelids) in different proportions, consumption needs in the area have been set at 2.5 Tn/Month*animal for an initial herd of 50,000 animals. Initial biomass value is set from the calculated biomass anomaly from PEWS at the starting of rainy season in July (month 1 in the model). Residual biomass is affected by a regeneration rate during the rainy season that changes according to a consumption ratio per animal with a maximum rate of 1.45. The model developed three possible scenarios for the Selibaby location. A first scenario considering a biomass anomaly of 1.5 Tn/Year with a stock of 50,000 animals; a worsening second scenario that reduces the biomass production in the case of drought at 1.0 Tn/year; and a final third scenario that considers an increasing migration of animals due to conflicts and an insecurity in the region in relation to the previous second scenario.

[14] Vensim DSS Software, Ventana Systems, Inc., Harvard, MA, USA, 2006; https://vensim.com/ (accessed 23 December 2024).

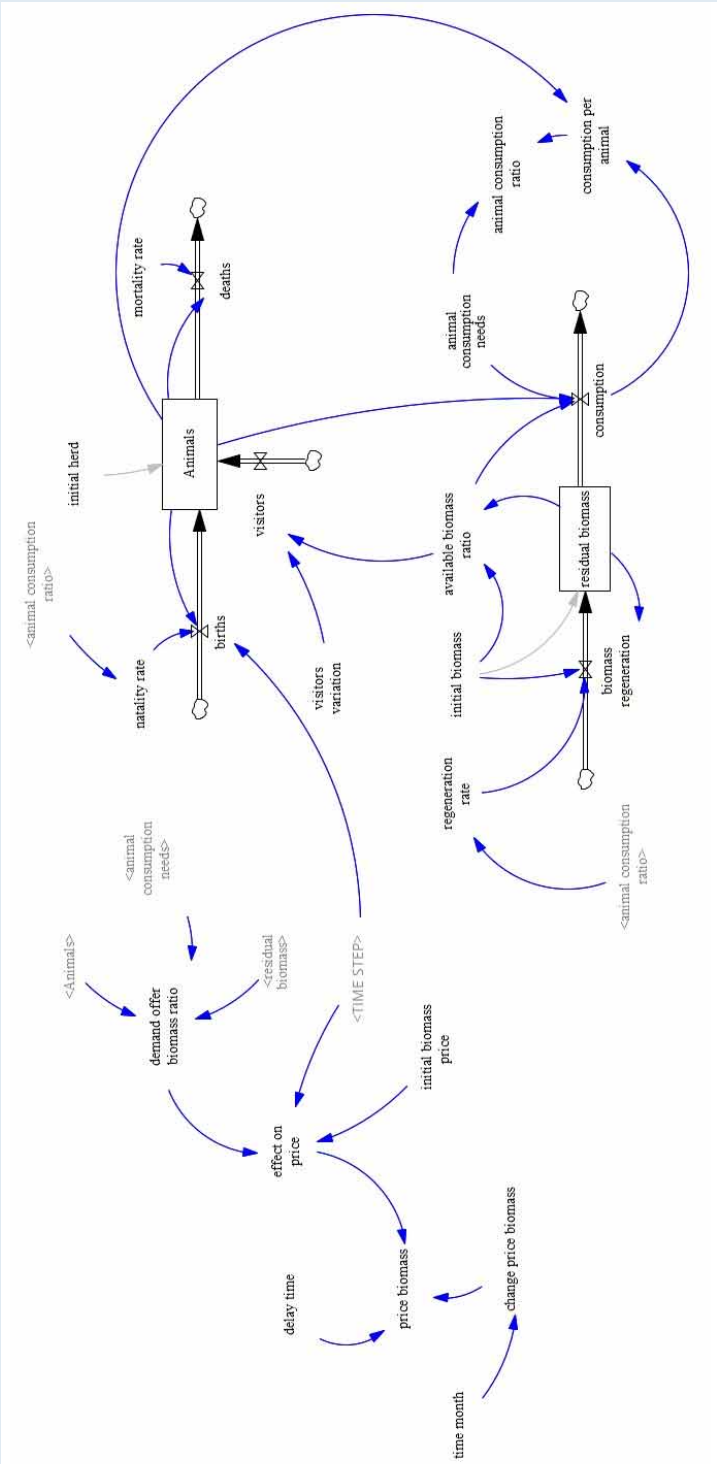

Figure 5. *A pastoral system dynamics model in the Selibaby location.*

4.3. Discussion of results

A sensibility analysis using the average absolute deviation shows that the migration of animals is the most influential variable on price of residual biomass (pastures). Comparing the three scenarios, the residual biomass stock never reaches a level close to overgrazing. In terms of socioeconomic vulnerability, price evolution of pastures has a similar evolution in the three scenarios, increasing significantly at the end of the dry season, which is the period of the year when households may experience budget stress (Figure 6).

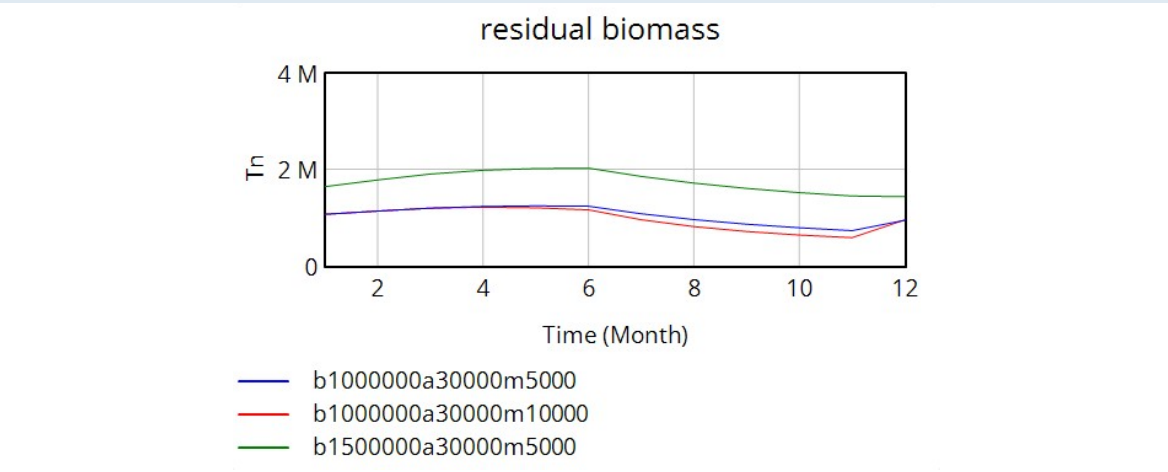

Figure 6. *Evolution of residual biomass: scenario 1 (green), scenario 2 (blue), and scenario 3 (red).*

The bimonthly PEWS report from February to March 2023 in the Guidimaka Wilaya, where Selibaby is located, shows a price variation from 20 MRU/50 kg (400 MRU/Tn) to 50 MRU/50 Kg (1000 MRU/Tn)[15]. Although the 2023 season had a positive anomaly (1.05%) with production of almost 2.0 M Tn, a simulation with a 0.78% anomaly (1.5 Tn/Year) does not show a significant change in the scenario's price change (Table 1). This may be due to the fact that, in any of the three scenarios, the residual biomass or pasture does not reach a level at the end of the dry season that impacts significantly on animal needs' consumption (Figure 7). Therefore, herders

[15] https://sigsahel.info/wp-content/uploads/2023/04ACF_bulletin_prix_marches_N7_Mauritanie_fevrier_mars_2023.pdf (accessed 23 December 2024).

do not need to purchase extra pasture, although in some cases they buy forages and, eventually, fodder to complement animal feeding.

Time (month)	Scenario 1 (MRU/Tn)	Scenario 2 (MRU/Tn)	Scenario 3 (MRU/Tn)
0	430	430	420
1	430	430	420
2	429	429	419
3	428	428	419
4	423	424	412
5	412	416	401
6	394	401	382
7	390	402	377
8	425	439	410
9	547	564	531
10	699	716	682
11	806	822	788
12	817	833	787

Table 1. *Monthly residual biomass price (MRU) per Tn in scenario 1, scenario 2, and scenario 3.*

When considering the adaptation strategies in relation to cultural resilience (scenario 3), increasing animal migration flows due to insecurity in the Sahel region disrupts traditional transhumance corridors. These flows have been preserved over time as a coping mechanism in front droughts, and are part of the nomadic traditional way of living and identity in relation to human-geosphere intersections. Thus, the disruption of biogeochemical cycles, ends in overgrazing (Figure 4) increasing vulnerability of pastoral communities and decreasing the carrying capacity of territories that lately may result in the common pool resources dilemma [Hardin, 1968].
Land evaluation for extensive grazing [FAO, 1988][16] is an option to better understand how to relate land quality with land use requirements; in order to increase productivity without overriding carrying capacity at the same time as preserving pastoralist identities. Without a deep technical knowledge of soils, climate, and human community interconnectedness giving a value to land use, technocratic artifacts, such as food security policies, "green walls," and governance mechanisms, will fail in vain. Of course, land evaluation must include herder's knowledge and user's expertise to avoid being left in the hands of technicians and technocrats, just as georisks adaptive governance moves from anticipation to action through appropriation.

[16] https://www.fao.org/4/t0412e/t0412e.pdf (accessed 23 December 2024).

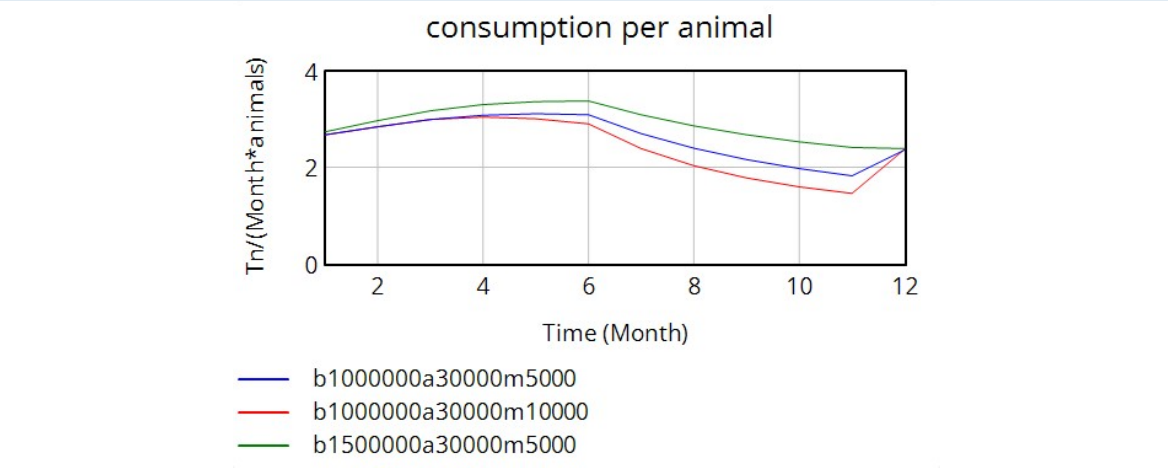

Figure 7. *Evolution of animal consumption: scenario 1 (green), scenario 2 (blue), scenario 3 (red).*

5. Conclusions and future developments

As pointed out by Bellaubi [2024a], anticipatory action is highly dependent on data extractivism. At the same time, data without a sociocultural context are meaningless, and numerical data cannot capture the complexity of reality. One of the challenges posed by artificial intelligence and machine learning methods is the atomisation of the human-geosphere intersections and so, the data scientism in the age of Anthropocene engages in a sort of dehumanisation and denaturalisation. For Silvia Peppoloni, "The major issue of our time is the trend towards atomization and reductionism, which does not enhance diversity but rather destroys the possibility of meaningful encounters, trapping everyone in the comforting individualism of their own narrow perspectives" (personal communication).

This paper shows that it is possible to overcome this reductionism under a conceptual framework and methodology in order to better understand human-geosphere intersections; as is the case of the vulnerable pastoralists in the Sahel affected by geohazards such as rainfall variability and droughts that determine seasonal biomass production anomalies.

Although forecasting is a key element in risk knowledge, as one of the pillars of anticipatory action, characterisation of vulnerability cannot be reduced to the statistics of big data analysis. The use of case studies modelling using SD allows interpreting a specific situation within a broader context, frequently hidden in the nuances of spaces of vulnerability and representing inequality distribution and allocation of georesources. In this way, the paper suggests to rethink the concept of vulnerability making the bridge between the geopolitics of power and geoethical thinking that should be at the core of decision-making processes and governance mechanisms, especially considering the most vulnerable communities. Case studies, as a method, recognise people's knowledge in being able to cope with geohazards increasing a cultural resilience, giving voice to the most vulnerable, which has considerable ethical implications from a Human Rights' rights perspective. Thus, DS modelling allows capturing the territorial evolution of adaptation in a way that the future does not depend entirely on the past, but on transformative [Holtorf, 2018] and frequently counterintuitive [Forrester, 1971] capacities and innovation in communities in their relationship with the geosphere.

Case studies may work as living labs [Higgings and Klein, 2011] to evaluate strategies and policies in synergy with local actors, foster local innovation and community-based strategies based on cultural resilience as co-production processes [Canseco and Bellaubi, 2022] with the following added value:

1. Case studies promote bottom-up modelling versus top-down modelling approaches, engaging and empowering communities to participate in research adopting a citizen science component[17].
2. The case study approach considers quantitative data from the field in triangulation with quantitative data, improving model variable calibration.
3. Case studies foster georisks adaptive governance and social learning considering knowledge of the human-geosphere intersections, knowledge of objectives, and knowledge of the process transforming current situations into future resilient territories; in parallel, carrying out monitoring and evaluation through benchmarking.
4. Using case studies facilitates the continuous decision-making process of improving governance of georesources (geogovernance) and land use planning, which is key for food systems sovereignty, fostering soil productivity, and reducing exposure to geohazards.

Beyond socioecological frameworks that focus on institutional governance, and political ecology analysis on territorial asymmetries of power, exploring the geoethical dimension of human-geosphere intersections using case studies coupling mapping and modelling, it may bring a better understanding of the challenges ahead. The researcher and modeller do not change the reality with a

[17] https://citizenscience.org/ (accessed 23 December 2024).

model, simulating the results of "good or bad" decisions, because all models are wrong [Sterman, 2002]. As Pablo Picasso (1881-1973) said, "art is the lie that allows us to understand the truth"; models are that "lie" that helps us to glimpse reality through its decomposition into categories, variables and indicators [Flores-Gutiérrez and Orozo-Hernández, 2023]. Instead, the hermeneutics of the modelling process challenges the modeller, transforming and confronting the modeller's understanding of the problem. This is not only about how models are used from an ethical perspective, but how models recognise the voice of the most vulnerable, their values, beliefs, and knowledge, and how they represent unequal patterns in the integrity of georesources and geohazards' allocation and distribution.

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Appendix: SD Model equations

```
(01)    animal consumption needs=
        2.5
    Units: Tn/(animals*Month)

(02)    animal consumption ratio=
        consumption per animal/animal consumption needs
    Units: Dmnl

(03)    Animals= INTEG (
        visitors+births-deaths,
            initial herd)
    Units: animals

(04)    available biomass ratio=
        residual biomass/initial biomass
    Units: Dmnl

(05)    biomass regeneration=
                    (residual  biomass*regeneration  rate)-STEP(residual
biomass*regeneration rate
    ,6)+STEP(initial biomass-residual biomass,11)
    Units: Tn/Month

(06)    births=
        (natality rate*Animals)/TIME STEP
    Units: animals/Month

(07)    change price biomass = WITH LOOKUP (
        time month,
                                                                ([(0,0)-
(11.9029,1000)],(1,400),(2,400),(3.78987,366.935),(
    4.91222,318.548),(6.19491,346.774),(6.99659,451.613

),(7.89448,725.806),(8.82443,951.613),(9.69025,1000),(10.6843,939.516),(
    11.45,596.774),(11.9029,411.29) ))
    Units: coins/Month
```

```
(08)    consumption=
        animal consumption needs*Animals*available biomass ratio
    Units: Tn/Month

(09)    consumption per animal=
        consumption/Animals
    Units: Tn/(animals*Month)

(10)    deaths=
        (mortality rate*Animals)
    Units: animals/Month

(11)    delay time=
        3
    Units: 1/Month

(12)    demand offer biomass ratio=
        (Animals*animal consumption needs)/residual biomass
    Units: 1/Month

(13)    effect on price=
        (initial biomass price*demand offer biomass ratio*TIME STEP)
    Units: coins

(14)    FINAL TIME  = 12
    Units: Month
    The final time for the simulation.

(15)    initial biomass=
        1.5e+06
    Units: Tn

(16)    initial biomass price=
        400
    Units: coins

(17)    initial herd=
        30000
    Units: animals
```

```
(18)    INITIAL TIME  = 0
    Units: Month
    The initial time for the simulation.

(19)    mortality rate=
        0.02
    Units: 1/Month

(20)    natality rate=
        0.02*animal consumption ratio
    Units: Dmnl

(21)    price biomass=
        SMOOTH((change price biomass+effect on price),delay time)
    Units: coins

(22)    regeneration rate = WITH LOOKUP (
        animal consumption ratio,
                                                        ([(0,0)-
(0.606936,0.055645)],

(0,0.01),(0,0.01),(0.531792,0.0217742),(0.716763,0.0375),(0.786127,0.05685
48

),(0.83815,0.0822581),(0.883305,0.120025),(1.00144,0.145),(1.1117,0.13273)

,(1.22984,0.111555),(1.29311,0.09159),(1.39523,0.069205),(1.45189,0.049090
9
    ),(1.75145,0.0272177),(2,0.01) ))
    Units: 1/Month

(23)    residual biomass= INTEG (
        biomass regeneration-consumption,
            initial biomass)
    Units: Tn

(24)    SAVEPER  =
            TIME STEP
    Units: Month [0,?]
```

```
    The frequency with which output is stored.

(25)    time month=
        TIME BASE(0,1)
    Units: Dmnl [0,1]

(26)    TIME STEP  = 1
    Units: Month [0,?]
    The time step for the simulation.

(27)    visitors=
              PULSE(2,  4  )*(visitors  variation)-PULSE(6,4  )*(visitors
variation*available biomass ratio
    )
    Units: animals/Month

(28)    visitors variation=
        5000
    Units: animals/Month
```

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