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Modelling and Decision Support for a Desertification Issue Using Cellular Automata Approach

Alassane Kone

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UNIVERSITÉ DE GUYANE
DOCTORAL SCHOOL N°587 : SANTÉ, DIVERSITÉS
ET DÉVELOPPEMENT EN AMAZONIE

T H E S I S

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Defended by

Alassane KONE

Modelling and Decision Support for a Desertification Issue Using Cellular Automata Approach

Thesis directed by Samira EL YACOUBI and Allyx FONTAINE

prepared at IRD of Guyane , LABORATORY ESPACE-DEV

defended on DECEMBER 20, 2023

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ABSTRACT

Desertification, as one of the major challenges impacting life on Earth, has far-reaching consequences that degrade the quality of human life, their daily activities, and their livelihoods. In response to its effects, international organizations have implemented various actions aimed at slowing down its progress and/or reducing its impacts.

This thesis is dedicated to addressing the fight against desertification. Its primary objective is to model the process of land degradation that ultimately leads to desertification. To achieve this, two models have been developed within this research.

The first model is based on a combination of continuous Cellular Automata and the MEDALUS assessment, which was developed by the Mediterranean Desertification and Land Use (MEDALUS) project of the European Union. The initial step involves assessing land degradation using the MEDALUS model, which evaluates desertification based on a sensitivity index derived from the geometric mean of four quality factor indexes : soil, vegetation, climate, and management(land use). This assessment method considers the significant parameters influencing the land degradation process. The second step involves modelling the land degradation process using a cellular automaton approach. The study area is divided into a grid of cells, and each cell's state (desertification sensitivity index) evolves over discrete time steps based on the states of its neighbouring cells, determined by a built transition function.

To incorporate essential properties of desertification, such as the transfer of activities, the initial model is enriched with anthropogenic factors, including land use practices, exploitability, and ownership. This enhanced model, referred to as the *Enhanced Model of Desertification*, offers the advantage of assigning weights to desertification factors. The weight assigned to each factor reflects its importance in the desertification process.

The *Enhanced Model of Desertification* serves as the basis for designing a decision support tool named DESERTification Cellular Automata Software (DESERTICAS). DESERTICAS is a specialized Cellular Automata software that models and simulates the spatio-temporal evolution of land degradation. It combines the continuous cellular automaton approach with the MEDALUS model while incorporating factors such as land use practices, exploitability, and ownership. By utilizing an initial configuration, DESERTICAS can simulate the progression of land degradation over time and space. The software is fully parameterized, providing flexibility in exploring various scenarios.

As a result, the two models introduced in this thesis facilitate the incorporation of dynamic processes into the MEDALUS model. They simulate the temporal and spatial evolution of an area by utilizing a transition function that incorporates continuous states. This expands upon the classical approach of Cellular Automata, where states are discrete, to cellular automata with continuous states. However, the *Enhanced Model of Desertification* offers a more comprehensive approach by enabling a detailed description of the microscopic processes associated with desertification.

One significant aspect of the developed models is the ability to identify a predominant factor that influences the entire system. The subsequent contribution of this thesis involves extracting this predominant factor from those already involved in the desertification phenomenon using the [DESERTICAS](#) software. Through a comparative analysis of the effects of different desertification factors, the predominance of management, which represents human actions, is highlighted in the the *Enhanced Model of Desertification*. Taking positive action on the management factor indirectly affects other desertification factors, interrupting degradation sources and slowing down or halting land degradation.

The final contribution of this thesis involves the adaptation and application of control theory to the two-dimensional Cellular Automata model on which [DESERTICAS](#) is based. This entails directly influencing the predominant factor by fixing its mean intensity. Using Genetic Algorithms, the intensity of the identified predominant factor (management) is determined. The objective of combining control theory and Genetic Algorithms is to integrate land protection actions into desertification simulations, specifically within the [DESERTICAS](#) software, thus transforming it into a decision support tool.

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abbreviations list

CA Cellular automata or Cellular automaton	2
GAs Genetic algorithms	2
DESERTICAS DESERTification Cellular Automata Software	iii
UNCCD United Nations Convention to Combat Desertification	6
SER Society for Ecological Restoration	15
UNCOD United Nations Conference on Desertification	16
UNCED United Nations Conference on Environment and Development	16
PACD Plan of Action to Combat Desertification	16
COP Conference Of the Parties	17
CST Committee on Science and Technology	17
GGW Great Green Wall	17
UN United Nations	14
MEDALUS Mediterranean Desertification and Land Use	iii
LADA Land Degradation Assessment in Drylands	20
FAO Food and Agriculture Organization	20
GIS Geographic Information System	20
SIEL Système Intégré pour la modélisation et l’Evaluation du risque de désertification	20
SSD Spatial System Dynamic	20
SSD Stochastic System Dynamic	20
NDVI Normalized Difference Vegetation Index	20
UNEP United Nations Environmental Program	26
ACRI Conference on Cellular Automata for Research and Industry	52
IConETech The International Conference on Emerging Trends in Engineering and Technology	52
INCD Intergovernmental Negotiating Committee	16
GHCA Greenberg-Hastings Cellular Automaton	44
FAO Food and Agriculture Organisation	20
DSI The Desertification Sensitivity Index	xi
EU European Union	17

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INTRODUCTION

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Abstract This introductory chapter sets out the context and issues related to the modelling of an environmental phenomenon such as desertification. Thanks to our work, by proposing a decision support tool, desertification can be properly understood and analysed under constraints that can be parameterised to match reality.

1.1 General context

Environmental issues are among the ills that undermine the quality of life on earth and considerably degrade human activities. Due to the seriousness of its consequences, desertification is one of the environmental issues of our century. Indeed, it is presented as a specific type of natural resource degradation including soils and threatens vast territories on all continents. Its intensity varies in time and space, as well as its causal factors. The research laboratory, UMR ESPACE-DEV, through its commitment and its long experience of cooperation in the Sahelian and Mediterranean region, is interested in this issue. Through its research activities, UMR ESPACE-DEV emphasizes the importance of observation tools, of analysis and environmental monitoring. This aims to a better understanding of the processes inherent in the phenomenon of desertification, their organization in information and knowledge systems and their mobilization in environmental observatories.

1.2 Problematic

To understand desertification, the first step of our work is to model it formally. Our approach consists in combining a desertification assessment method based on field data with a model of computation based on cellular automata (Cellular automata or Cellular automaton (CA)). The phenomenon of desertification is then considered as a spatial property verified by the state of the studied field in certain areas said to be vulnerable or sensitive to desertification. The state evolution of these areas is predicted through the dynamics of the built model that is used for our decision-support tool. This tool can then be used for prediction purposes.

Genetic algorithms (GAs) are associated with CA to introduce protective actions in order to reduce or slow down the impacts of the desertification process. The termination of the constructed GAs are determined by the mathematical theory of controllability in CA.

The studied field is divided into cells in order to identify the microscopic rules of transition as well as the mechanisms of interaction between cells in order to obtain the macroscopic behaviour of desertification. This approach corresponds to the use of CA. CA are fully discrete dynamic systems that can constitute a powerful simulation environment in which a set of transition rules allows to determine the state of each cell taking into account the characteristics and states of the cells in its neighbourhood. Despite their simplicity at the microscopic description level, emergent properties characterizing complex systems can be observed. This is what makes them very attractive for modelling and simulating natural systems containing a large number of identical components with local interactions and a spatio-temporal dimension. These models, which have a simple architecture, have been used successfully in several fields including the modelling of complex systems, image processing, pattern recognition, etc.

GAs are evolutionary algorithms using terminologies from biology. Their aims is to solve an optimization problem when there exists no exact solution method. The

solution must be determined in a reasonable time and approximates to the best the desired value through the optimization of a cost function. **GAs** offer great simplicity in solving complex problems.

1.3 Contributions

The main contributions of this thesis are :

- to develop a generic methodology that allows the assessment of vulnerability indices of desertification. The indice used is the one for sensitivity to desertification developed in the MEDALUS project. This indice is based on the assessment of four main desertification factors, which are soil, vegetation, climate, and management. Each of these factors is a grouping of its main characteristics referred to as sub-factors ;
- to determine the fundamental properties of desertification allowing to characterize its microscopic processes. These properties will serve as a basis for the extraction of the evolution rules allowing to build a **CA** model. The first property used in the context of our modeling is combination of desertification factors. Indeed, desertification is the advanced stage of a land degradation process that results from a combination of various factors. This typically includes deforestation, over-exploitation of soils, unsustainable agricultural practices, climate change, and other environmental and human factors. This process leads to the transformation of once-fertile lands into desert or semi-desert areas. The second property is the irreversible nature of desertification. Indeed, when land degradation reaches a certain advanced threshold, the process becomes naturally irreversible, and restoring it requires immense resources. The pressures on land are also considered as a desertification property. Land experiences two primary forms of pressure, both of which result from external factors contributing to degradation. The first form, known as stress, encompasses conditions that limit the land's productivity capacity, including factors like water availability, mineral nutrients, and sub-optimal temperatures. Stress is closely linked to extreme climatic conditions and aridity, and severe stress hampers the recovery or reestablishment of vegetation. The second form, referred to as disturbance in this context, is tied to the partial or complete destruction of land components and is frequently a consequence of intensive human activities ;
- to model an area by a built **CA** and predict its spatio-temporal dynamics according to its interactions with the neighbourhood. In built **CA**, each land area is divided into cells whose evolutions over time depend on a built transition function based on desertification properties. Two models is developed in this context. In the first model, based on a coupling of **CA** and the MEDALUS model, the state of each cell evolves based on desertification sensitivity indices of neighbouring cells. Meanwhile, the second model addresses the limitations of the previous one by incorporating additional desertification factors

from the MEDALUS model such as exploitability, land ownership and land use. The constructed CA served as the basis for the development of a decision support tool to monitor the evolution status of a land area ;

- to introduce protective actions in the desertification modelling by combining the last modelling CA, GAs and the concept of controllability in CA. Indeed, after identifying management as the predominant factor, land degradation can be stopped or slowed down by addressing it. Therefore, GAs is used to determine the appropriate value of management to bring the system back to a desired state. The determined management value is used to apply control theory to the built CA, thus influencing the land degradation process.

1.4 Thesis plan

This manuscript is organized as follows. In the next chapter, a general overview including a state of the art on desertification process is presented. CAs, used in the modelling, are described in Chapter 3. Chapter 4 describes the main lines of the desertification modelling by integrating the properties and factors of desertification. The results of the realized models are listed in a software called DESERTICAS whose design and basic elements are described in Chapter 4. The integration of action in the achieved model is done in Chapter 5 through the combination of the controllability notion, the GAs and modelled CA. At the end of this thesis, a general conclusion and some perspectives are given.

DESERTIFICATION ISSUE

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Abstract The application of the work led in this thesis is the complex system of desertification. Thus, it is advisable to make its in-depth study in order to clearly identify all its contours and extract the basic elements used for its modelling. This chapter aims to make this bibliographical synthesis while taking care to clearly define desertification as well as its main characteristics.

2.1 Desertification : a land degradation

Land degradation is a natural or human-induced process that negatively affects the land by preventing it from functioning effectively within an environmental system [89]. The process of degradation reduces or destroys the capacity of land for agricultural, vegetable and animal productions, and also for forest production [95]. Indeed, it refers to the reduction of the current and the potential of the land to produce quantitatively/qualitatively goods or services by various processes [67] and first affects the soil, the main component of the land. When the degradation of soil reaches a certain degree of severity, the others components of the land are also gradually affected : nature and density of vegetation spontaneous, the dynamics of water on the ground and in the soil, the nutrient reserves, the fauna of the soil, crop yield, farming method and type of land use [95, 89]. It also affects soil and water conservation in terms of quantity and quality [97]. Indeed, in degraded land less water can be infiltrated and rainwater in this case becomes surface runoff [97].

Land degradation leads to the deterioration of physical, chemical and biological or economic properties of soils, and long-term the loss of natural vegetation [133, 24, 97] as presented in Fig. 2.1. Indeed, depending on their causes, this degradation can take different forms including the loss of nutritive matter, the loss of topsoil surface, the loss of vegetation, landslides, increased salinity and soil acidification, soil pollution, etc. [101, 24, 96].

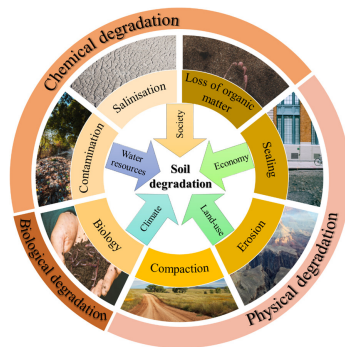


FIGURE 2.1 – Major land degradations [24]

2.1.1 Desertification, what is it ?

The word desertification has a Latin origin : -fication, which means the action of doing (or creating) comes from fieri, the passive form of the verb facere, to do, while desert is derived from both the adjective desertus, meaning uninhabited, and the noun desertum, a desert area [80]. Since its origins, the concept of desertification has been shrouded in controversy and ambiguity. As a result, no single definition of the term has been acceptable [58]. Contrary to widespread opinion, desertification is not the transformation of the land into desert neither the displacement of sand dunes [133]. Indeed, according to United Nations Convention to Combat Desertifica-

tion (UNCCD), desertification is defined as the degradation of soils, landscapes and terrestrial bio-productive systems in arid, semiarid and sub-humid areas, resulting from several factors such as climate change and human activities [133, 33, 98]. This degradation occurs everywhere, but it is defined as desertification when it occurs in dry areas [133]. Indeed, the unsustainable use of the land resources in these areas leads to their deterioration reaching unrecoverable levels [25]. Desertification is the advanced or final step of the degradation process [55, 26] and creates similar conditions like those of the desert [133, 97]. The system goes from an alternately stable state to a *desertified* state [96, 26]. The land degradation process is also a factor of the reduction or loss of biological and economic productivity of lands, pastures and forests [133]. This process takes various forms depending on the component of the land affected. Indeed, desertification can directly affect the soil which will degrade over time, disappear and move through the process of erosion [101]. However, it can also affect vegetation which will be uprooted or unable to regenerate [96]. It can also be expressed by the scarcity of water resources [84].



FIGURE 2.2 – A baobab tree in an arid landscape in eastern Kenya (Source : World Bank / Flore de Preneuf)

2.1.2 Areas subject to desertification process

Areas subject to desertification are dry areas, namely arid, semi-arid and sub-humid regions [97]. These areas are characterised by a Index of Aridity denoted by IA [133] (cf. Tab.2.1) and defined in Eq.(2.1) :

$$IA = \frac{P}{PET} \quad (2.1)$$

where P is the ratio of precipitation and PET is potential evapotranspiration defined as the amount of evaporation that would occur if a sufficient water source were available.

Area	IA	Share of the world's land- surface
Arid	$0.05 \leq IA < 0.2$	12.1%
semi-arid	$0.2 \leq IA < 0.5$	17.7%
sub-humid	$0.5 \leq IA < 0.65$	9.9%
Total drylands	$0.05 \leq IA < 0.65$	39.7%

TABLE 2.1 – Dry areas according to the aridity index and Share of world's land-surface

These areas, subject to desertification, are dry and characterized by low, infrequent, irregular and unpredictable rainfall; large variations between day and night temperatures; soils containing little organic matter and little water, and a fauna and a flora adapted to climatic variations (drought-resistant, adapting to salt water and able to withstand the lack of water) [133, 84]. Fig.2.3 shows the distribution of areas subject to the process of desertification on Earth.

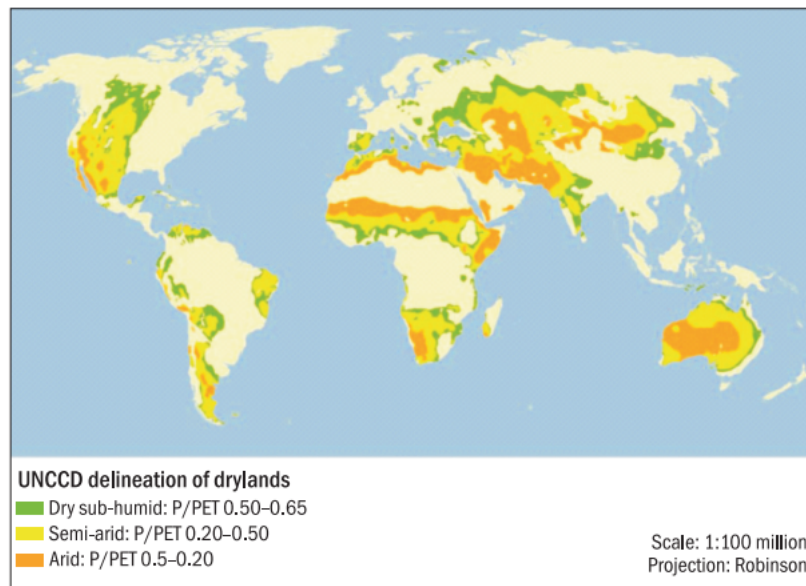


FIGURE 2.3 – Global distribution of drylands (Source : Sorensen (2007))

Most of the planet's 2000 million dryland residents live in developing countries. The vast majority lives below poverty line and without adequate access to fresh water. Drylands take up 41.3% of the Earth's land surface and up to 44% of all cultivated land is in the drylands. Drylands support 50% of the world's livestock, account for nearly half of all farmland, and are major wildlife habitats. Because of the difficult climate conditions, drylands have given rise to an incredible diversity of highly specialized species[99]. This biodiversity is essential for maintaining the eco-balance and protecting human livelihoods, which depend on it. A relatively high

number of endemic species occupy these areas, which include diverse habitats such as sandy land, forest and woodland, savanna and steppe, wetlands, ponds, lakes and rivers [133].

2.2 Desertification factors

Desertification is a very complex process and its magnitude depends on factors like environmental conditions and human activities [42]. It is a specific degradation in drylands and results from human activities or it is a natural phenomenon aggravated by the effect of human activities [95]. The factors leading to desertification have significant negative effects on several environmental components of which the soil is the first affected by this process.

2.2.1 Factors leading to desertification

Once the physical, chemical and biological components of the soil are affected, natural regeneration is not possible in a human lifetime [101]. The factors that can lead to this change in land state can be grouped into three types, namely biological, human and climatic factors [96].

2.2.1.1 Anthropogenic factors

In countries where major economic resources are dependent on agricultural activities, there are few alternative sources of income, or none at all [133]. Thus, a combination of human factors leads to increased pressure on dryland ecosystems to provide services such as food, fodder, energy, construction materials as well as water for watering humans and livestock, for irrigation and sanitary needs [136].

Soil is damaged by excessive use when farmers neglect [1] or shorten fallow periods, which are necessary to allow the soil to recover sufficiently to produce enough food to feed the population. This in turn causes the soil to lose organic matter [25], limiting plant growth and reducing vegetation cover. The bare soil is more vulnerable to the effects of erosion [133]. The main human activities which are desertification factor are described below.

- Over-cultivation exhausts the soil; indeed, the intensification of agriculture promotes erosion and loss of soil nutrients when the nutrients exported in crops exceed those provided by atmospheric deposition or by fertilizers [96].
- Overgrazing removes the vegetation cover that protects it from erosion and causes salt accumulation in shallow soils [96, 97, 26].
- Deforestation destroys the trees that bind the soil to the land [133] and thus affects the vegetation which is the main source of soil protection [45];
- Poorly drained irrigation systems turn croplands salty [133]. Indeed, salt accumulation can lead to a partial or total loss of the soil ability to provide the amount of water needed by plants [97, 106].

- Irrigation with water of high salt concentration increases soil salinity causing unproductive desert land [26].
- Unsustainable agricultural practices, resulting from poor land management, cause soil erosion and salt accumulation in shallow soils [96, 97, 133]. This type of land management is the consequence of a lack of knowledge on the part of users of remote agricultural areas from the center of decision-making, political instability in developing countries, pressure on ecosystems at through accelerated population growth (need for housing, food and resources) and a lack of public policy on the use of agricultural land [96].
- Bush and forest fires lead to the loss of vegetation, drastically to the reduction of organic matter in the soil, the inability of the soil to regenerate adequate vegetation and the desertification of the land. Indeed, the rate of erosion increases after the fires and this is due to the absence of vegetation [26].
- Deep ploughing of soil reduces soil depth and water retention capacity and thus contributes to its degradation [93].
- Wood collection and repeated burning destroy vegetation and expose land to degradation process [87].
- Extractive industries increase land degradation by drawing heavily on groundwater, disturbing land and accelerating soil erosion [133].

2.2.1.2 Chemical and biological factors

The chemical factors of desertification are described below.

- The accumulation of salt and other toxic products by the soil caused by the irrigation with poor quality water (deposition of salt after evaporation), exfiltration of water from salty and shallow groundwater (deposition of salts in the subsoil) and drainage of this waters. [96, 84, 133, 70]. The high concentration of salts in the soil gives rise to saline or alkaline soils [80].
- The land acidification caused by poor irrigation practice [133, 104].
- The accumulation of fertilizers and pesticides that may be toxic to human, plants and animals [67, 126, 95].

The major biological factors, responsible for the degradation/desertification of land and their fertility and prevent the growth and the recovery of the population of the vegetation [96], are described below.

- The erosion which poses a serious risk of land degradation and desertification in dryland ecosystems, leading to significant reduction in vegetation growth, siltation of waterways, filling of valleys and reservoirs and delta formation along coastal areas. The leaves that fall from the trees reduce the action of the wind on the surface of the ground [46, 25].
- The removal and depletion of nutrient-rich particles from the soil by intensification of agriculture, water and wind erosion [65, 96, 97, 26, 67];

- The drastic reduction of organic matter in the soil by deforestation followed by intensive agriculture, the burning of vegetation, short fallow periods [26, 133, 100, 67];
- Decreasing soil water content caused by an accelerated evaporation process and a decrease in the infiltration capacity of shallow soils [97, 96];
- Decreased permeability and loss of retention capacity caused by soil compaction by agricultural machinery [70, 96];
- The deterioration of the structure of the earth leads to the formation of crusts on the surface of the soil thus leading to desertification in two ways : by reducing the growth of young plants and by reducing the infiltration of water [26, 95].

2.2.1.3 Climatic factors

The arid, semi-arid and dry sub-humid climatic conditions are characterized by a seasonal climate and also by ecological and soil conditions, which make the ecosystems vulnerable due to the fragility of the environment and the low rate of biomass production during dry periods. Thus, infiltration capacities become low and soil erodability increases [26]. An unequal annual distribution of precipitation and the occurrence of extreme events are climatic factors of desertification. The reduction in rainfall combined with a rate of evapotranspiration drastically reduces the soil moisture needed for plant growth [26]. Aridity is a critical factor in the evolution of natural vegetation through water stress caused by the reduction of vegetation cover [26]. Extreme weather events, such as drought or flooding, can also speed up the degradation process [133]. Indeed, drought occurs when rainfall is significantly below normal recorded levels, causing severe hydrological imbalances with adverse effects on land resource production systems. High temperatures, which last for several months with infrequent and erratic rainfall, lead to drought and difficult growing conditions for plants and trees [75]. As a result, significant hydrological imbalances jeopardize natural production systems [133]. In addition to precipitation, temperature and wind are important climatic factors that can accelerate the process of desertification through the process of evaporation [101]. Indeed, high wind speeds combined with temperature is a determining factor for the assessment of water stress in soils and vegetation in arid and semi-arid areas. High wind speeds do not help soils and plants to retain their water content and this leads to the decline of strong vegetation and the land [101]. Fig.2.4 presents an example of climatic feedbacks of the desertification process.

2.2.2 Factors accelerating desertification

2.2.2.1 Socio-economic factors

A lack of public policy of land conservation, a lack of laws on agricultural land use and the non-application of the policies in force can lead to poor soil management

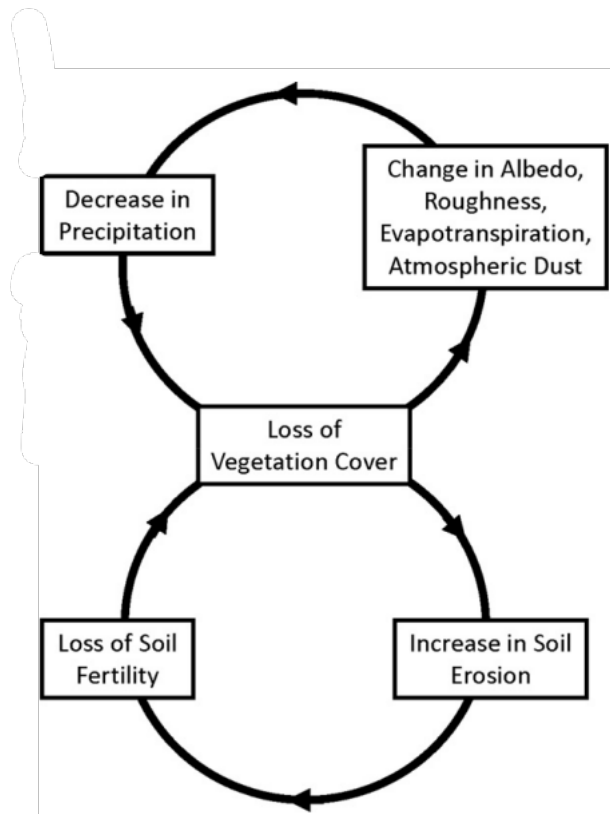


FIGURE 2.4 – Examples of desertification feedbacks [101]

and lack of knowledge on the part of users of agricultural areas remote from the center of decision-making. This type of management is a source of unsustainable agricultural practices and excessive grazing, an accumulation of salt in shallow soils and accelerating soil degradation [96, 84].

Accelerated population growth creates needs for housing, food and resources in drylands. Thus, it causes additional pressures on ecosystems and amplifies the effects of factors responsible of the land desertification [21, 120]. Indeed, population growth leads to an increase in urban sprawl, which thus leads to a decrease in arable land. This decrease in arable land results from the decrease in vegetation cover and causes the process of desertification [84].

2.2.2.2 Slope intensity

The aspect of the slope is considered as an important factor in the process of soil degradation/desertification. Indeed, the aspect of the slope can cause a slow recovery of vegetation and a high rate of erosion, low vegetation cover [26]. Erosion becomes acute when the slope angle exceeds a critical value and increases logarithmically [49, 116].

2.2.2.3 Aridity

Aridity is an overall moisture deficit especially when resulting from a permanent absence of rainfall for a long period of time and under average climatic conditions [73]. Thus, it is one of the main causes of soil vulnerability as regards the degradation factors involved in desertification. Aridity also causes open vegetation covers and a high soil salinization risk [49]. Indeed, it is a critical environmental factor in the evolution of natural vegetation through water stress caused by the reduction of vegetation cover [26]. While the irrigation system buffers some of the effects of aridity, the poor irrigation system contributes to land degradation by increasing salinization [73, 106]. Thus the effects of aridity accentuate the impacts of desertification factors and thus contributes to accelerate land degradation.

2.2.2.4 Climate change

In the long and medium term, climate change will contribute to accelerating the process of desertification, while in the short term, land use practices leading to land degradation can influence climate change [97, 131]. Indeed, climate change affects considerably soil moisture, increases soil drought and aridity. Thus, the soil moisture recycling system, important in the precipitation recycling process, is strongly affected and leads to a spiral of land degradation leading to desertification [96, 41].

2.3 Actions to combat desertification

When the desertification process is underway, the degradation of land structure and its functioning can be corrected by adopting different strategies and arrangements [48]. Indeed, several global initiatives have been launched to combat land degradation evolution, including restoration, rehabilitation [132] and reassignment of degraded drylands.

2.3.1 Degradation prevention

To prevent land degradation, planning methods and conservationist technologies have been developed for different ecosystems. The most common are described below [2] :

- Avoiding using land highly susceptible to degradation.
- Collection, selection, improvement, and storage of native genetic resources.
- Creation, management and recovery of protected natural areas, with rigid exploitation limits.
- Diagnosis of degradation and/or conservation of management zones in areas with potential for agricultural production.
- Use of no-tillage system, with rotation, intercropping and/or succession of crops and/or livestock in agroforestry arrangements.

- Use of resource residues.
- Surface storm-water drainage to promote control of erosion, increase water retention through the construction of small dams, increase water table level (through underground dams), divert upstream waters from gullies (through terraces and catchment areas) or downgrade water level through alternative drainage systems in areas under flooding.
- Train environmental education officers to ensure the training, implementation, management and monitoring of plans, programs for the recovery of degraded lands and also the management and conservation of soil and water.
- Applying good agricultural practices using lands based on their limits and potentialities and maintaining or improving soil chemical, physical, and biological properties. This enables higher soil aggregation, avoids its compression, increases water storage, and the availability of essential nutrients to plant growth.
- Combat the Effects of the Wind by constructing barriers and stabilizing sand dunes with local plant species [42]. Fig.2.5 presents an example of degradation prevention in Brazil. It consists to build terraces to avoid surface drainage in wheat crop.



FIGURE 2.5 – Example of degradation prevention (Brazil) [2]

2.3.2 Restoration

The United Nations (UN) has declared the years 2021 to 2030 as the Decade for Ecosystem Restoration [76]. The term **restoration** is drawn from the science of restoration ecology [4] and it is the most prominent practice among ecologists to

restore ecosystems [4]. Depending on the type of actions carried out, two types of restorations can be observed.

According to the Society for Ecological Restoration (SER), **the restoration sensu stricto** is defined by the re-establishment of the biodiversity, of the structure and features of ecosystems that still have a sufficient level of resilience (non-irreversible degradation) for human intervention to be, if possible, limited to a reduction and then control of its pressure level [48, 52]. **The restoration sensu lato** simply aims to stop degradation and put a degraded ecosystem, but still presenting a sufficient level of resilience, back on the dynamic trajectory it was supposed to be on before the disturbance [48]. Despite this difference, the primary objective of **restoration sensu stricto** and **restoration sensu lato** is to restore the biodiversity, structure and dynamics of the pre-existing ecosystem [48]. Indeed, to restore degraded lands, crop techniques should be improved by stabilizing the soil while enriching them with organic matter, selecting and associating different crop varieties as in polyculture, and reducing land pressure [42].

Furthermore, there are different approaches to ecological and ecosystem recovery, such as rewilding or extreme forms of restoration such as “de-extinction.” This is due to the inherent complexity of assisting nature to recover from anthropogenic harm [4].



FIGURE 2.6 – Half-moons, restoration of a pastoral zone, Niamba plateau, Torodi, Niger, 2017

2.3.3 Rehabilitation

As for **rehabilitation**, it aims to put the ecosystem back on a favorable trajectory by repairing, as quickly as possible, the damaged or simply blocked functions of resilience and productivity through the reintroduction of plant material and soil micro-organisms or even tillage allowing a consequent improvement of its water and

trophic functioning [52]. Thus, intervention through **rehabilitation** constitutes an alternative for the recovery of the vegetation of these ecosystems [32, 54].

2.3.4 Land reallocation

Land reallocation is the general term describing what happens when part (or all) of a landscape, whatever its state, is transformed and assigned a new use. This new state is possibly unrelated to structure and/or functioning with the pre-existing ecosystem [52, 48]. Modifying an ecosystem, through the management that is made of it, in order to favor a particular element or function, at the cost of constant interventions, also constitutes a reassignment [48, 31]. Unlike restoration and rehabilitation, reallocation actions are commonly carried out by the populations. These actions require permanent inputs in the form of energy, water and/or fertilizers [48, 127].

2.3.5 International initiatives to combat desertification

The term desertification was first used by Lavauden in 1927 to describe severely overgrazed lands in Tunisia and was then used by Aubreville in 1949 [3, 58, 87] to show excessive soil erosion due to deforestation in the French West Africa [10]. Subsequently alarmed by this long drought in the sub-Saharan Africa during the early 1970s, the term desertification was then first used to describe this crisis and also first applied politically [58]. Indeed, the General Assembly of UN adopted through its Economic and Social Council, at its twenty-ninth session in 1974, decided as a matter of priority to initiate concerted international action to combat desertification, and to convene in 1977 a United Nations Conference on Desertification to give impetus to the international action to combat desertification. Thus, the United Nations Conference on Desertification (UNCOD) was held at Nairobi from 29 August to 9 September 1977. This conference selected the Lavauden/Aubréville term desertification for communicating on this issue and a comprehensive Plan of Action to Combat Desertification (PACD) was adopted [58, 75, 91, 35, 123]. The adopted definition effectively extended the natural hazard of the Sahel drought into a human hazard by adding a human cause to climatic variation. Thus, desertification was defined by a diminution of the biological potential of land in any ecosystem [10]. Tackling desertification took center stage at the seminar 1992 of United Nations Conference on Environment and Development (UNCED) - also known the Earth Summit - held in Rio de Janeiro. The Rio Conference called on the UN General Assembly to establish an Intergovernmental Negotiating Committee (INCED) to prepare, by June 1994, a Convention to Combat Desertification [44, 35, 123]. At this conference, the definition of the term desertification was revised again during the 1992 UNCED as “land degradation in arid, semi-arid, and dry sub-humid areas, resulting from various factors, including climatic variation as well as human activities” [22, 133]. On June 17, 1992, the UN adopted the United Nations Convention to Combat Desertification (UNCCD) which was established in 1994. The UNCED meaning of the

desertification was chosen by UNCCD to describe this issue [10, 75, 59]. It is the sole legally binding international agreement linking environment and development to sustainable land management. The Conference Of the Parties (COP), the main decision-making body of UNCCD, was established by the Convention. The COP is made up of governments and organizations such as the European Union (EU) and is responsible for guiding the Convention so that it can respond to global challenges and national needs [44, 37, 133, 123]. The COP has been meeting biennially since 2001, and has held 15 sessions where the fifteenth was held for 9 – 20 May 2022 in Abidjan, Cote d'Ivoire. The Committee on Science and Technology (CST) of UNCCD is a subsidiary body of the COP and provides it with information and advice on scientific and technological matters relating to combating desertification and mitigating the effects of drought, using the most upto-date scientific knowledge. The CST is multi-disciplinary, open to the participation of member states, and composed of government representatives with relevant expertise. It reports on its work at each session of the COP [133, 44]. Since the creation of the UNCCD, many initiatives of global scope, for which COP15 will constitute an important milestone, have been undertaken.

The Great Green Wall (GGW) (cf. Fig.2.7) is a major greening initiative launched in 2007 which aims to restore, until 2030, 100 million hectares of degraded land in the 11 countries of the sudano-sahelian zone. It concerns degraded land across the conflict-ridden regions of Sahel, North Africa and the Horn of Africa. In addition to degraded land restoration, it will also allow to sequester 250 million tons of carbon and create 10 million local green jobs and income generating activities among affected communities [105, 76, 47].

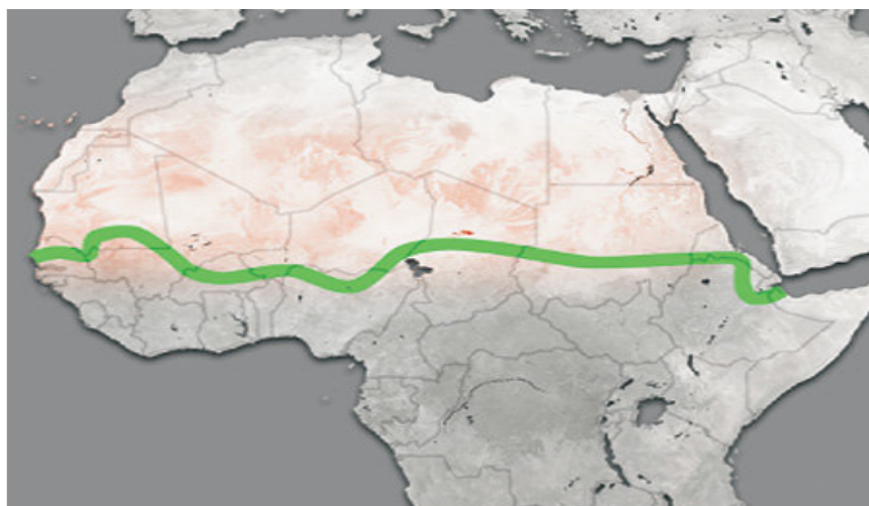


FIGURE 2.7 – Route of Great Green Wall of Africa [47]

In recognition of the date of June 17, 1992 symbolizing the adoption by the UN of UNCCD, the day of June 17 is celebrated as the World Day to Combat

Desertification and Drought. The main purpose of this celebration is to remember the dangers of desertification and drought in the world. This year, the theme of this day is "Together to defeat drought" and it places particular emphasis on the actions to be taken upstream to avoid the disastrous consequences of drought for humanity and planetary ecosystems [92].

Other green wall initiatives include the Three-North Shelterbelt project, also known as the great green wall of China. Initiated in 1978, the plan was to raise a 4,480-km-long wall of trees spanning through thirteen provinces of China. The reforestation project was designed to stop the Gobi Desert from advancing and mitigate the sandstorms that send thick sand dust into the streets of Beijing. So far, 35 million hectares of land has been reforested in 20 years. The initiative is set to reach the goal of increasing the world's forest cover by 10% in 2050. In concert with tree planting efforts, the project contains grazing bans and restricted lumber practices in degraded areas and incentives for planting certain crops [76, 77]

2.4 Desertification properties

The modelling of desertification is based on a knowledge of its elementary processes described by properties.

2.4.1 Factor combinations

Desertification is caused by a combination of factors that change over time and vary by location. These include indirect factors such as population pressure, socio-economic and policy factors, and international trade as well as direct factors such as land use patterns and practices and climate-related processes. [136, 26, 68, 17].

2.4.2 Irreversibility

Desertification has irreversible character because if a disturbance changes the land from the vegetated state to the critical threshold of the degraded state, the removal of this disturbance will not return to the initial state [26, 96]. Indeed, if the process is not well controlled, desertification will become more severe and reach an irreversible state once the climate and/or human disturbance reaches a certain threshold [130]. Also, the excessive loss of soil, nutrients, and sometimes even seeds from the ecosystem affects the capability of the vegetation to recover and constitutes the principal mechanism of irreversible damage to the environment [87]. The Irreversibility of desertification should refer to a situation in which the costs of reclamation were greater than the return from a known form of land use [75].

2.4.3 Transfer operation

In rural areas, land is generally the property of a person, a community or state authorities. Its degradation significantly reduces its plant and its financial productivity and drives operators to explore new land. The exploration of new land is

conditioned by the type of desired use, the usable characters and its ownership. Indeed, a land can be exploited only if it is not exploited, favorable to intended use and belongs to the initiator of the planned activity or has to the approval of its owner. Thus lands, initially unexploited, can be used by its owner by transferring its using from a degraded land to a better quality land with the same characteristics and the same ownership. This transfer operation can only be done by the owner of these two lands or with his agreement [52, 79].

2.4.4 Pressures on land

Two types of pressure are most often exerted on land and these pressures are induced by external degradation factors. The first pressure, called stress, consists of conditions that restrict capacity of land production such as water, or mineral nutrients and sub-optimal temperatures. Stress is related to the extreme climatic factor and the aridity condition of land and severe stress prevents recovery or reestablishment of the vegetation. The second, here referred to disturbance, is associated with the partial or total destruction of land components and most often arises from extreme human activities [40]. Desertification can be defined as the set of all environmental degradation processes in hot drylands (hyperarid, arid, semiarid and sub-humid regions), as a result of either climatic stress or human mismanagement, or both [87]. In sum, extreme levels of the degradation factors, such as climate and human using, generate stress conditions in land and accelerated its degradation [101, 14, 58, 87].

2.5 MEDALUS model

2.5.1 State of the art on the desertification assessment

Given the seriousness of the consequences of this phenomenon, the United Nations has defined strategies for the prevention and control of land degradation. In this context, several common and shared methodologies have been developed in order to assess, model and understand the desertification phenomena.

A first approach is based on the prey-predator model [57, 46, 90]. This method is based on two differential equations, the first of which describes the evolution of the human population used as the predator and the second describes the evolution of natural resources representing the prey in terms of gain and loss as well as their interactions. An improved version of this model incorporates other parameters such as soil and subsoil erosion, costs of production, of investments and the profitability of the exploitation of natural resources in the degradation process. Thus, a dynamic model based on eight equations is thus established[56]. This kind of modelling is limited to interactions between humans and vegetation while neglecting the effects of other important factors [14].

A second approach is to quantify desertification based on indicators associated to its factors [43, 84, 137]. These indicators come from sources of information including

remote sensing images, topographic data, geological data, etc. [7, 45, 95]. MEDALUS is one of the most popular project that was supported by Europe for this issue [26, 84, 97, 43]. It is based on a desertification sensitivity. Another variant uses synthetic indices to assess desertification. This index is an integer between 1 and 5 depending on the degree of land degradation [95].

The third approach uses software or modelling tools based on the quantitative assessment of desertification. Based on MEDALUS approach, POWERSIM simulator [84] provides a temporal evolution of the desertification phenomenon but does not take into account microscopic and spatial changes of the soil degradation. Another software, Land Degradation Assessment in Drylands (LADA), that was developed by Food and Agriculture Organisation (FAO) of the United Nations, aimed at assessing and mapping land degradation at different spatial scales [94]. It is based on the assumption that the main causes of land degradation are due to human activities on the land. However, the assessment is made at a given time and does not integrate the dynamic aspect in the model. In addition and using the Geographic Information System (GIS) platform, the software *Système Intégré pour la modélisation et l'Évaluation du risque de désertification (SIEL)* was built in order to quantify and model spatially agricultural practices along with available natural resources [79, 72, 71]. However, the interactions between the different areas called activity centers have not been integrated in the modelling process. Finally, a Stochastic System Dynamic (SSD) [114] and Spatial System Dynamic (also called SSD) [15, 34] models for simulating desertification were developed by integrating climate, soil water, population, economy, pasturage, and land use. These systems have the particularity to not being exhaustive. Indeed, some important desertification factors are not taken into account. Another attempt towards building a model that would predict the risk for land degradation, from information contained in satellite images was carried out in [113]. Here the assessment of desertification is based on biological and physical variables from remote sensing [113, 137]. The albedo-Normalized Difference Vegetation Index (NDVI) couple, derived from satellite data, is generally used for the desertification assessment [137, 135]. Indeed, the albedo is depend on the vegetation cover and also the characteristics of the soil (humidity, roughness, etc.). Thus with the reduction of the vegetation cover, the albedo increases relatively [137, 135]. NDVI is the most widely used vegetation index. It reflects the abundance and activity of green vegetation and leaf area. Thus a high NDVI value corresponds to dense plant cover and a lower NDVI value corresponds to significant human activities [113, 137, 101].

2.5.2 Principle of MEDALUS

The MEDALUS assessment is a method of estimating land degradation developed by the commission of the European Union. In this method, all of the basic land degradation factors, called sub-factors, are grouped into four main types linked to the biotic and abiotic components of the environment [67] : soil, vegetation, climate and management factors [36, 43, 113, 26, 84]. The land, composed of soil and

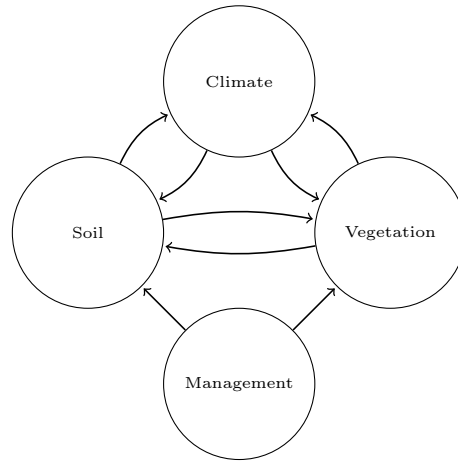


FIGURE 2.8 – Influence diagram of desertification factor

vegetation, is the main element affected by the impact of the degradation factors which are the climate and human actions (management) [12]. Fig.2.8) presents the interactions between these different factors. These factors and their sub-factors are evaluated from a quality index.

2.5.3 Soil factor

Soil is a determining factor in the process of desertification. Indeed, when the soil is not able to provide rooting space and/or water and nutrients necessary for plant growth, it follows a process of continuous degradation leading to an irreversible state called a state of desertification [96]. Thus, soil quality indicators relate to two fundamental properties : water availability and resistance to erosion. These two properties can be measured from indexes of sub-factors which are listed in Table 2.2 [25, 64].

The index of soil factor, noted s_l , is given by geometric mean of all its sub-factor indexes (cf. Eq.(2.2)).

$$s_l = (s_{Te} \times s_{PM} \times s_{Sl} \times s_{St} \times s_{Dr} \times s_{De})^{\frac{1}{6}} \quad (2.2)$$

where s_{Te} , s_{PM} , s_{Sl} , s_{St} , s_{Dr} and s_{De} are the respective indexes of soil sub-factors texture, parent material, slope, stoniness, drainage and depth. Each value of the index of the soil factor is associated to a state of quality described in Table 2.3.

2.5.4 Vegetation factor

Vegetation is one of the major contributors to desertification in dry areas because it provides protection for the soil and also represents a mean of preventing erosion [45]. Its roots stabilize and fertilize the soil and contribute to its dynamics [86]. Grazing for livestock, deforestation, fires or land use change can irreversibly damage

Sub-factor	Class	Description	Characterization	Index
Texture	1	Good	mean and sandy	1.0
	2	Moderate	Sandy clay, silty and medium	1.2
	3	Poor	Clay, clayey silt	1.6
	4	Very poor	Very sandy	2.0
Parent material	1	Good	Shale, basic and ultrabasic rock, conglomerate, unconsolidated rocks	1,0
	2	Moderate	Limestone, marble, granite, riolite, ignimbrite, gneiss, sandstone, siltite	1.7
	3	Poor	Marne, pyroclastic rocks	2.0
Slope	1	Flat, wavy undulated	< 6%	1.0
	2	corrugated	6 – 18%	1.2
	3	inclined	18 – 35%	1.5
	4	Very inclined	> 35%	2.0
Stoniness	1	Very stony	> 60%	1.0
	2	Stony	20 – 60%	1.3
	3	Low stony	< 20%	2.0
Drainage	1	Good	Good system of drainage	1.0
	2	Moderate	Imperfect drainage system	1.2
	3	Low	Bad drainage system	2.0
Depth	1	Deep	> 75cm	1.0
	2	Moderate	30 – 75cm	1.4
	3	Low	15 – 30cm	1.7
	4	Very low	< 15cm	2.0

TABLE 2.2 – Sub-factor index of soil factor in MEDALUS model

Class	Description	Index
1	High quality	$I_1^l = [1; 1.14[$
2	Moderate quality	$I_2^l = [1.14; 1.45[$
3	weak quality	$I_3^l = [1.45; 2]$

TABLE 2.3 – Quality index of soil factor.

the restoration capabilities of vegetation [63]. The main sub-factors to qualify the state of quality of the vegetation as well as the associated index are listed in 2.4 [25, 64, 36, 43].

Sub-factor	Class	Description	Characterization	Index
Fire risk	1	Low	Earth, Chott and Sebkha	1.0
	2	Moderate	courses, hills	1.3
	3	Very high	Cultures, forests	2.0
Erosion protection	1	Very high	mountainous areas	1.3
	2	moderate	courses, hills	1.8
	3	Low	Arabes earth et Chott Sebkha	2.0
drought resistance	1	High	mountainous areas	1.2
	2	Moderate	Earth et Chott Sebkha	1.4
	3	Low	courses, hills	1.7
	4	Very low	Cultures, forests	2.0
Vegetation cover	1	High	> 40%	1.0
	2	Low	10 – 40%	1.8
	3	Very low	< 10%	2.0

TABLE 2.4 – Sub-factors index of vegetation factor in MEDALUS model according to [36]

The index of vegetation factor, noted s_v , is given by geometric mean of all its sub-factor indexes (cf. Eq.(2.3)).

$$s_v = (s_{Fr} \times s_{Ep} \times s_{Dre} \times s_{Vc})^{\frac{1}{4}} \quad (2.3)$$

where s_{Fr} , s_{Ep} , s_{Dre} and s_{Vc} are the respective indexes of vegetation sub-factors natural fire risk, erosion protection, natural drought resistance and vegetation cover. Each value of the index of the vegetation factor is associated to a state of quality described in Table 2.5.

Class	Description	Index
1	High quality	$I_1^v = [1; 1.13[$
2	Moderate quality	$I_2^v = [1.13; 1.38[$
3	Weak quality	$I_3^v = [1.38; 2]$

TABLE 2.5 – Quality index of vegetation factor.

2.5.5 Climate factor

The main climate sub-factors are : rainfall, aridity and slope orientation. Rainfall expresses the annual average of precipitation observed in a given area. It is a

determining climatic factor in the process of desertification. Indeed, it is responsible for the soil humidity and the vegetation cover. Indeed, the reduction in the annual average rainfall leads to drier conditions and an increase in climate variability during the year [97]. Also, the increasing frequencies of droughts, based on the reduction of annual precipitation, and events with extreme frequencies and magnitudes that can change the average climate, lead to desertification [97]. Aridity is a climatic process resulting in low average annual precipitation and a high rate of evapotranspiration. The orientation of the slope translates the degree of exposure of the plant cover and the soil to the process of sunlight. It has a considerable effect on the process of evapotranspiration and therefore on soil moisture. The main sub-factors to qualify the state of quality of the climate as well as the associated index are listed in 2.6 [25, 64, 36, 43].

Sub-factor	Class	Description	Characterization	Indice
rainfall	1	High	$> 500mm$	1.0
	2	Moderate	$250 - 500mm$	2.0
	3	Low	$< 250mm$	3.0
Aridity	1	Hyper-arid	$BGI < 50$	1.0
	2	Arid	$50 - 75$	1.1
	3	Semi-arid	$75 - 100$	1.2
	4	Dry sub-humid	$100 - 125$	1.4
	5	Wet sub-humid	$125 - 150$	1.8
	6	Humid	$BGI > 150$	1.8
Slope orientation	1	Good	North-west, North-east	1
	2	Low	South-west, South-east	2.0

TABLE 2.6 – Sub-factors index of climate factor in MEDALUS model according to [36]

The index of climate factor, noted s_w , is given by geometric mean of all its sub-factor indexes (cf. Eq.(2.4)).

$$s_w = (s_{Ra} \times s_{Ar} \times s_{So})^{\frac{1}{3}} \quad (2.4)$$

where s_{Ra} , s_{Ar} and s_{So} are the respective indexes of climate sub-factors rainfall, aridity and slope orientation. Each value of the index of the climate factor is associated to a state of quality described in Table 2.7.

2.5.6 Management factor

Human activity, called management, is a factor of land degradation because its intensity can expose the land to deep stress [133]. The main sub-factors to qualify

Class	Description	Index
1	High quality	$I_1^w = [1; 1.15]$
2	Moderate quality	$I_2^w = [1.15; 1.81[$
3	Weak quality	$I_3^w = [1.81; 2]$

TABLE 2.7 – Quality index of climat factor.

the state of quality of the management factor as well as the associated index are listed in 2.8 [25, 64, 36, 43].

Sub-factor	Class	Description	characterization	Index
Crops	1	Low using intensity of soil		1.0
	2	Mean using intensity of soil		1.5
	3	High using intensity of soil		2.0
Pasture	1	Low density	< 20 head by km^2	1.00
	2	Moderate density	$20 - 60$ head by km^2	1.33
	3	High density	$60 - 100$ head by km^2	1.66
	4	Very high density	> 100 head by km^2	2.00
population growth	1	Very low	$< 0\%$	1.0
	2	Low	$0 - 1, 5\%$	1.2
	3	Moderate	$1, 5 - 3\%$	1.4
	4	High	$3 - 6\%$	1.8
	5	Very high	$> 6\%$	2.0
Respect of polities	1	Full	$> 75\%$ of the area is under protection	1.0
	2	Partial	$75 - 25\%$ of the area is under protection	1.5
	5	Incomplete	$< 25\%$ of the area is under protection	2.0

TABLE 2.8 – Sub-factors index of management factor in MEDALUS model according to [36, 64]

The index of management factor, noted s_m , is given by geometric mean of all its sub-factor indexes (cf. Eq.(2.5)).

$$s_m = (s_{Cr} \times s_{Pa} \times s_{Pg} \times s_{Rp})^{\frac{1}{4}} \quad (2.5)$$

where s_{Cr} , s_{Pa} , s_{Pg} and s_{Rp} are the respective indexes of management sub-factors crops intensity, pasture intensity, population growth and Respect of polities. Each value of the index of the management factor is associated to a state of quality described in Table 2.9.

Class	Description	Index
1	High quality	$I_1^m = [1; 1.25[$
2	Moderate quality	$I_2^m = [1.25; 1.50[$
3	Weak quality	$I_3^m = [1.50; 2]$

TABLE 2.9 – Quality index of management factor

2.5.7 Desertification sensitivity index

The desertification sensitivity index (DSI) is determined by the geometric mean of the quality indexes of the factors soil (s_l), vegetation (s_v), climate (s_w) and management (s_m) [26] (cf. Eq.(2.6)) which are in the range $[1; 2]$.

$$DSI = (s_l \times s_v \times s_w \times s_m)^{\frac{1}{4}} \quad (2.6)$$

The index DSI range values and its associated state quality are defined in Table 2.10.

Class of weight	state of desertification
$I_5 = [1.78; 2]$	Very-degraded
$I_4 = [1.53; 1.78[$	Degraded
$I_3 = [1.38; 1.53[$	High
$I_2 = [1.22; 1.38[$	Moderate
$I_1 = [1; 1.22[$	Low

TABLE 2.10 – Corresponding states of desertification sensitivity index DSI

2.6 Desertification impacts

Desertification is one of the major problems affecting our environment in the 21st century. Indeed, it threatens more than 1.5 million people worldwide and affects a quarter of the land in less than 100 countries, it spreads over half a billion hectares per year and reduces the surface water and groundwater [133].

The United Nations Environmental Program (UNEP) estimated that 35% of the land surface of earth is at risk, and the livelihoods of 850 million people are directly affected by desertification. 75% of the world's drier lands, representing 45,000,000

km^2 are affected by desertification, and every year 6,000,000 hectares of agricultural land are lost and become virtual desert. In all, more than 110 countries have dry lands that are potentially threatened by desertification. Africa, Asia and Latin America are the most threatened by desertification [42].

The desertification process reduces or destroys the capacity of land for agricultural, crop and animal production, and for forest production [95]. Indeed, degradation first affects the soil, the main component of land. When soil degradation reaches a certain degree of severity, the other components of the land are also progressively affected : the nature and density of spontaneous vegetation, the dynamics of water on the soil and in the soil, nutrient reserves, soil fauna, crop yield, farming method, livestock, land use type, increased frequency of sand and dust storms and increased flooding due to inadequate drainage or poor irrigation practices [95, 133, 42]. Off-site effects of land degradation are mostly associated with erosion as there is movement of soil material, transported a variable distance from the erosion site by water, wind or gravity. These effects are : lowering of groundwater levels and water scarcity, drop of electricity productivity, abrasion of plants by sandstorms, blockage of roads by sand deposits, siltation of young plants, silting and siltation of dam reservoirs, waterways, canals irrigation and estuaries [95, 11].

Indirect impacts of desertification are lack of food production, poverty, social upheaval resulting from competition for land use and fostering conflict, loss of productive land, consequent increase in land pressure on other land, rural exodus to cities, excessive cost of degraded land restoration, degradation of conditions and standard of living, migration to urban centers [133, 95].

CELLULAR AUTOMATA APPROACH

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Abstract : Desertification is a spatio-temporal phenomenon operating on areas. To model such a phenomenon, Cellular Automata are well suited. Chapter 3 introduces concepts from this theory.

3.1 Outline of Cellular Automata

From the theoretical point of view, Cellular Automata (CA) were introduced in the late 1940s by John Von Neumann and Stanislaw Ulam. One can say that the cellular part comes from Ulam, and the automata part from Von Neumann [103]. "Automaton" (plural : "automata") is a technical term used in computer science and mathematics for a theoretical machine that changes its internal state based on inputs and its previous state. Thus, cellular automata are mathematical models for describing complex natural systems containing a large number of simple and identical components that interact with each other [6, 107, 60]. CA are composed of adjacent elements, called cells, arranged as a regular d-dimensional lattice, which evolves in discrete time steps. Each cell, is characterized by an internal state whose value belongs to a finite discrete set [103, 18].

The cellular automata states evolve in discrete steps, on the principle that the next state of a cell is determined by its previous state and that of a set of cells called the neighbouring cells [30, 107]. More precisely, the state of each cell is updated simultaneously at discrete time steps, based only on the states within its neighbourhood at the preceding time step using common local transition rules, table or function [30, 50, 102]. The state set is usually defined as finite and discrete, which often causes non-linearity in the system's dynamics [112, 28, 74]. Thus, all three of their dimensions (space, time and state) are normally discrete [103, 109, 118]. Even starting from complete disorder, their irreversible evolution can spontaneously generate ordered structure [118]. In short, the essential characteristics of cellular automata are : a set of cells arranged in a lattice, a set of states, a neighbourhood and a local dynamics [109, 110].

A set of states of cellular automata is the set of all possible values that the cells can take at a given time. The state is generally described by a number or a property verified by the studied system [53, 115]. However recent studies have extended the notion of state to a combination of numbers or properties [19].

Before using CA in the context of our modelling, it is necessary to formally define them and provide some examples of CA found in the literature.

3.2 Formal definitions related to CA

Definition 3.1 (Cellular automata) *The cellular automata are defined by a quadruplet $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$ [18, 110] where :*

- \mathcal{L} is the lattice of cells whose dimension is $d \in \mathbb{N}$. Thus, $\mathcal{L} = \mathbb{Z}^d$,
- \mathcal{S} is a finite set of possible states values for the cells.
- \mathcal{N} is the function that specifies the neighbourhood of cell c which locally determines the interaction of cell c with its environment. This neighbourhood is usually the same for all cells but it can vary through space and time [122, 108]. It is defined in Eq.(3.1).

$$\begin{aligned} \mathcal{N} &: \mathcal{L} \rightarrow \mathcal{L}^n \\ c &\mapsto \mathcal{N}(c) = \{c_1, c_2, \dots, c_n\} \end{aligned} \quad (3.1)$$

where the cell c_i , $i = 1, \dots, n$ are the neighbouring cells and n is the size of $\mathcal{N}(c)$. In most of the case, the cell c is in its neighbourhood.

- f is the transition function which calculates the state of a cell at time $t + 1$ using the state of the neighbouring cells at time t . It is defined in Eq.(3.2).

$$\begin{aligned} f &: \mathcal{S}^n \rightarrow \mathcal{S} \\ s_t(\mathcal{N}(c)) &\mapsto f(s_t(\mathcal{N}(c))) = s_{t+1}(c) \end{aligned} \quad (3.2)$$

Where $s_t(c)$ is the state of cell c at time t and $s_t(\mathcal{N}(c)) = \{s_t(c'), c' \in \mathcal{N}(c)\}$ is the state of the neighbourhood of c .

Definition 3.2 (Configuration) The configuration of CA \mathcal{A} at time t corresponds to the set $\{s_t(c), c \in \mathcal{L}\}$, it is given by the function described in Eq.(3.3) [108, 122].

$$\begin{aligned} s_t &: \mathcal{L} \rightarrow \mathcal{S} \\ c &\mapsto s_t(c) \end{aligned} \quad (3.3)$$

Where $s_t \in \mathcal{S}^{\mathcal{L}}$ is called the configuration at time t .

The global dynamics of CA are given by Eq.(3.4).

$$\begin{aligned} F &: \mathcal{S}^{\mathcal{L}} \rightarrow \mathcal{S}^{\mathcal{L}} \\ s_t &\mapsto s_{t+1} \end{aligned} \quad (3.4)$$

F maps the configuration of CA at time t a new configuration at $t + 1$. The function F is related to f by the relation in Eq.(3.5).

$$F(s_t) = f \circ s_t \circ \mathcal{N} \quad (3.5)$$

Definition 3.3 (Global transition function) The global evolution of CA $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$ is given by the couple (s_0, F) where s_0 is the initial configuration and $s_t = F^t(s_0)$ is the configuration of CA at time t (Cf. Eq.(3.6)).

$$F^t = \underbrace{F \circ F \circ \dots \circ F}_{t \text{ times}} \quad (3.6)$$

The transition function f describes the local evolution (i.e at the cell level) of the CA, whereas the global transition function F describes the global evolution (i.e at the configuration level).

The following section details the components of the previously described CA, including the most common lattice, common neighbourhoods and boundary conditions.

3.3 Features of Cellular Automata

3.3.1 Lattice geometry

Most of the time, the topology of the lattice \mathcal{L} is regular. It consists of a simple shape and cell size that covers the space. The geometry of a regular lattice \mathcal{L} depends on its dimension d also called the dimension of the CA. The cells completely fill the d -dimensional space and the lattice is reproduced identically by translations in d independent directions. Then, its geometry can be selected. In the one-dimensional (1D) case, \mathcal{L} is limited to a linear array of cells (cf. Fig.3.1).

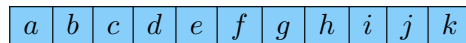


FIGURE 3.1 – Lattice of 1D CA

In dimension 2, lattices can be triangular, square (cf. Fig.3.2), hexagonal or any other way of tiling the 2D space. The usual geometry is the square one, because is easiest for defining the neighbourhood. However, there are mathematical transformations (shearing, offset of successive lines, merging cells, etc.) that always reduce to a square lattice (cf. Fig.3.3 and Fig.3.4). However, if we need a more isotropic interaction, the hexagonal one can be used [9].

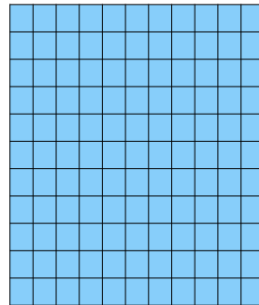


FIGURE 3.2 – Lattice of 2D CA

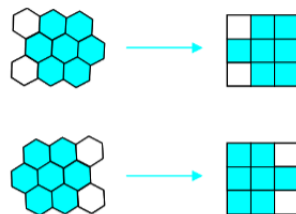


FIGURE 3.3 – Correspondence between lattices of a cell on a hexagonal grid and on a rectangular grid

In three dimensions (3D) there are many possible regular lattices but the cubic lattice is mostly used [9].

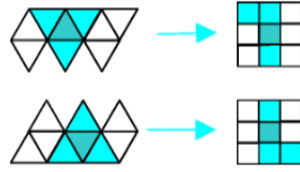


FIGURE 3.4 – Correspondence between lattices of a cell on a triangular grid and on a rectangular grid

3.3.2 Set space

In general case, the set of cell state \mathcal{S} is presented as a finite set of natural integers $\mathcal{S} = \{0, 1, \dots, k - 1\}$. However, in some specific cases, the state of the cells is not an integer but a word (tree or burning tree as in the trivial example of the fire spread model), a colour (black or white as in the game of life (cf. subsection 3.4.2) or any other discrete value. In these particular scenarios where the cell states are not represented by integers, values of the state space \mathcal{S} are simply arbitrary values which correspond to the states of the cells. For example, in Conway's Game of Life [51], the colours white and black can be respectively mapped by the integer 0 and 1 [122].

3.3.3 Neighbourhood format

The neighbourhood $\mathcal{N}(c)$ of a cell c is the set of neighbouring cells that interact with the cell c . This is a set of cells that have a significant effect on the state of a chosen cell for the next step. The neighbourhood of a cell may contain the cell itself. However, it can be punctured, i.e $c \notin \mathcal{N}(c)$.

The standard neighbourhood in dimension 1 is also called usual or classical neighbourhood. It is defined by $\mathcal{N}_{std} = \{-1, 0, 1\}$ where 0 represents the position of the observed cell, -1 represents the position of its left cell and 1 is the position of its right cell. It is the most studied neighbourhood because it is the smallest neighbourhood allowing to transmit information in both directions. It can be extended to a standard neighbourhood of radius r . Thus, for an integer $r \geq 1$, the standard neighbourhood is then : $\mathcal{N}_{std(r)} = \llbracket -r, r \rrbracket$.

The most used neighbourhood types for two-dimensional CA are presented in Fig.3.5.

The Moore neighbourhood of a cell $c = c_{ij}$ of coordinates (i, j) with a radius r is defined by Eq.(3.7).

$$\mathcal{N}(c_{ij}) = \{c_{kl} \in \mathcal{L}, |k - i| \leq r \text{ and } |l - j| \leq r\} \quad (3.7)$$

The Von Neumann neighbourhood of a cell $c = c_{ij}$ of coordinates (i, j) with a radius r is defined by Eq.(3.8).

$$\mathcal{N}(c_{ij}) = \{c_{kl} \in \mathcal{L}, |k - i| + |l - j| \leq r\} \quad (3.8)$$

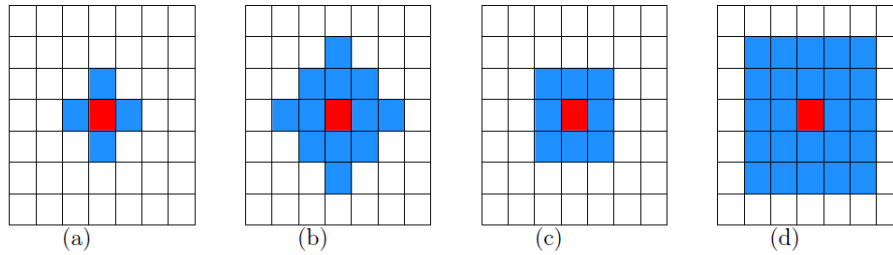


FIGURE 3.5 – The common neighbourhoods of 2D CA : (a) Von Neumann $r=1$, (b) Von Neumann $r=2$, (c) Moore $r=1$, (d) Moore $r=2$

The minimal 2D neighbourhood is defined by $\mathcal{N}_{min} = \{(0,0), (1,0), (0,1), (-1,-1)\}$. It is the smallest two-dimensional neighbourhood such that a cell of the plane can send information to the origin. However, the lack of symmetry makes it more complex to manipulate than the previously defined neighbourhoods. The study of CA operating on this kind of neighbourhoods allows to understand the real implications of symmetry. It is much less studied than the neighbourhoods of Moore and Von Neumann.

Other neighbourhoods can be defined as long as they are uniform and finite.

3.3.4 Boundary conditions

In theory, CA should not have a termination. Indeed, one usually requires the lattice to be infinite in all dimensions. However, some natural phenomena, object of the modelling, require constraints on the edges to be realistic [128]. Boundary conditions define how the notion of topological neighbourhood includes the boundaries of the lattice. The cells located at the boundary does not have the same neighbourhood as the others of the grid. Generally, there are three types of boundaries that are considered in the study of CA : periodic, reflexive, and fixed-value boundaries.

The periodic boundaries are part of soft boundaries and consist in extending periodically the lattice. Under periodic boundary conditions, the canvas is considered to be folded so that the extreme cells are taken to be adjacent to each other. In other word, edges wrap around. For example, in 1D cellular automata shown in Fig.3.6, the two extreme cells a and k are considered to be adjacent and represent boundary cells that receive copies of the indicated lattice cells at each time. The nine cells in the center represent the lattice that is being updated.

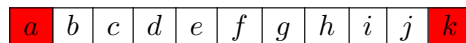


FIGURE 3.6 – 1D CA with periodic boundaries

In the two-dimensional periodic boundaries, top and bottom edges are connected, and the left and right edges are connected and leads to the topology of a torus (cf. Fig.3.7).

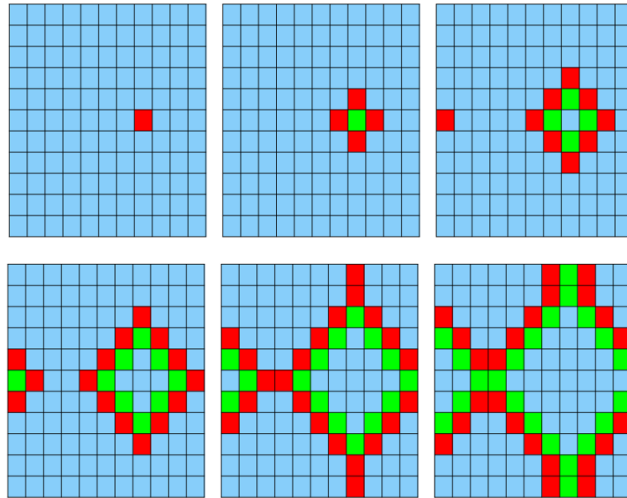


FIGURE 3.7 – 2D CA with periodic boundaries

The **fixed boundaries** are part of hard boundaries and correspond to Dirichlet boundary conditions for differential equations. Fixed boundary conditions are obtained by simply prescribing a fixed value for the cells on the boundary. Indeed, edge cells have a fixed state which can be determined by studied problems (cf. Fig.3.8, Fig.3.9, Fig.3.10 and Fig.3.11).

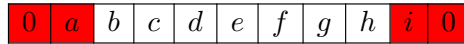


FIGURE 3.8 – 1D CA with fixed boundaries : Null boundaries

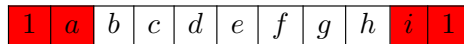


FIGURE 3.9 – 1D CA with fixed boundaries

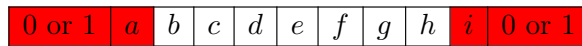


FIGURE 3.10 – 1D CA with fixed boundaries : Random boundaries

Note, that all three types of boundary conditions can be combined, except for the case when one side of the lattice has a periodic boundary condition. Then the opposite side must also have periodic boundary condition as well [69].

3.3.5 Initial conditions of CA

The initial conditions of CA, denoted s_0 , are a fundamental aspect in modelling and studying these discrete dynamic systems. Indeed, the evolution of CA is also based on their initial configurations which can be either built from the studied

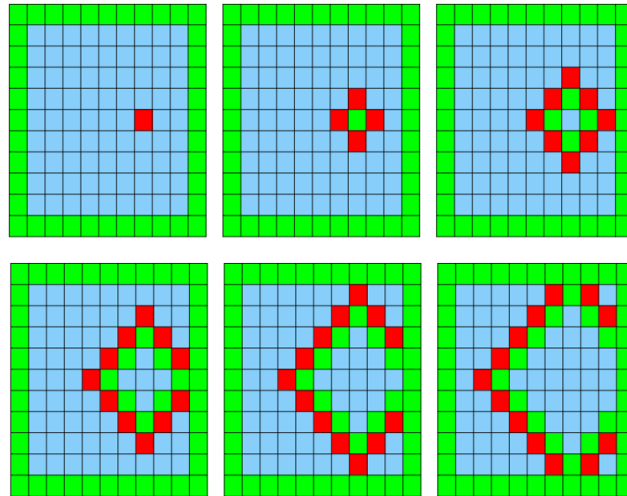


FIGURE 3.11 – 2D CA with reflective boundaries

problem, or fixed arbitrarily or randomly chosen. They define the starting state of each cell in the grid and play a crucial role in the system subsequent evolution.

Some key points to consider when discussing the initial conditions of CA are :

- Initial state : Initial conditions specify the starting state of each cell in the grid. This can be a simple configuration, such as all cells in a particular state (all live cells in Conway's Game of Life [51])(cf. subsection 3.4.2), or a more complex configuration with pre-existing patterns.
- Impact on dynamics : Initial conditions have a significant impact on the long-term dynamics of CA. Depending on the initial arrangement of cells, the system can evolve in completely different ways [118]. Some configurations may lead to periodic evolutions, others to chaotic behavior, and others to stable configurations.
- Exploration of state space : Different initial conditions are used to explore the state space of CA [8]. This helps understand how the system responds to different starting configurations and observe emerging behaviors [66].
- Patterns and structures : Initial conditions can give rise to interesting patterns and structures in CA. For example, in Conway's Game of Life, some initial configurations generate gliders, oscillators, or spaceships, which are structures that move or oscillate predictably [51](cf. subsection 3.4.2).
- Sensitivity studies : CA can be sensitive to initial conditions, meaning that small changes in the starting configuration can lead to very different outcomes [82]. This makes the analysis of initial conditions essential for understanding the stability and variability of CA behaviors.
- Periodic and boundary conditions : In some setups, boundary conditions can be periodic, meaning that the edges of the grid are connected, or non-periodic

(cf. 3.3.4), meaning that the edges are isolated. These choices also affect CA dynamics.

In summary, the initial conditions of CA are a key element in modelling and analyzing these systems. They profoundly influence how CA evolve over time and play a central role in understanding emergent behaviors and patterns that can form in these discrete dynamic systems.

3.3.6 Strategies for updating cellular automata

The updating cellular automata is generally done in three steps :

The global algorithm of updating cells : Cell state updating can be synchronous, asynchronous and block-synchronous. The synchronous CA updates the states of all cells at the same time with the convention that the state of a cell evolves according to the previous state of its neighbours. For a asynchronous CA, the state of a cell is updated and the choice of the updated cell is most often made according to a uniform distribution. For the block-synchronous case, the space is divided into blocks of cells and, at each time step, a block is chosen randomly, uniformly,... to be updated.

The deterministic or probabilistic transition rules : The transition functions in CA determine how the states of the cells evolve based on the states of its neighbours and predefined rules. These rules are crucial for understanding the behavior of CA over time. It can be deterministic or probabilistic.

With the deterministic rule, CA always evolves in the same way from the same initial configuration to a single particular next state. Let \mathcal{L} be the lattice of cells of CA and any configuration of a neighbourhood \mathcal{N} of size n . Mathematically, the transition function f defines a deterministic rule if and only if Eq.(3.9) is verified.

$$\forall t \in I, \exists! s^i \in \mathcal{S} \text{ such as } f(s_t(\mathcal{N})) = s^i \quad (3.9)$$

with \mathcal{S} a set of states and I discrete time interval.

In the literature, particular forms of deterministic rules exist. Indeed, if we consider the transition function $f : \mathcal{S}^n \rightarrow \mathcal{S}$ defined by Eq.(3.10).

$$f(s_t(\mathcal{N}(c))) = \phi\left(\sum_{i=1}^n \alpha_i s_t(c_i)\right) \quad (3.10)$$

where α_i are constant integer called the weight or coefficient of $c_i \in \mathcal{N}(c)$ and the sum \sum is considered modulo of the cardinal of \mathcal{S} . ϕ is an application defined in a set $\{c_1, c_2, \dots, c_n\}$ and $c_i \in \mathcal{N}(c)$.

- Additives rules : A transition rule is said to be additive if Eq.(3.11) is verified.

$$f(s_t(\mathcal{N}(c))) = \sum_{i=1}^n \alpha_i s_t(c_i) \quad (3.11)$$

For example in Fig.3.12, the transition function consists in making the sum modulo 2 of the states of the cell and its two neighbours. It suffices to know

the behavior of this automaton on the initial configuration everywhere equal to 0 except in the center where it is worth 1 to deduce its general behavior by the principle of superposition.

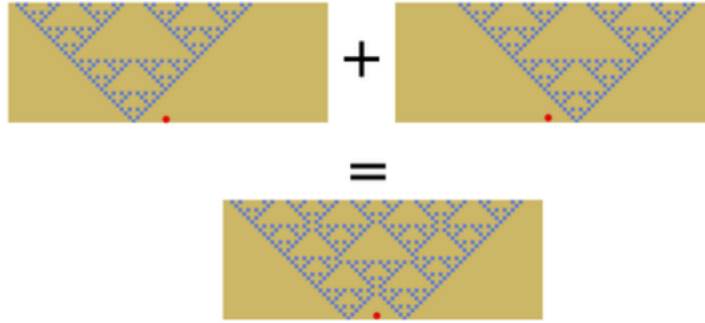


FIGURE 3.12 – Example of additive CA.

- Totalistic rules : If $\alpha_i = 1$ with $1 \leq i \leq n$ in Eq.(3.10), we obtain a class of rules of cellular automata called totalistic defined by Eq.(3.12). In other words, CA are totalistic if the subsequent state of a cell depends only on the sum (or equivalently, the average) of the previous states of its neighbours.

$$f(s_t(\mathcal{N}(c))) = \phi\left(\sum_{i=1}^n s_t(c_i)\right) = s_{t+1}(c) \quad (3.12)$$

Probabilistic rules form a very important class of transition rules. In this case, the function f does not have exactly one result for each type of neighbourhood but provides one or more possible values with associated probabilities (cf. Fig.3.13). A probabilistic rule is formally described by the transition function defined by Eq.(3.13).

$$f : \begin{array}{l} \mathcal{S}^{n+1} \rightarrow [0; 1] \\ s_t(\mathcal{N}(c)) \mapsto s^i \end{array} \quad \text{with probability } p_i = p(s^i | \mathcal{N}(c)) \quad (3.13)$$

where p_i is the probability to obtain the state s^i for a cell c from its neighbourhood $\mathcal{N}(c)$.

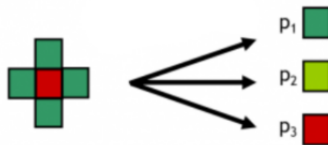


FIGURE 3.13 – Example of CA with probabilistic rules, $p_1 + p_2 + p_3 = 1$

3.4 CA examples

In this part, some classic cellular automata will be formally presented as well as their space-time diagram which allows to analyze or to study their spatio-temporal evolution.

3.4.1 Elementary Cellular Automata

The *elementary CA* were introduced by the English mathematician Stephen Wolfram in 1983 [117]. They are the simplest class of one-dimensional cellular automata.

- $\mathcal{L} = \llbracket 1, N - 1 \rrbracket$ is a one-dimensional lattice of N cells.
- The set of state $\mathcal{S} = \{0, 1\}$ is a Boolean state space. Indeed, the state correspond to two possible values for each cell i.e 0 or 1.
- The used neighbourhood is $\mathcal{N} : c_i \mapsto \{c_{i-1}, c_i, c_{i+1}\}$ composed of cell c_i and its two neighbours such as the cell to its left c_{i-1} and the cell to its right c_{i+1} located at a distance of 1 from it.
- The rules to determine the state of a cell in the next generation depends only on the current state of the cell and its two nearest neighbours. The evolution of an elementary CA is completely described by predefined rules, typically determined by a transition table. This table specifying the state that a given cell will have in the next generation based on the states of its neighbours.

There are 2^3 possible configurations for a cell and its two immediate neighbours. The rule defining the cellular automata must specify the resulting state for each of these possibilities. So there are $2^{2^3} = 256$ unique elementary rules, each corresponding to a specific configuration of cell state changes. Each rule can be indexed with an 8-bit binary number. Fig.3.14 illustrates an example of the evolution of rule 30 ($30 = 00011110_2$) starting with a single black cell.

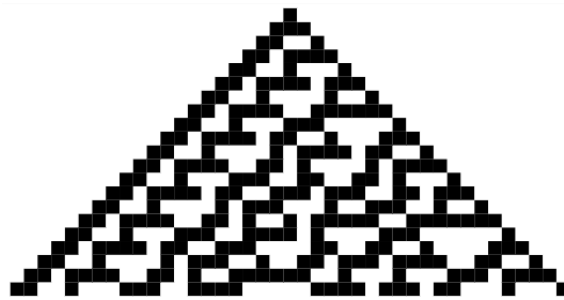


FIGURE 3.14 – Space-time diagram of 20 generations of the rule 30 elementary CA with a single black cell in the initial iteration

Fig.3.16 shows some *elementary cellular automata* numbers by applying some rules (cf. Fig.3.15) of the *elementary Cellular Automata*. These CA give particularly interesting pattern propagated for 15 generations and starting with a single black cell in the initial iteration.

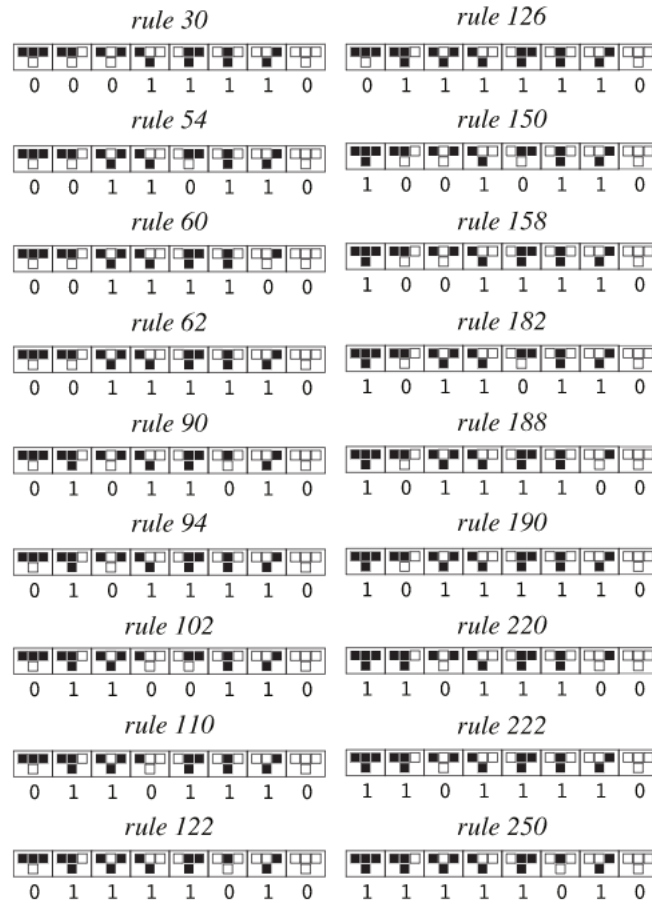


FIGURE 3.15 – Main Rules of elementary CA

3.4.2 The game of life

The game of life are cellular automata, proposed by John H. Conway. It is a very simple modelling of the behavior of a population of cells on a grid evolving over time via rules of disappearance and reproduction. *The game of Life* is an example of a special class of "totalistic" cellular automata, in which the value of a site depends only on the sum of the values of its neighbours at the previous time step, and not on their individual values. The components of this CA $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$ are :

- \mathcal{L} is a two-dimensional grid of cells. Thus, $\mathcal{L} = \mathbb{Z}^2$,
- The set of state $\mathcal{S} = \{0, 1\}$ where 1 corresponds to the alive state of the cell (occupied cell) and 0 corresponds to the dead state (unoccupied cell).
- The used neighbourhood is Moore's order 1. Thus, each cell has eight neighbours which are the cells placed directly around it.
- At each time, the state of the cell is modified according to the following rules (cf. Fig.3.17) :

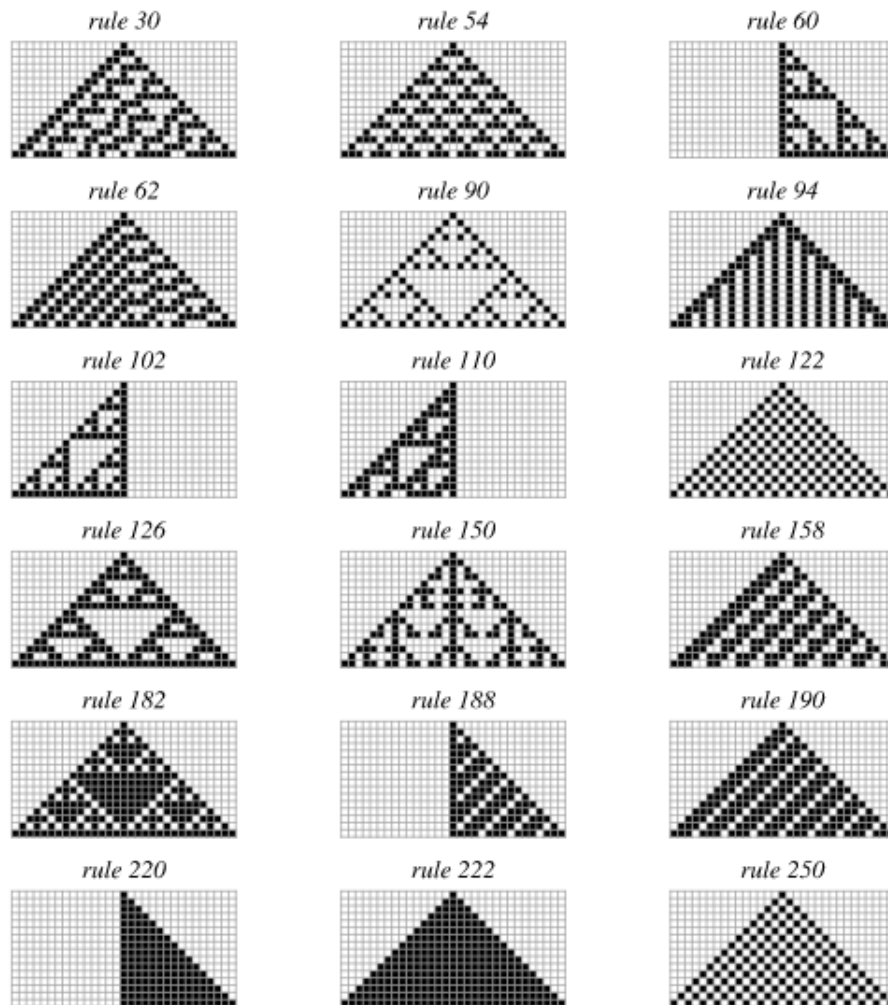


FIGURE 3.16 – 15 generations of some CA numbers starting with a single black cell in the initial iteration

- The death : If an alive cell has less than 2 living neighbours, it dies by loneliness.
- The death : If a cell is alive and has more than 3 neighbours, it dies by overpopulation.
- The birth : If an empty (dead) cell has exactly 3 neighbours, it is born (by reproduction).
- Maintaining : If a living or empty cell has exactly 2 neighbours, it remains in the same state.

These rules can be interpreted by considering that a birth requires a certain gathering of populations (3 in this case), that the cells cannot survive too much isolation (less than 2 neighbours) and that too high a concentration (more than 3 neighbours) smothers them.

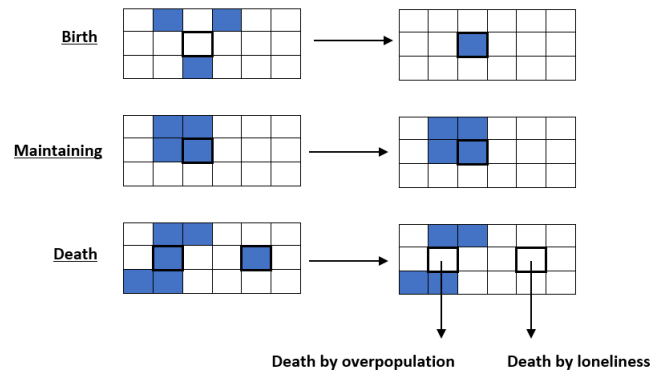


FIGURE 3.17 – Transition rules of game of life

As the game of life evolves from an initial configuration, particular forms more or less durable over time can be distinguished. They can be classified into different species.

- **The stable forms.** The "block" is an example of a stable form, which does not vary over generations. It stays "frozen" forever, or until a mobile form "disturbs" it. Other stable forms exist(cf. Fig.3.18).

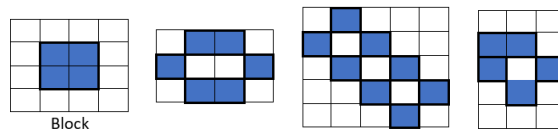


FIGURE 3.18 – Examples of stable forms

- **The pulsar.** There are 3 main pulsar (cf. Fig.3.19), allowing to generate, just with their small number of cells, real "giant" configurations. They generate patterns with a periodicity of 2, 3 and 15 in time (cf. Fig.3.19).

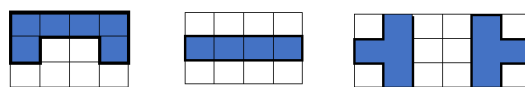


FIGURE 3.19 – 3 main of pulsar

- **The oscillators.** These are periodic structures, which resume their shape after 2 iterations (cf. Fig.3.20). A penta-decathlon is a period-15 oscillator (cf. Fig.3.24).
- **The spaceship.** These are animated structures, which move horizontally in the game space. Their movement is carried out in 4 steps. There are the 3 types of spaceships represented in Fig.3.21.
- **The glider.** They adopt a particular form of vessel. It is simply composed of 5 cells in each of the 4 stages of its evolution (cf. Fig.3.22). They are

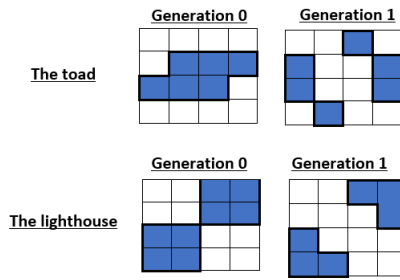


FIGURE 3.20 – The oscillators

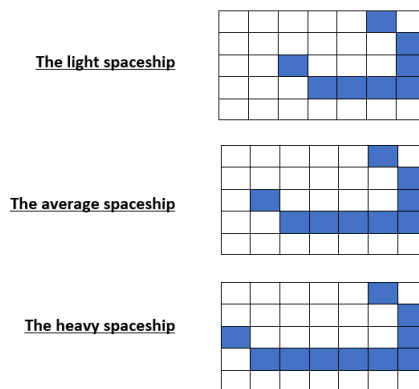


FIGURE 3.21 – The main spaceships

animated structures that move diagonally in the game world, proving that an elementary form can be born, die but also move. The collision of two gliders destroys them both.

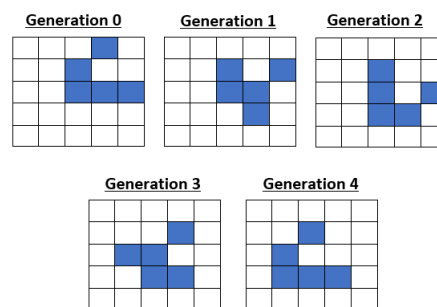


FIGURE 3.22 – The glider evolution

- **The eaters.** As for the eaters, they devour the cells which are located within reach of the 3 cells of its head constituting in a way its hook. the Fig.3.23 shows the example an eater which swallows a glider.

The game of life is irreversible. This means that it is not possible to propose

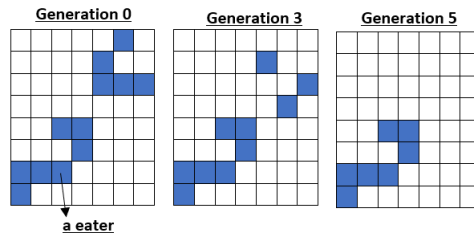


FIGURE 3.23 – The eater action

rules to deduce from a configuration its state at the previous time step.

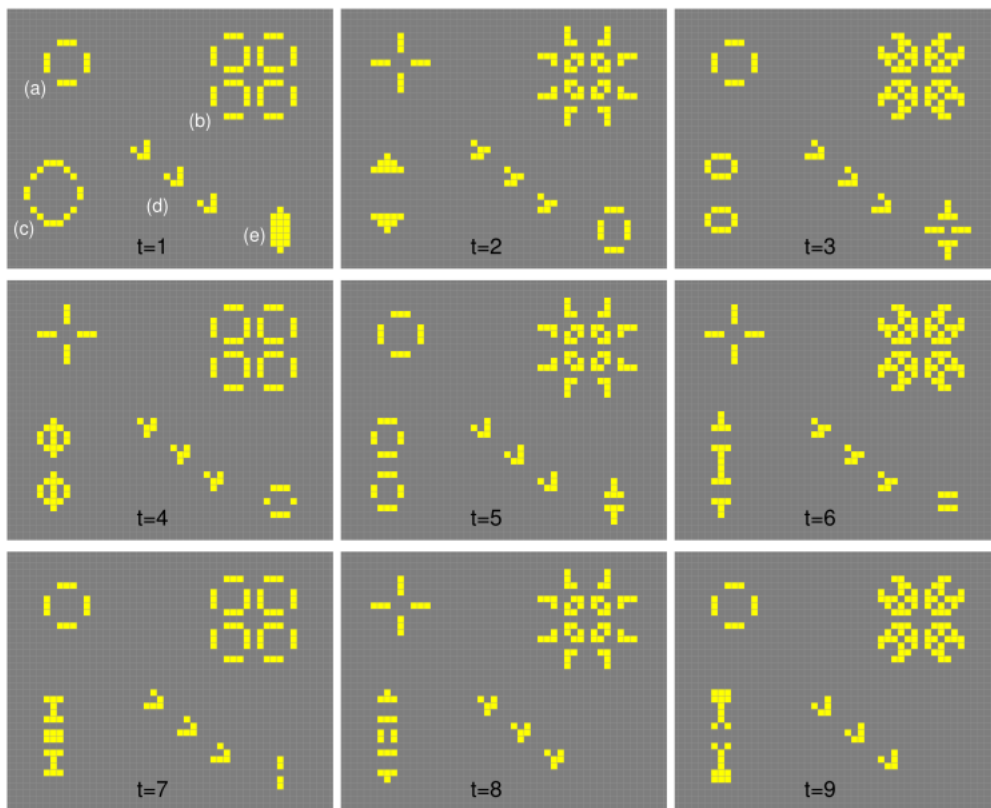


FIGURE 3.24 – An example of the game of life in which pattern (a) and (b) are pulsars, pattern (c) is a penta-decalon, pattern (d) is a glider and the living pattern (e) at the beginning which dies after 7 time steps

3.4.3 Greenberg-Hastings

The *Greenberg-Hastings Cellular Automaton (GHCA)*, is a two dimensional CA to mimic pattern formations of excitable media. The components of the *Greenberg-Hastings CA* $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$ are :

- \mathcal{L} is a two-dimensional grid of cells. Thus, $\mathcal{L} = \mathbb{Z}^2$.
- In a GHCA, each cell can be in one of three states : resting or quiescent, excited or refractory. Thus, the set of state $\mathcal{S} = \{0, 1, 2\}$ where 0 corresponds to the resting state, 1 corresponds to the refractory state and 2 corresponds to the excited state.
- The used neighbourhood is Von Neumann's order 1.
- The transition rule is as follows (cf. Fig.3.25) :
 - An excited cell at time t becomes refractory at time $t + 1$.
 - A refractory cell at time t becomes quiescent at time $t + 1$.
 - If a given cell is in the resting state at time t and at least one of its neighbours is in the excited state at time t , then the given cell will be in the excited state at time $t + 1$, otherwise (no neighbour is excited at time t) it remains in the resting state at time $t + 1$.

The probabilistic version of the GHCA modifies the third transition rule as follows : A resting cell at time t becomes excited at time $t + 1$ with probability p if at least one of its neighbourhoods is excited at time t ; otherwise, the cell remains resting at time $t + 1$.

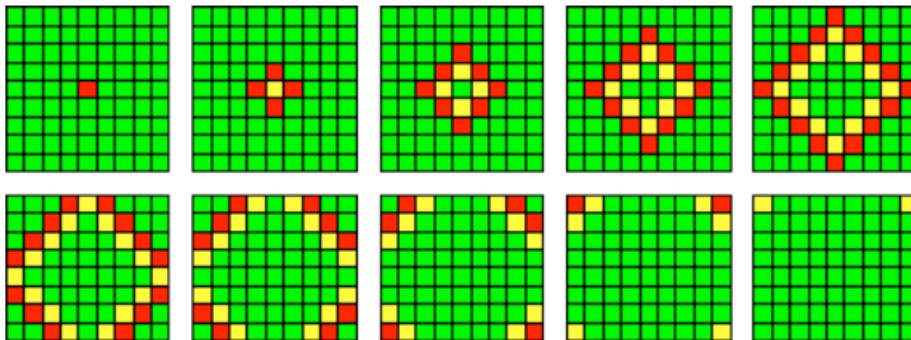


FIGURE 3.25 – 10 generations of an example of GHCA with one excited cell : Green color corresponds to resting state, red color to excited state and yellow to refractory state

The first advantage of GHCA is ease of computation. Indeed, the model can be understood quite well using simple hand calculations, not involving a computer. The second advantage is that, at least in this case, one can prove a theorem characterizing those initial conditions which lead to repetitive behavior.

3.4.4 Langton's ant

Langton's ant is originally two-dimensional cellular automata invented by the American Christopher Langton in 1986. This is a hypothetical animal moving on a 2D lattice according to simple rules. The two-dimensional grid cells can be white or black. Initially, all cells have the same white color. One of these cells is chosen

arbitrarily as the initial location of the ant and therefore has the color black. The transition rules are very simple :

- If the ant is on a white cell, it turns 90 degrees to the right (R), changes the color of the cell to black, and moves forward one cell.
- If the ant is on a black cell, it turns 90 degrees to the left (L), changes the color of the cell to white, and moves forward one cell.

The ant therefore undergoes the movement rules associated with the cells that are colored. In any case, the color of the cell is flipped. One of the main properties of *Langton's ant* is that it is one of the simplest systems for highlighting an example of emergent behavior (cf. Fig.3.26).

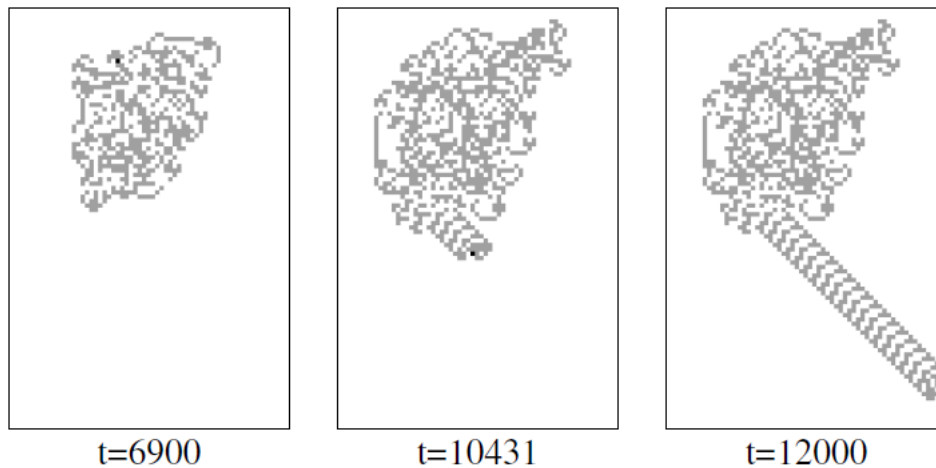
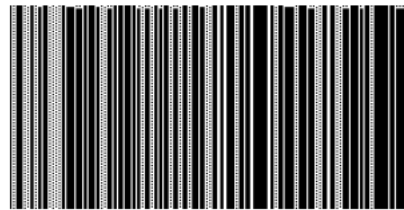
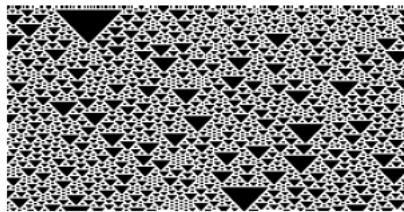


FIGURE 3.26 – Example of evolution of Langton's ant

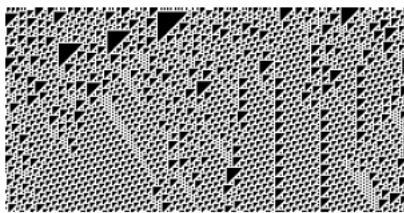
3.5 CA classification

The simple structure of cellular automata attracts scientists, researchers and practitioners to continue their research in different fields of science and technology [74]. According to WOLFRAM [119], four classes of CA can be distinguished using their behavior [50]. This classification establishes that from random initial conditions, CA will reach in a long time, one of the following classes of global behaviour [9, 119] (cf. Fig.3.31).

- Class 1 or class of stability : patterns evolve into homogeneous stable final configurations(cf. Fig.3.27).
- Class 2 or class of oscillating : patterns evolve into oscillating structures (cf. Fig.3.28).
- Class 3 or class of chaos : patterns evolve in a pseudo-random or chaotic manner (cf. Fig.3.29).

FIGURE 3.27 – Automate 1D, $r=1$ and rule 160FIGURE 3.28 – Automate 1D, $r=1$ and rule 108FIGURE 3.29 – Automate 1D, $r=1$ and rule 128

- Class 4 or class of complexity : patterns evolve into stable and repetitive structures, that interact in very complex ways, and do not belong to any of the previous three categories (cf. Fig.3.30).

FIGURE 3.30 – Automate 1D, $r=1$ and rule 110

One of the main criticisms of this classification lies in its inability to determine whether cellular automata are Turing-universal. This is because Wolfram only defines the class from random initial configurations, but no particular structure created specifically. Despite this, this classification remains the most studied.

In the literature, a second classification is proposed by David Eppstein. This classification defines four classes of cellular automata :

classification		
type	num.	rules
strong	39	2, 7, 9, 10, 11, 15, 18, 22, 24, 25, 26, 30, 34, 35, 41, 42, 45, 46, 54, 56, 57, 58, 62, 94, 106, 108, 110, 122, 126, 128, 130, 138, 146, 152, 154, 162, 170, 178, 184.
moderate	34	1, 3, 4, 5, 6, 8, 13, 14, 27, 28, 29, 32, 33, 37, 38, 40, 43, 44, 72, 73, 74, 77, 78, 104, 132, 134, 136, 140, 142, 156, 160, 164, 168, 172.
weak	15	0, 12, 19, 23, 36, 50, 51, 60, 76, 90, 105, 150, 200, 204, 232.

FIGURE 3.31 – Classification relation

- Class 1 for CA with obligatory expansion : Any initial pattern extends indefinitely in all directions.
- Class 2 for CA with impossible expansion : No pattern can extend beyond its initial limits.
- Class 3 for CA with impossible contraction : The patterns do not necessarily extend indefinitely, but can never shrink below their initial limits.
- Class 4 for CA with possible expansion and contraction.

3.6 Cellular Automata properties

Traditionally, cellular automata have the following properties [16].

- **Self reproduction.** It is an important property of life. In CA, it refers to the ability of certain configurations within the CA to generate new configurations that are identical or similar to the original one.

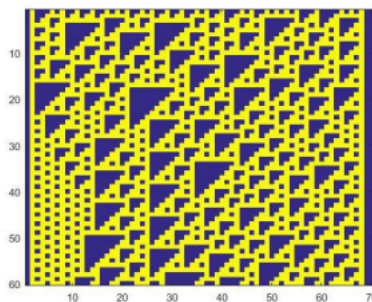


FIGURE 3.32 – Self reproduction in class 4 CA

- **Parallelism.** Individual cell updates are performed independently of each other; it means that all of the updates are being done at once.

- **Locality.** The state of updated cell is based solely on its previous state and its nearest neighbours.
- **Behavioral homogeneity.** All cells share the same local step. All cells then share the same state set, too.
- **Spatial homogeneity.** The lattice is regular. Most commonly, the CA arranges the cells in an array or grid.
- **Synchronicity.** The global step applies each cell's local step at every (discrete) moment in time.
- **Invertibility.** CA are invertible if it possesses at least a configuration which has no ancestors. In terms of CA global dynamics F , the invertibility is equivalent to the injectivity and surjectivity of the map F .
- **Irreversibility.** CA are said to be irreversible if each of their configurations has a unique successor in time, whereas it can have several predecessors. The existence of multiple predecessors implies that the application, which to time t , maps to the configuration s_t is non-invertible. Thus, the CA produce an irreversible behavior in which the information on the initial states is lost during their evolution.
- **Reversible CA.** CA \mathcal{A} are said to be reversible when there are CA \mathcal{B} in the same alphabet \mathcal{S} such that Eq.(3.14) is verified.

$$\forall c \in \mathcal{S}^{\mathbb{Z}}, \mathcal{A}(\mathcal{B}(c)) = \mathcal{B}(\mathcal{A}(c)) = c \quad (3.14)$$

For instance, the CA identity or shift (cf. Fig.3.33) are among the simplest reversible automata.

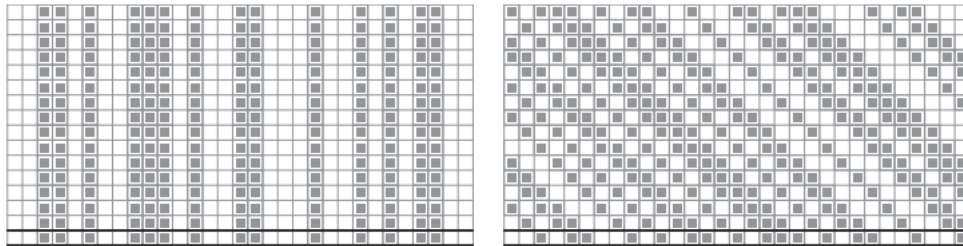


FIGURE 3.33 – Identity and shift space-time diagrams

Fig.3.34 shows an example of reversible CA with reflexive boundary conditions. At the sixth iteration, the initial configuration reappears.

- **Undecidability.** One of the important characteristics of CA is the character of undecidability which affects many of their properties. Thus, determining if CA have an inverse is undecidable : it will never be possible to write a program taking any CA as parameters and being able to decide if yes or no this CA has an inverse. Similarly, the future of CA is undecidable. There is no general method to determine if a CA will not die out after a certain number of generations or if it will stabilize.



FIGURE 3.34 – Space-time diagrams of reversible CA example

3.7 Some CA weakness

CA models are highly effective tools for simulating various types of systems. However, they have certain weaknesses that cannot limit their applicability. One key weakness is their reliance on local neighbourhoods for information propagation. This characteristic prevents action-at-a-distance and hinders explicit spatial interaction between cells. Moreover, real-world neighbourhoods often exhibit diverse shapes and sizes that may not align well with the CA grid structure.

Another limitation arises when modelling physical phenomena, as it is crucial to ensure that the fundamental objects being represented accurately correspond to the involved physical processes. In the context of geographical systems, CA models face an additional drawback : the lack of mobility for automata cells within their lattice environment. This becomes problematic when dealing with mobile entities such as pedestrians, migrating households, or relocating firms.

Nonetheless, researchers have found ways to overcome this limitation by utilizing the cells as fixed locations through which agents can move and, more importantly, communicate with other agents. By treating cells as static reference points rather than entities with mobility, the constraint of cell immobility has been effectively addressed in CA models.

SPATIO-TEMPORAL MODELLING OF DESERTIFICATION

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Abstract : This part is a chapter intended for the modelling of desertification dynamics by Cellular Automata in short **CA**. Indeed, the basic elements of methods and tools described in Chapters 2 and 3, are adapted to the context of desertification modelling. Two modelling methods based on **CA** and the **MEDALUS** model are presented. The first modelling uses the coupling of Cellular Automata and United Nations (**UN**) assessment for predicting desertification evolution. This work is the subject of the publication whose references are : *Coupling cellular automata with MEDALUS assessment for the desertification issue*, A.,Koné, A., Fontaine, S., El yacoubi, The International Conference on Emerging Trends in Engineering

and Technology (The International Conference on Emerging Trends in Engineering and Technology (IConETech)-2020), Jun 2020, St. Augustine, Trinidad and Tobago. <https://doi.org/10.47412/VQGH6804>

The second compensates the insufficiencies of the first from additional anthropogenic factors. The references of published paper related on this work are : *DESERTICAS* , a Software to Simulate Desertification Based on *MEDALUS* and Cellular Automata, 14th International Conference on Cellular Automata for Research and Industry (Conference on Cellular Automata for Research and Industry (ACRI)), A.,Koné, A.,Fontaine, M., Loireau, S., N., Jangorzo, S., El yacoubi, ACRI 2020, LNCS 12599. The extended version of this article is being published.

4.1 Coupling CA with MEDALUS assessment for desertification issue

In this section, the first modelling of desertification we have designed is presented. It consists of coupling Cellular Automata (CA) - described in Chapter 3 - and United Nations (UN) assessment for predicting desertification process called MEDALUS - described in Section 2.5. The first step of this modelling consists in assessing the degradation level of land with the MEDALUS model using *DSI* - described in Subsection 2.5.7. The second step is to model the land degradation evolution using CA approach.

4.1.1 Proposed Model

The methodology adopted in this section consists in representing the evolution of the desertification phenomenon by means of cellular automata model $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$ whose transition function f is based on the MEDALUS assessment.

4.1.1.1 Cellular space

The CA we have designed is defined on a regular grid where each element called cell has a position and a shape depending on the space dimension and on the considered phenomenon. The CA lattice \mathcal{L} is chosen like being a square of size $W \times H$ and divided into square identical cells and represented by : $\mathcal{L} = \{0, 1, \dots, W - 1\} \times \{0, 1, \dots, H - 1\}$. This choice is explained by the fact that land division into cells leads its microscopic evolution through the elementary evolution of cell states. Indeed, the evolution at the microscopic level of cells impels a global dynamics in the whole studied area. Each cell represents a portion of the study area and will be denoted by c_{ij} whose coordinates are defined by $(i, j) \in \mathcal{L}$. The evolution of this grid is based on the desertification sensitivity index of each cell that will serve to establish the transition rules according to the chosen neighbourhood.

4.1.1.2 Cell state

Each cell has a state chosen in a finite set that can evolve over time. However, the land evolution is obtained by the intensity of degradation factors and the implicit interactions between them. This evolution implies a speed of degradation. By fixing states in a discrete set, the speed of degradation is implicitly suppressed. To correct this fact, we define an extended version of the classical CA named continuous CA that uses continuous state. The cell state expresses its degradation state which is also its participation level to the desertification process. In fact, a cell having a low or moderate state participates weakly in the degradation process and a cell with a degraded or very degraded state participates actively in a spreading of desertification phenomenon. The cells states are in the interval $[1; 2]$. We denote by $s_t(c)$ the state of a cell c at the time t . When the cell and time are clearly indicated, we will simplify

the notation of the state $s_t(c)$ by s and the state of the cell c at the next time $s_{t+1}(c)$ will be denoted by s^+ .

4.1.1.3 Neighbourhood

The neighbourhood is chosen by the fact that the evolution of an area is primarily based on its interactions with all surrounding areas. The human activities and climatic parameters of each cell affect its neighbourhood land. Thus, the Moore's neighbourhood order 1 is suitable to model the interaction between the different parameters of lands and it corresponds to a radius $r = 1$. Let $\mathcal{N}(c)$ be the neighbourhood of a cell $c = c_{ij}$ of size $|\mathcal{N}(c)| = 9$ such that Eq.(4.1) is verified :

$$\mathcal{N}(c) = \{c_{i'j'} \in \mathcal{L}, \max(|i - i'|, |j - j'|) < r\} \quad (4.1)$$

where $n = |\mathcal{N}(c)| = 9$.

4.1.1.4 Transition function

The transition function considers the state of each cell and its interactions with its neighbourhood. These interactions allow to define the stress conditions, described in Subsection 2.4.4, for a given cell. Indeed, a cell is in the stress condition if its state and its neighbourhood state reach extreme conditions or huge degradation levels such as high, degraded and very degraded state. Let $\mathcal{N}(c) = (c_1; c_2; \dots; c_8)$ be the neighbourhood of cell c where c_i and $s_t(c_i)$ represent respectively the i -th neighbour of the cell c and its state at time t . The state $s_t(\mathcal{N}(c))$ of the neighbourhood $\mathcal{N}(c)$ is given by Eq.(4.2) :

$$s_t(\mathcal{N}(c)) = (s_t(c_1) \times s_t(c_2) \times \dots \times s_t(c_8))^{\frac{1}{8}} \quad (4.2)$$

We have defined two properties (Properties 1 and 2) to express stress suffered by cells. Thus, the stress cells verify Eq.(4.3) and Eq.(4.4).

Property 1 *The states of cell c and its neighbourhood reach the upper part of the range of degraded state such as Eq.(4.3) is verified :*

$$\frac{\min(I_4) + \min(I_5)}{2} \leq s_t(c) < \min(I_5) \text{ and } \frac{\min(I_4) + \min(I_5)}{2} \leq s_t(\mathcal{N}(c)) < \min(I_5) \quad (4.3)$$

Property 2 *The state of cell c reaches the upper part of the range of high state and its neighbourhood reaches the upper part of the range of very degraded state such as Eq.(4.4) is verified :*

$$\frac{\min(I_3) + \min(I_4)}{2} \leq s_t(c) < \min(I_4) \text{ and } \frac{\min(I_5) + \max(I_5)}{2} \leq s_t(\mathcal{N}(c)) \quad (4.4)$$

where I_3 , I_4 and I_5 are described in Table 2.10.

4.1. Coupling CA with MEDALUS assessment for desertification issues 55

Let f be the transition function, defined in Eq.(4.5) and Eq.(4.6), that maps the state $s_t(c)$ of a cell c at time t to its state $s_{t+1}(c)$ at time $t + 1$ according to its neighbourhood state $s_t(\mathcal{N}(c))$. $s_{t+1}(c)$ is given by the geometric mean of its index $s_t(c)$ and the index of its neighbourhood $s_t(\mathcal{N}(c))$ at time t . However, if the cell c is in a very *degraded* state and its neighbourhood is in *high* or *degraded* state (irreversible condition), it keeps its state at time $t + 1$ and a stress cell changes its state to a superior state. These fundamental rules are explained by these facts : (1) *desertified* or very degraded state is almost irreversible in degradation situation [96, 26] and (2) bad climate conditions and human pressures lead to a stress in the exposed land by the degradation process [101].

$$f : \begin{array}{l} [1; 2] \times [1; 2] \quad \rightarrow \quad [1; 2] \\ (s_t(c); s_t(\mathcal{N}(c))) \quad \mapsto \quad s_{t+1}(c) \end{array} \quad (4.5)$$

$$s_{t+1}(c) = \begin{cases} Id(s_t(c)) \text{ if } s_t(c) \in I_5 \text{ and } (s_t(\mathcal{N}(c)) \in I_3 \text{ or } s_t(\mathcal{N}(c)) \in I_4) \\ s_t(\mathcal{N}(c)) \text{ if } s_t(c) \in I_4 \text{ and } s_t(\mathcal{N}(c)) \in I_5 \\ \min(I_5) \text{ if } s_t(c) \text{ and } s_t(\mathcal{N}(c)) \text{ verify Eq.(4.3)} \\ \min(I_5) \text{ if } s_t(c) \text{ and } s_t(\mathcal{N}(c)) \text{ verify Eq.(4.4)} \\ (s_t(c) \times s_t(\mathcal{N}(c)))^{\frac{1}{2}} \text{ if not} \end{cases} \quad (4.6)$$

where Id is the identity function, I_3 is the range of *high* state, I_4 the range of *degraded* state and I_5 the range of very degraded state in Tab.2.10.

$$s_{t+1}(c) \text{ is qualified as } = \begin{cases} \textit{weak} \text{ if } s_{t+1}(c) \in I_1 \\ \textit{moderate} \text{ if } s_{t+1}(c) \in I_2 \\ \textit{high} \text{ if } s_{t+1}(c) \in I_3 \\ \textit{degraded} \text{ if } s_{t+1}(c) \in I_4 \\ \textit{very degraded} \text{ if } s_{t+1}(c) \in I_5 \end{cases} \quad (4.7)$$

Depending on a cell state and its neighbourhood, three kinds of processes can be described : degradation, regeneration and stability. A cell c is in the process of degradation if its state $s_t(c)$ is in a range inferior to the range of its neighbourhood state $s_t(\mathcal{N}(c))$ in Tab.2.10 excepted the case of Eq.(4.4) i.e $s_t(c) < s_{t+1}(c)$. A cell c is in the process of regeneration if its state $s_t(c)$ is in a range superior to the range of its neighbourhood state $s_t(\mathcal{N}(c))$ in Tab.2.10 i.e $s_t(c) > s_{t+1}(c)$. A cell c is in the process of stability or conservation if its state $s_t(c)$ is in the same range with its neighbourhood state $s_t(\mathcal{N}(c))$ excepted the case of Eq.(4.3). A *degraded* cell is in the stress state when its neighbourhood states reaches a certain value of the *degraded* level (Eq.(4.3) and Eq.(4.4)). The states of all stress cells change from *high* or *degraded* to *degraded* or *very degraded*. The transition rules are obtained by applying the transition function defined by Eq.(4.6). For example, if a cell c and its

neighbourhood $s_t(\mathcal{N}(c))$ is in the *weak* state at time t , it will keep its state at time $t + 1$. If the cell c is in the *weak* state and its neighbourhood $s_t(\mathcal{N}(c))$ is in a *high* state at time t , it becomes *degraded* and its state at time $t + 1$ will be *moderated*. If a cell c is in a *high* state and its neighbourhood $s_t(\mathcal{N}(c))$ is in a *weak* state at time t , it will be regenerated and its state at time $t + 1$ will be *moderate*.

4.1.2 Simulations

4.1.2.1 Initial State/Configuration

The initial configuration of the studied area is given by the quality index of the four desertification factors. The initial state of each cell c is given by its desertification sensitivity index $s_t(c)$. Each value of $s_t(c)$ according to Tab.2.10, corresponds to a quality state which can be *weak*, *moderate*, *high*, *degraded* and *very degraded*. Let $l_0(c), v_0(c), w_0(c)$ and $m_0(c)$ be soil, vegetation, climate and management quality indexes of a cell c at initial time $t = 0$. The initial desertification sensitivity index $s_0(c)$ of each cell c is given by Eq.(4.8) :

$$s_0(c) = (l_0(c) \times v_0(c) \times w_0(c) \times m_0(c))^{\frac{1}{4}} \quad (4.8)$$

And denote by $s_0 = \{s_0(c); c \in \mathcal{L}\}$ the initial configuration of the cellular automata.

We have used for our simulations in this thesis simulated data from MEDALUS model composed of four matrices l_t, v_t, w_t and m_t of dimension $W \times H$ where W and H are the lattice's width and height respectively. In our example $W = H = 40$. The initial data are put in the matrices l_0, v_0, w_0 and m_0 whose values are between 1 and 2. These matrices correspond respectively to the initial indexes of soil, vegetation, climate and management factors. The data from these matrices are used to determine the initial state s of the grid which is presented in Fig.4.1(a).

4.1.2.2 Results and Discussion

The built CA model was implemented using a Python code and the evolution of the studied area starting from the described initial state is represented in Fig.4.1. The elementary processes of degradation, regeneration and stability are observed. The very *degraded* cells (in orange) actively participate in the degradation of cells states. Thus, the neighbouring area in a *good* quality state (in dark green) is *degraded* by them progressively until reaching advanced degradation levels. This is explained by the fact that in advanced degradation conditions, climatic parameters are bad and human activities are intense. This situation creates additional pressures on neighbouring lands until their progressive degradation. Before the degradation, the *good* state cells (*weak* and *moderate*) improve their neighbourhood with *moderate* state because their good climatic conditions and good human practices positively influence practices in non *desertified* areas. In the *degraded* zone (in yellow), the stress cells are *desertified* from time $t = 10$ and subsequently contributed to the desertification of the degraded area. The curves on Fig.4.2 shows that the elementary

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processes of degradation, regeneration and stability take place. Initially, *very degraded* cells curve is growing and *degraded* cells curve is decreasing. Indeed, the major part of *degraded* cells became *very degraded* (*desertified*). The non-symmetrical form of the two curves is explained by the fact that certain cells according to their state do not transit by the *degraded* state before being *desertified*. Indeed, if a cell has a *high* state and its neighbourhood has an upper part of desertification level, this cell goes directly to the *desertified* state. The evolution of the number of cells with *weak* degradation is decreasing because the bad neighbouring climatic conditions and the human activities expansion deteriorate their states. The *moderate* state curve trend is increasing and decreasing. Its increase is essentially done by the cell with *weak* state deterioration. It decreases when cell with *weak* state are stabilized and thereafter the *moderate* state cells are deteriorated to *high* or *degraded* cell state. The trend of *high* cell state is almost stable because it represents the degradation transit state between *moderate* and *degraded* states. The major part of cells goes through *high* state before degrading.

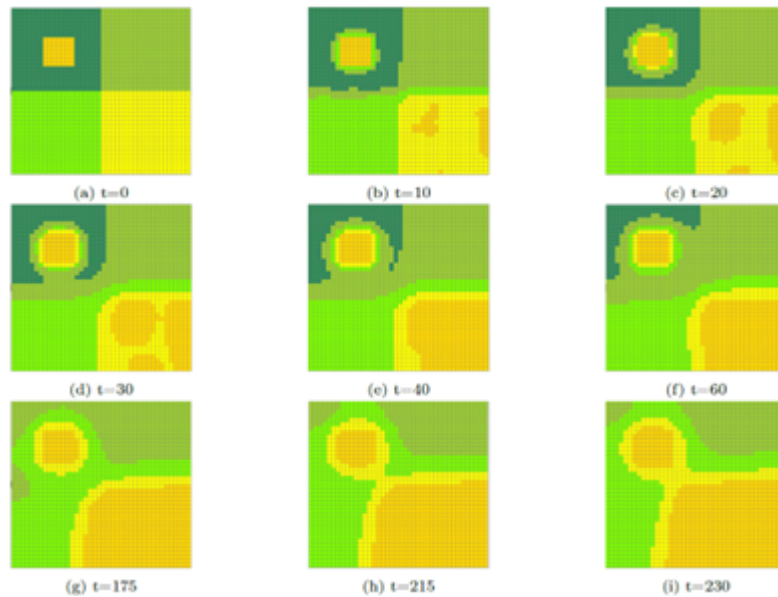


FIGURE 4.1 – Evolution of an area initially distributed by the sensitivity level to the desertification

4.1.3 Limits of this modelling

Our first attempt towards constructing a more realistic model that would assess the desertification expansion in risked areas. The proposed model was based on continuous cellular automata whose state set and transition function were extracted from the MEDALUS method. This model allowed to simulate the evolution of an area with moderate slope and an annual time step. The considered cell evolution is strongly influenced by practices around. The used of Moore's neighbourhood of ra-

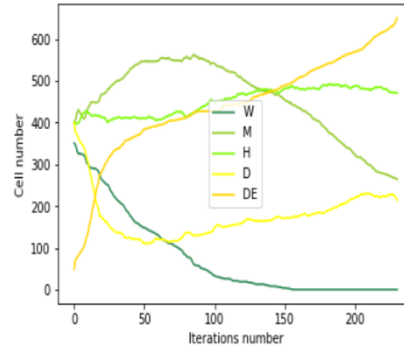


FIGURE 4.2 – Evolution of the number of cells in various levels sensitivity to the desertification during the time interval $[0 ; 230]$ in the considered study area (W=*Weak*, M=*Moderate*, H=*High*, D=*Degraded* and DE=*Very degraded*)

dius 1 allows to consider the influence of all the surrounding neighbouring cells. The elementary processes of degradation, regeneration and stability are well observed. The realized curves trends show these processes and the interaction between the different states in evolution process of land. In this MEDALUS based model, parameters are used to calculate the cells initial states. The combination of MEDALUS method and CA approach introduced a dynamical process in the model. Indeed, this coupling operation allows to simulate the evolution of the studied area in time and space. Moreover, the different ranges of values in MEDALUS model are fixed. This fact could cause a discontinuity between the data because its evolution can generate non homogeneous classes. As a perspective, the ranges of values can be determined by a classification method to ensure homogeneity in data evolution and each MEDALUS parameter can evolve through established rules based on their basic processes. Moreover, to avoid the trend in a complete degradation of all cells, some control parameters will be introduced in the next step of this thesis. These parameters will help to follow the spreading of the desertification phenomenon and to act with management action. Also, a study of the relative fronts between degraded and non-degraded areas is worth considering.

4.2 Enhanced model of desertification for analysis

To fill the gaps in the modelling of desertification in Section 4.1, we developed a new mathematical model of desertification integrating additional parameters [12]. Indeed, our model is based on a coupling of continuous CA and MEDALUS model [14] enhanced by anthropogenic factors [12]. This section is compiled from our articles [12, 13].

Number	land use
1	Crops lands
2	Pastures, cattle passages
3	Forests
4	residential areas
5	Water streams
6	Roads

TABLE 4.1 – Land use types.

4.2.1 Additional anthropogenic factors and desertification dynamic

The previous model, carried out in Section 4.1, was limited to a basic evolution of the state of land degradation. Our final modelling goes beyond that by considering the fundamental properties related to the dynamics of the state of the land such as the transfer of activities and the conditions of its realization.

Indeed, the extreme degradation of a land exploited by humans for their activities most often requires the transfer of these activities to new unexploited land. Also, the land exploitation [38] is conditioned by its ownership will or its agreement [83]. This operation is only possible between two areas with the same type and according to the agreement of the owners. This situation leads to add a first additional factor called land use type [125]. It is divided in six main types symbolized by an index which is an integer number between 1 and 6 and denoted by p [12](cf. the Table 4.1).

It is therefore necessary to control this use by adding a new parameter called the exploitability factor. This factor helps to frame the transfer operations of activities from a degraded and exploited area to an unexploited area in good condition. Its index is denoted by e and takes 1 or 0 for exploited or unexploited land respectively.

Also, the land exploitation [38] is conditioned by its ownership will or its agreement [83]. Thus, the last additional parameter added is the ownership factor designated by o . The index of ownership factor is the same number for two areas with the same owner.

The combination of these three new factors makes transfer operations feasible and therefore, make desertification modelling more realistic [12]. These new factors are anthropogenic and were identified during field campaigns and through an in-depth knowledge of the functioning of drylands in the Sahel [78].

4.2.2 Description of the Enhanced Model of Desertification

In our modelling, called *Enhanced Model of Desertification*, the CA model integrates desertification factors and their main properties described in Section 2.4. The built-CA are based on spatio-temporal changes of land degradation states [12, 14] and it is defined as follows.

4.2.2.1 Cellular space

As in the basic model described in Section 4.1, the CA lattice \mathcal{L} is supposed to be a square of size $W \times H$ and divided into square identical cells and represented by \mathcal{L} of cells : $\mathcal{L} = \{0, 1, \dots, W - 1\} \times \{0, 1, \dots, H - 1\}$. Each cell represents a portion of the study area and will be denoted by c whose coordinates are defined by $(i, j) \in \mathcal{L}$.

4.2.2.2 State of each cell

To determine the states of the cells and their dynamics, each cell must obey to the fundamental properties of desertification, such as the combination of factors, reversibility and stress condition which are defined in Section 2.4. The state of a cell c must then integrate the quality indices given by the MEDALUS model. These indices at time t are noted $l_t(c)$, $v_t(c)$, $w_t(c)$, $m_t(c) \in [1, 2]$ and represent the soil, vegetation, climate and management indices respectively.

To take into account the activity transfer property in the dynamics, the state of a cell at time t , must also include indices of anthropogenic factors denoted by $p_t(c) \in [1, 6]$, $e_t(c) \in \{0, 1\}$ and $o_t(c) \in \{1, 2, \dots, k\}$, where k is the owner assigned number in the study area.

The final state of a cell c at time t will be denoted by $\xi_t(c)$ and defined by $\xi_t(c) = (l_t(c), v_t(c), w_t(c), m_t(c), p_t(c), e_t(c), o_t(c))$ and its state at time $t + 1$ is denoted by $\xi_{t+1}(c) = (l_{t+1}(c), v_{t+1}(c), w_{t+1}(c), m_{t+1}(c), p_{t+1}(c), e_{t+1}(c), o_{t+1}(c))$. $\xi_t(c)$ and $\xi_{t+1}(c)$ belong to the set of states $\mathcal{S} = [1, 2]^4 \times [1, 6] \times \{0, 1\} \times \{1, 2, \dots, k\}$.

4.2.2.3 Neighbourhood of a cell

The neighbourhood of a cell $c \in \mathcal{L}$ is composed of the cell itself and its surrounding cells that are supposed to affect its evolution. As previous, we consider the Moore neighbourhood of radius r defined as $\mathcal{N}(c) = \{c_{i,j'} \in \mathcal{L}, \max(|i-i'|, |j-j'|) \leq r\}$. As all cells in the neighbourhood have the same influence on the central cell c regardless of their position, they will be denoted by c_i , $1 \leq i \leq n$ and $|\mathcal{N}(c)| = n + 1$ is the neighbourhood size. We extend the notation ξ to the neighbourhood of the cell c by Eq.(4.9).

$$\xi_t(\mathcal{N}(c)) = (\xi_t(c), \xi_t(c_1), \xi_t(c_2), \dots, \xi_t(c_n)) \quad (4.9)$$

It is observed that the most important factors that have significant local influence in the evolution of land degradation are soil (l), vegetation (v), climate (w) and management (m). This will be characterised for a neighbourhood $\mathcal{N}(c)$ by four values computed as the geometric mean of these factors for all the neighbouring cells c_i , $i = 1, \dots, n$ and gives for each $q \in \{l, v, w, m\}$ (Eq.(4.10)).

$$q_t(\mathcal{N}(c)) = (q_t(c_1) \times q_t(c_2) \times \dots \times q_t(c_n))^{\frac{1}{n}} \quad (4.10)$$

Additionally, the overall evolution of the state of cell c will depend on its the desertification sensitivity index $ds_t(c)$ (see Eq. 2.6) that is a real number given in the

interval $[1; 2]$ as described in [14]. This will be updated according to the evolution of each factor l , v , w and m .

4.2.2.4 Mathematical description of desertification properties

The transition rules developed will allow to update the state evolution of a cell c according to its state, the state of its neighbourhood and desertification properties.

Indeed, extreme levels of the degradation factors, such as climate and management, generate stress conditions in land and accelerated its degradation. The stress conditions of a cell c are applied when Properties 3 and 4 occur [101, 14].

Property 3 *The state of DSI $ds_t(c)$ of a cell c reaches the upper part of the range of Degraded state and its climate and management indexes are High i.e. $c \in D_1$ (cf. Eq.4.11).*

$$D_1 = \{c \in \mathcal{L} \mid center(I_4) \leq ds_t(c) < upper(I_4) \text{ and } w_t(c) \text{ or } m_t(c) \text{ are High} \} \quad (4.11)$$

where $center(I_i)$ and $upper(I_i)$ are respectively the center and upper bound of the interval I_i (see Table 2.10).

Property 4 *The state of DSI $ds_t(c)$ of a cell c reaches the upper part of the range of High state and its climate $w_t(c)$ and management $m_t(c)$ indexes reach the upper part of High range values i.e $c \in D_2$ (cf. Eq.4.12).*

$$D_2 = \{c \in \mathcal{L} \mid center(I_3) \leq ds_t(c) < upper(I_3) \text{ and } center(I_3^w) \leq w_t(c) \text{ or } center(I_3^m) \leq m_t(c)\} \quad (4.12)$$

where I_3^w and I_3^m are described in Table 2.7 and 2.9.

Properties 3 and 4 are respectively extended and more complete versions of properties 1 and 2. Indeed, properties 3 and 4 have the advantage of integrating the main factors of degradation which are human action and the climate in the stress process of land.

At least, the activity of the owner on a degraded cell is usually transferred in a cell having good condition. Thus lands, initially unexploited, can be used by its owner by transferring the activity from a *Degraded* land to a better quality land with the same characteristics and the same ownership. This transfer operation can only be done by the owner of this two lands or with his agreement and does not take into account the chosen neighbourhood radius [52, 79]. The transfer operation verifies Property 5.

Property 5 *The transfer operation is possible between two cells c and c' , if $(c; c') \in D_3$ (cf. Eq.4.13).*

$$D_3 = \{(c, c') \in \mathcal{L} \times \mathcal{L} \mid p_t(c) \in [1; 2; 3], ds_t(c) < min(I_4), e_t(c) = 0, e_t(c') = 1, ds_t(c') \in I_5, p_t(c) = p_t(c') \text{ and } o_t(c) = o_t(c')\} \quad (4.13)$$

where I_4 and I_5 are described in Table 2.10.

4.2.2.5 Weighted geometric mean and the weights of desertification factors

The transition rules developed allow to update the state evolution of a cell c according to its state and the state of its neighbourhood. The combination of all those components gives the degradation index of cell c [26, 25]. To integrate this property in the transition function, we first define the parameters α and a generic function g_α .

Let $\alpha = (\alpha_1; \alpha_2; \dots; \alpha_9)$ be a tuple of factor powers such that $\alpha_i \in [0; 1]$ and $\sum_{i=1}^9 \alpha_i = 1$. Let g_α be the α -weighted geometric mean defined by Eq. (4.14).

$$g_\alpha : \mathcal{S}^{n+1} \rightarrow [1; 2]$$

$$g_\alpha(\xi_t(\mathcal{N}(c))) = l_t^{\alpha_1}(c) \times l_t^{\alpha_2}(\mathcal{N}(c)) \times v_t^{\alpha_3}(c) \times v_t^{\alpha_4}(\mathcal{N}(c)) \times w_t^{\alpha_5}(c) \times w_t^{\alpha_6}(\mathcal{N}(c)) \times m_t^{\alpha_7}(c) \times m_t^{\alpha_8}(\mathcal{N}(c)) \times ds_t^{\alpha_9}(c) \quad (4.14)$$

4.2.2.6 Desertification properties on a generic function

We now define the generic function h used to take into account Properties 3, 4, 5 and the properties of combination of factor and irreversibility in the transition function.

One of the main characteristics of desertification is the natural irreversibility described in Subsection 2.4.2. If the state of DSI $ds_t(c)$ of the cell c reaches a *very degraded* state, it keeps its DSI state. Desertification has irreversible character because if a disturbance changes the land from the vegetated state to the critical threshold of the degraded state, the removal of this disturbance will not return to the initial state [26, 96]. This irreversibility results in a very high desertification index. Thus the indexes of four factors, soil, vegetation, climate and management, are high and weakly variable.

Moreover, in the stress conditions, a cell changes its DSI state $ds_t(c)$ to one of superior states. Beside the particular conditions described previously, the DSI state of a cell c is given by the combination of desertification factors[26]. For $x \in \{l, v, w, m\}$, we define Eq.4.15.

$$h_x : [0, 1]^9 \times \mathcal{S}^{n+1} \rightarrow [1; 2]$$

$$h_x(\alpha, \xi_t(\mathcal{N}(c))) = \begin{cases} x_t(c) & \text{if } ds_t(c) \in I_5 \text{ (Irreversibility)} \\ \max(\min(I_5); g_\alpha(\xi_t(\mathcal{N}(c)))) & \text{if } c \in D_1 \text{ or } D_2 \text{ (Properties 3 and 4)} \\ (x_t(c) \times x_t(c'))^{\frac{1}{2}} & \text{if } x = m \text{ and } \exists! c' \in \mathcal{L}, (c, c') \in D_3 \text{ (Property 5)} \\ g_\alpha(\xi_t(\mathcal{N}(c))) & \text{otherwise (Normal condition)} \end{cases} \quad (4.15)$$

4.2.2.7 Transition function of desertification CA

For a cell c , the transition function f computes in parallel each component of a cell c from its state and the states of its neighbourhood. Thus, its is defined by Eq.4.16.

$$\begin{aligned}
 f &: \mathcal{S}^{n+1} \rightarrow \mathcal{S} \\
 \xi_{t+1}(c) &= (f_l(\xi_t(\mathcal{N}(c))), f_v(\xi_t(\mathcal{N}(c))), f_w(\xi_t(\mathcal{N}(c))), f_m(\xi_t(\mathcal{N}(c))), p_t(c), \\
 &\quad f_e(\xi_t(\mathcal{N}(c))), o_t(c)) \\
 f_l(\xi_t(\mathcal{N}(c))) &= h_l((\alpha_{l1}; \alpha_{l2}; 0; 0; 0; 0; 0; 0; \alpha_{l9}), \xi_t(\mathcal{N}(c))), \\
 f_v(\xi_t(\mathcal{N}(c))) &= h_v((\alpha_{v1}; 0; 0; \alpha_{v4}; 0; 0; 0; 0; \alpha_{v9}), \xi_t(\mathcal{N}(c))), \\
 f_w(\xi_t(\mathcal{N}(c))) &= h_w((\alpha_{w1}; 0; 0; \alpha_{w3}; 0; \alpha_{w5}; \alpha_{w6}; 0; 0; 0), \xi_t(\mathcal{N}(c))), \\
 \text{where } f_m(\xi_t(\mathcal{N}(c))) &= h_m((0; 0; 0; 0; 0; 0; \alpha_{m7}; \alpha_{m8}; 0), \xi_t(\mathcal{N}(c))), \\
 f_e(\xi_t(\mathcal{N}(c))) &= \begin{cases} 1 & \text{if } \exists! c' \in \mathcal{L}, (c; c') \in D_3 \\ 0 & \text{if } \exists! c' \in \mathcal{L}, (c'; c) \in D_3 \\ e_t(c) & \text{else} \end{cases}
 \end{aligned} \tag{4.16}$$

4.2.2.8 Desertification processes by applying the transition function

Thus, depending on the evolution of cell states, three kinds of processes can be described : degradation, regeneration and stability. A cell c is in the process of degradation if its *DSI* states verify $ds_t(c) < ds_{t+1}(c)$ where $ds_t(c)$ and $ds_{t+1}(c)$ are respectively its *DSI* states at time t and $t+1$. A cell c is in the process of regeneration if its *DSI* states verify $ds_t(c) > ds_{t+1}(c)$. A cell c is in the process of stability or conservation if its *DSI* states verify $ds_t(c) = ds_{t+1}(c)$.

4.3 DESERTICAS , a software for assessing desertification

The *Enhanced Model of Desertification*, developed in Section 4.2, is used for the achievement of a configurable simulation software. The data of the studied area is imported into the software and it is highly parameterizable. The parameters are chosen by the user. The software has the ability to predict the spatio-temporal dynamics of a studied area. Thus, it serves as a decision support tool to protect land for the degradation process leading to desertification.

We then have designed a software **DESERTICAS** (DESERTification Cellular Automata Simulator) [12] to simulate and assess land degradation by means of the *Enhanced Model of Desertification* (described in Section 4.2). This model combines **MEDALUS** assessment to a continuous **CA** approach [14].

4.3.1 DESERTICAS technical details

Written in Python [39], DESERTICAS is the software designed to model the phenomenon of land degradation based on our proposed mathematical model : *Enhanced Model of Desertification*. Numpy library is used to download the data in the desired format like CSV and the CA cells are built with the function Canvas of Tkinter Library. The evolution of cells at each time step are shown through the display of all the created cells. The curves of evolution of the cells states are built and displayed through the module matplotlib combined with module pylab. The DESERTICAS code is written by using the paradigm of modular programming and two main modules are created : The first contains the function to built a configuration of the system called DESERTICASInterface.py and the second contains CA transition functions and curve display functions (cf. Fig.4.3).

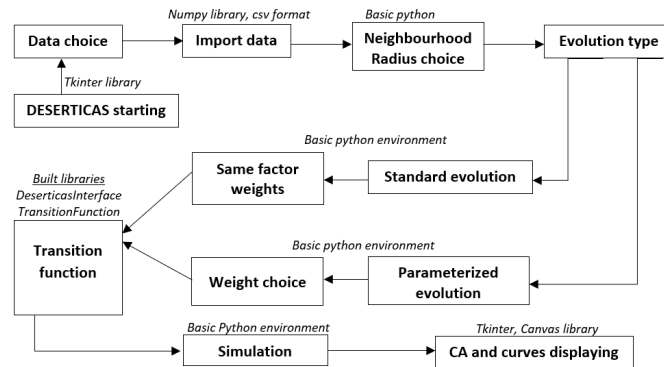


FIGURE 4.3 – Scenarii of use of DESERTICAS

4.3.2 DESERTICAS Graphical User Interface

In GUIs interface, the results are displayed through two canvas. The first one displays the evolution of the CA lattice and the second one presents the different curves of cell evolution according to their states at each time step. After importing data and choosing the parameters, the initial configuration of the grid will be displayed in the first canvas. The control buttons activate and control the evolution of the cells states on the grid at each time step. The grid configuration and the evolution curves of the cell states are simultaneously displayed in GUIs interface.

The interface of DESERTICAS is presented in Fig.4.4. It is divided into four parts : Data importation, parameter choices, displaying of CA and curve, control buttons.

To facilitate its use, some parameters have been adapted as below [12].

4.3.3 Data choice and importation

After starting DESERTICAS, the first step is devoted to the initialization of the land state which is the basis of the simulation and thus the cell states of the study

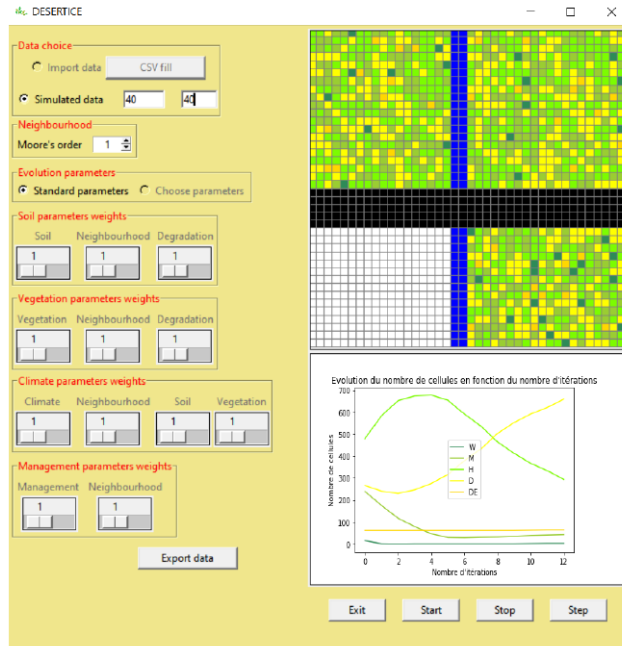


FIGURE 4.4 – DESERTICAS Graphical User Interface

area are initialized. The user can choose to import data from a CSV file using the "CSV fill" button or to generate simulated data. The data related to the quality index of the four desertification factors, the land type, the exploitability and the ownership factors are generated or imported at the end of this step. Let $l_0(c)$, $v_0(c)$, $w_0(c)$, $m_0(c)$, $p_0(c)$, $e_0(c)$ and $o_0(c)$ be respectively quality index of soil, vegetation, climate, the management, the land use type, the exploitability and ownership factors of a cell c at initial time $t = 0$. These initial chosen data in DESERTICAS implicitly initialize the state $\xi(c)$ to $\xi_0(c) = (l_0(c), v_0(c), w_0(c), m_0(c), p_0(c), e_0(c), o_0(c))$.

4.3.4 Neighbourhood choice

The used neighbourhood is of Moore type with radius $r \in \{0, 1, 2, 3\}$. Depending on the influence of the interactions between the desertification factors, the neighbourhood can be set to 0 if it is not considered in the evolution. The neighbourhood choice implicitly initializes the variables $\xi_t(\mathcal{N}(c))$ to $\xi_0(\mathcal{N}(c))$. The desertification index $ds_0(c)$ is also set.

4.3.5 Parametrization using the weights on the factors

The evolution of each factor index takes into account the weight tuple α as defined in the transition function f in Eq. 4.16. The weights α_i , $i \in \{1, 2, \dots, 9\}$ are considered as integer and thereafter normalized by their sum. To make the interface readable, the tuples are divided into : $\alpha_l = (\alpha_{l1}; \alpha_{l2}; \alpha_{l9})$, $\alpha_v = (\alpha_{v3}; \alpha_{v4}; \alpha_{v9})$, $\alpha_w = (\alpha_{w1}; \alpha_{w3}; \alpha_{w5}; \alpha_{w6})$ and $\alpha_m = (\alpha_{m7}; \alpha_{m8})$. The default weights proposed by

DESERTICAS are such that all the factors have the same impact in the desertification process. That is to say : $\alpha_l = (1; 1; 1)$, $\alpha_v = (1; 1; 1)$, $\alpha_w = (1; 1; 1; 1)$ and $\alpha_m = (1; 1)$. However, thanks to a slider, users can choose their own weightings to give more intensity to certain factors.

4.3.6 Result display

The results are displayed through two canvas (cf. Fig.4.4). The first one displays the evolution of the CA lattice and the second one presents the different curves of cell evolution according to their states at each time step. After importing data and choosing the parameters, the initial configuration of the grid will be displayed in the first canvas. The control buttons activate the evolution of the cells states on grid at each time step. It also allows to display simultaneously the grid configuration and the evolution curves of the cell states.

4.4 Simulations of desertification phenomena with DESERTICAS

4.4.1 Simulation parameters and results

The three simulations presented in Fig.4.5, extracted from DESERTICAS software, are obtained on the same initial configuration area. The size of the area is $W \times H = 40 \times 40$. This area is composed of four parts delimited by a street (in black) and a river (in blue). On the bottom left, we have a residential area (in white). On the three other parts, the state of each cell are random and they are represented by the following colors : orange for *very degraded*, yellow for *degraded*, green for *high*, khaki for *moderate* and dark green for *low*. As we are studying more specifically arid zones, we assume that the climate has a high level. Another assumption is that on the right side of the river, there is a high human pressure characterised by a high management factor and on the up left side, there is a good management of the land.

4.4.2 Discussion

A general observation is that the elementary processes of degradation (right side), regeneration (up left side) and conservation (bottom left side) occur simultaneously during the evolution. This comes from the fact that land factor states such as soil and vegetation are degraded or improved by the intensity of climate and human management factor and the management factor differs from left to right side.

We are first interested in the impact of the neighbourhood. On Fig.4.5 (a) and (b), standard values for the coefficients α are used. The difference here is the choice of r to 1 and 2 respectively. We observe that the degradation process on the right side is emphasized when the neighbourhood influencing the behavior of the cell is bigger. This can be explained by the fact that there is a general degradation aspect

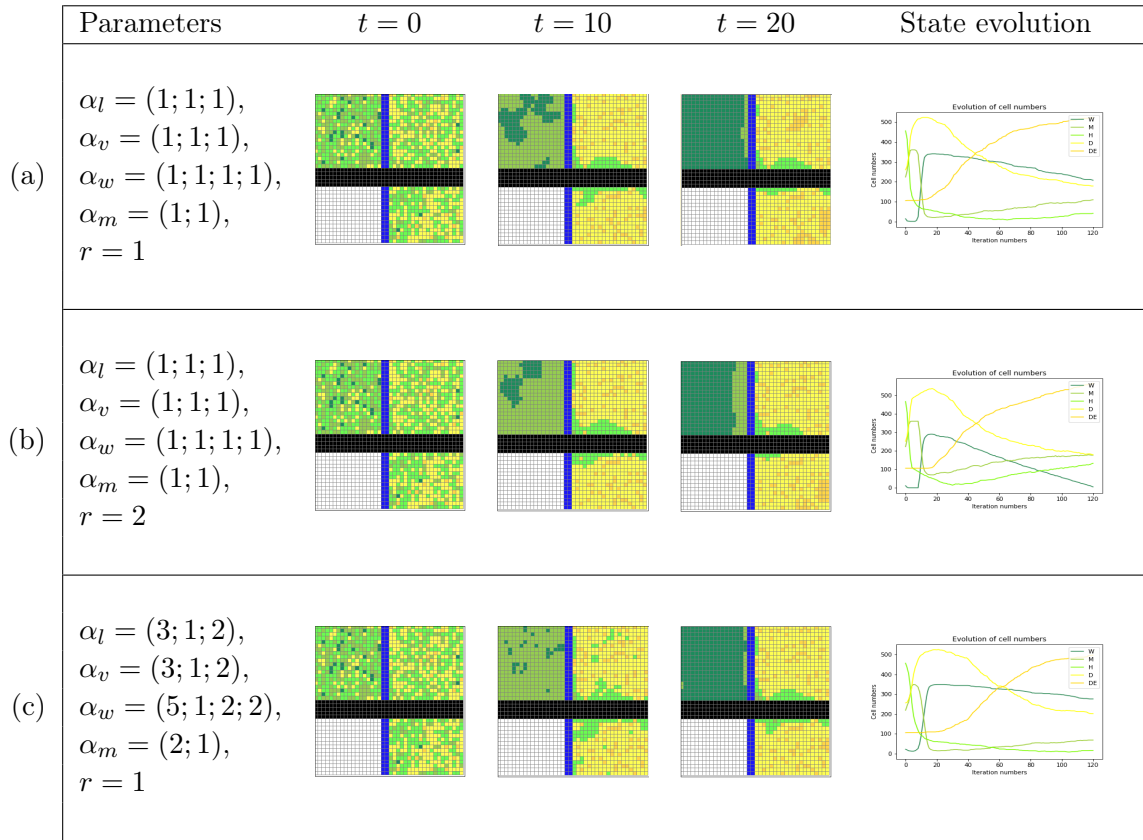


FIGURE 4.5 – Evolution of the same area with different parameters

in the neighbourhood : we observe few aggregated cells with low or moderate states, most of them are high or degraded.

In Fig.4.5 (a) and (c), we have the same neighbourhood with $r = 1$ but the coefficients α differ. Those figures highlight the huge impact of the choice of the coefficients on the speed of the evolution of cell states. Choosing the right parameters gives a more realistic model for convergence. Setting all the coefficients to the same value for soil factors ($\alpha_l = (1; 1; 1)$) gives a bigger weight (equal to 2) to the external influences, *i.e.* neighbourhood and global state than the local state of the cell. Then the land factor will tend to an homogeneous value and the local aspect is neglected. The reasoning is the same for vegetation, climate and management. Refining factors can solve this problem of fast convergence by taking more into account the local characteristics. Hence, we tried different factors, and it appears that the one chosen in Fig.4.5 (c) are closer to reality. The last column shows the evolution of the numbers of cells according to the interpretation of their states : *very degraded* (DE), *degraded* (D), *high* (H), *moderate* (M) and *low* (W). The same tendency are observed in term of growth and decline. Early peaks that flatten out are explained by human practices that harmonize on the sub-areas. There is an increasing number of degraded cells explained by the arid climate and by half of the area with high

human pressure. This phenomenon is similar to what can be observed in SIR model in epidemiology [20]. The difference is in the slope which are less steep in Fig.4.5 (c) what reinforces our interpretation about a slower convergence.

4.4.3 Conclusions

We have designed an *Enhanced Model of Desertification* based on MEDALUS and additional factors. Its purpose is to simulate land evolution from the initial configuration according to a built-transition function. This function is based on the fundamental properties of land degradation process like factors combination, irreversible character, its impacts, etc. Also, this model is done according to a chosen neighbourhood radius and coefficients assigned to the different factors. The coefficients represent the factors weights in weighted-geometric mean and allow to take into account the importance of these factors in the evolution process. The chosen parameters *i.e.* coefficients and the neighbourhood allow to control cell degradation speed. Indeed, high coefficients associated to land factors allow to slow down the degradation process while identical coefficients to degradation factors accelerate the process until total extinction of cells (*desertified*). Also, a larger neighbourhood allows to consider many cells of the CA grid in the given cell evolution and participates actively in the degradation speed growth. These different choices are made according to the user's knowledge of the desertification microscopic processes and the study area characteristics. That poses the adequacy and optimization problems rely on these parameters. As a perspective, the neighbourhood radius and the weighted-geometric mean coefficients can be determined by an optimization method or artificial neural networks. Using, the second method of optimisation is conditioned by obtaining data from the earlier periods.

We then have designed the software DESERTICAS based on our *Enhanced Model of Desertification*. Its purpose is to make simulations of land evolution from the initial configuration.

DESERTICAS is a decision support tool which can be used to control and protect the land against degradation. Unlike other existing desertification monitoring software, it allows to simulate land degradation state in time and in space from an initial configuration. This is a notable advance in the strategies for fighting desertification through an annual monitoring. In its current form, DESERTICAS is limited to the annual modelling of the land states under the effect of degradation factors. It does not include control actions aimed at curbing the harmful effects of its factors on the land quality state. As second perspective, actions can be integrated to follow the cells evolution and alert in high degradation level case. This actions will be guided by the control parameters of the model.

CONTROLLING DESERTIFICATION WITH CELLULAR AUTOMATA AND GENETIC ALGORITHMS

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Abstract : Whereas the previous chapter focused on modelling desertification phenomena and developing an effective tool that takes into account the main processes governing its evolution, this chapter goes further and investigates the possibilities of acting efficiently on the system to reduce the disastrous effects of this phenomenon.

The main originality of this chapter is the adaptation and the application of some concepts of systems theory to our CA model that could enrich the built software DESERTICAS. We focus here on two aspects directly related to the studied phenomenon of desertification : the spreadability analysis that will study the expansion property of desert zones and the control that could prevent/stop this expansion. We propose to act directly on a predominant factor by fixing its mean intensity. This leads to act indirectly on all the other factors in the model and slow down or stop land degradation processes. The predominant factor in the *Enhanced Model of Desertification* is the management and its optimal intensity will be determined by an approach based on Genetic Algorithms (GAs). The aim is to integrate a GA-based optimization process into the DESERTICAS model to determine effective land protection actions and turn it into a decision-support tool.

5.1 Introduction

Desertification is identified as a spatio-temporal process whose multiplicity and complexity make it difficult to quantify. Its attribution to climate variability and change, as well as to human activities, also varies in space and time. Drylands can expand or contract depending on environmental conditions but also on land use practices. Modelling such a process must not only take into account all these factors but also integrate the possibilities of actions that can be implemented to reduce their impact on the quality of life on earth.

Most of the actions proposed in the literature are based on land rehabilitation and restoration [21, 81]. Indeed, some of the work is based on ecological rehabilitation through engineering projects to minimise environmental impacts on farmland, deforested land, transport facilities and water conservation through sand and dust storms and other aspects of desertification [21, 54]. Moreover, the rehabilitation of mobile sandy lands, and water conservation have facilitated the return of good conditions on some land. [134]. The method of large-scale restoration of degraded land is used by combining enrichment planting of native woody and fodder grass plants with large-scale land preparation for rainwater harvesting and soil permeability [85].

The **DESERTICAS** model has highlighted the predominance of human actions through a comparative study of the impact of all factors on the desertification process (Cf. Subsection 5.3). These actions are combined in the *Enhanced Model of Desertification* in the form of the management parameter (cf. subsection 5.3) in [13]. By giving an intensity to management factor index, it allows to act on all desertification factors and also act in the global system. Depending on the overall desired condition of the study area, **GAs** are used to determine the adequate value of management leading to the result. Genetics algorithms represent a powerful supervised modelling tool that is used in the optimization of complex systems. Indeed, it has successfully been used to optimize the control parameters in automatic control field [27], to solve Traveling Salesman Problem [23], to design lens [61], to optimize computer network performances [129], etc.

The main contribution of this chapter is to combine systems theory, **GAs** and cellular automata in order to build a decision-making tool for desertification. In terms of systems theory, we will consider two concepts related to spreadability and control of cellular automata and show how they can be highlighted by means of **DESERTICAS**. The spreadability can be easily and directly demonstrated in simulations, whereas control requires greater precision. It consists of defining the control variable and explaining how can we act on this variable in order to ensure resorption of desertification spread.

The results of this chapter will be published in an article currently in the final stages of writing.

5.2 An overview of analysis and control of CA models

5.2.1 Spreadability of desertification

The spreadability concept has been introduced to find dynamics which describe the phenomenon of spatial expansion with time of a given property [109]. The spreadability of dynamic systems is motivated by the phenomena of expansion in the evolution of dynamic systems. The idea is related to the fact that the subdomains where the state of a distributed system is enforced to obey a spatial property are non-decreasing [5, 110].

Let Ω be an open bounded domain in the Euclidean space \mathbb{R}^n and $I = [0, T]$ a time interval. Consider a distributed parameter system (S) whose state is denoted by Eq.(5.1).

$$z(., t) : \Omega \rightarrow \mathbb{R} \quad (t \in I) \quad (5.1)$$

Assume \mathcal{P} to be a given property which may describe a spatial constraint on the state of the system (S) and let θ_t be the subdomains of Ω where the state obeys the property \mathcal{P} . θ_t verifies Eq.(5.2).

$$\theta_t = \{x \in \Omega \mid \mathcal{P}z(x, t)\} \quad (5.2)$$

Using these concepts, the following definitions are established in relation to CA.

Definition 5.1 (Spreadability of dynamic system) *A system (S) is said to be \mathcal{P} -spreadable during the time interval I along the (θ_t) s if the family $(\theta_t)_{t \in I}$ defined in Eq.(5.2) non-decreasing.*

Definition 5.2 (Spreadability of CA) *Let \mathcal{A} be CA defined by $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$ and \mathcal{P} a given property defined by the relationship Eq.(5.3).*

$$\mathcal{P}s_t(c) \Leftrightarrow s_t(c) = s \quad (5.3)$$

with $s \in \mathcal{S}$ corresponding to the desired profile and the state s is assumed to be attainable from time t_0 . Consider Eq.(5.4) :

$$\theta_t = \{c \in \mathcal{L} \mid \mathcal{P}s_t(c)\} \quad (5.4)$$

The CA \mathcal{A} is said to be \mathcal{P} -spreadable from $\theta_{t_0} = \{c \in \mathcal{L} \mid \mathcal{P}s_{t_0}(c)\}$ if $\theta_t \subset \theta_{t+1}, \forall t \geq t_0$.

Definition 5.3 (Spreadability in measure) *The CA \mathcal{A} is said to be spreadable in measure or \mathcal{A} -spreadability during the time interval $I = [t_0, T]$ if Eq.(5.5) is verified.*

$$mes(\theta_{t'}/\theta_t) \leq mes(\theta_t/\theta_{t'}) \quad \forall t, t', t_0 \leq t' \leq t \leq T \quad (5.5)$$

where $mes(x)$ is the Lebesgue measure of x . When it comes to use the number of elements of the set x , $|x|$ will be used.

The above definition simply means that the surface gained, i.e the number of cells gained, during spreading is greater than that lost during the time interval $[t', t]$, where t is greater than or equal to t' .

Definition 5.4 (Spreadability of degradation) *The areas subject to the degradation process in our Enhanced Model of Desertification have states belonging to either the interval I_4 for degraded states or to the interval I_5 corresponding to desertified states (cf. Tab.2.10). Let \mathcal{A} be CA modelling the area subject to the degradation process and \mathcal{P} a property of land degradation defined by the relationship Eq.(5.6).*

$$\mathcal{P}s_t(c) \Leftrightarrow s_t(c) \in (I_4 \cup I_5) \quad (5.6)$$

The CA \mathcal{A} is said to be spreadable in degradation measure if $|\theta_t| < |\theta_{t+1}|, \forall t \geq t_0$. $|\theta_t|$ is the number of cells that satisfy the property \mathcal{P} at time t (degraded or desertified areas).

Definition 5.5 (Spreadability of desertification) *The areas subject to the desertification process in our Enhanced Model of Desertification have states belonging to the interval I_5 corresponding to desertified states (cf. Tab.2.10). Let \mathcal{A} be CA modelling the area subject to the degradation process and \mathcal{P} a property of land desertification defined by the relationship Eq.(5.7).*

$$\mathcal{P}s_t(c) \Leftrightarrow s_t(c) \in I_5 \quad (5.7)$$

The CA \mathcal{A} is said to be spreadable in desertification measure if $|\theta_t| < |\theta_{t+1}|, \forall t \geq t_0$. $|\theta_t|$ is the number of cells that satisfy the property \mathcal{P} at time t (desertified areas). So, the desertified areas grow considerably.

Example of desertification spreadability

In Fig. 5.1, the number of *desertified* cells is non-decreasing during the time interval $[0; 120]$. It corresponds to spreadability in desertification measure as described in Eq.(5.7). In this figure, the general trend is that, due to the expansion of the monitored degradation property, the number of cells in good states decreases over time, while the number of cells in a *desertified* state increases significantly. In our developed model, the spreadability in desertification measure is indeed verified i.e the *desertified* areas are expanding. Our work ahead is to act on the system with appropriate controls to halt or slow down this expansion in order to prevent the degradation of all the cells in the studied area and avoid also its complete desertification. To curb this growing expansion, we will employ the theory of controllability, which should be defined in the next subsection.

5.2.2 Control of cellular automata

Controlling a system consists in studying its behavior in terms of inputs (controls) and outputs (observations). The objective of the control of CA is to

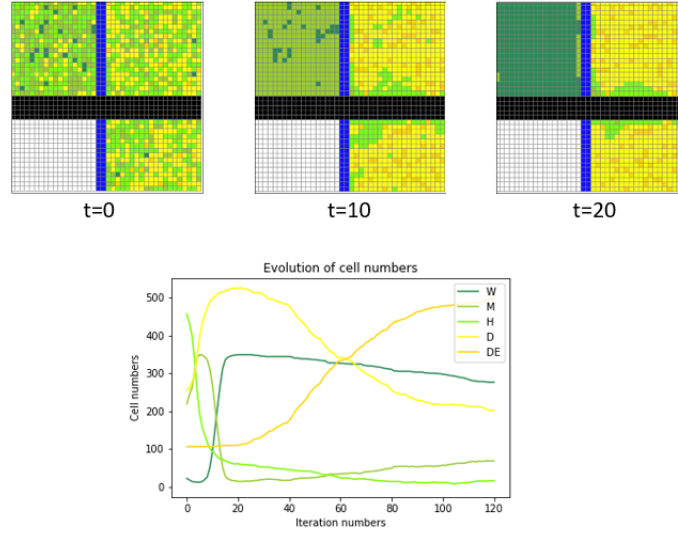


FIGURE 5.1 – Non-decreasing of the number of *desertified* cells in the considered study area (W= *Weak*, M= *Moderate*, H= *High*, D= *Degraded* and DE= *Desertified*)

determine how can we act on their dynamics (via inputs or controls) in order to achieve some predefined objectives. A formalisation of the notion of control and actuators for CA has been firstly introduced in [109, 110]. This will allow to define some analysis concepts on CA such as controllability using a state representation as it is stated in classical control theory when systems are described by partial differential equations. This also will allow cellular automata to be considered as distributed parameter systems where the state and control variables depend on time and space and the systems behaviour is described in terms of inputs and outputs [6, 110, 108].

The control is done through inputs (actuators) that have a spatial structure (number, spatial location and distribution) and its parameter is the predominant factor determined in the Section 5.3.

Let \mathcal{A} be CA defined by $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, f)$. Let us consider the following general hypothesis [108] :

- $\mathcal{L} = \mathbb{Z}^d$ is the cellular lattice.
- $I_T = \{0, 1, \dots, T\}$ is a discrete time horizon.
- \mathcal{L}_k is a subdomain that defines the region of the lattice \mathcal{L} where the CA are excited. It contains k cells that may be connected or not.
- Let us consider the control space given in Eq.(5.8).

$$\mathcal{U} = \mathcal{C}(I_T \times \mathcal{L}_k, \mathbb{R}) \tag{5.8}$$

Where $\mathcal{C}(I_T \times \mathcal{L}_k, \mathbb{R})$ is the set of continuous functions from $I_T \times \mathcal{L}_k$ to \mathbb{R} . It consists of all the bounded controls in (5.9).

$$u : I_T \times \mathcal{L}_k \rightarrow \mathbb{R} \\ (t, c) \mapsto u_t(c) \tag{5.9}$$

Definition 5.6 (Actuator in CA) An actuator is a couple (\mathcal{L}_k, g) where \mathcal{L}_k represents a subdomain of \mathcal{L} that supports the actuator and g is its spatial distribution in \mathcal{L}_k [111, 108].

Definition 5.7 (Zone actuator) An actuator is said to be [111, 108] zone actuator if \mathcal{L}_k is a nonempty sub-region of \mathcal{L} .

Definition 5.8 (boundary actuator) An actuator zone is said to be a boundary actuator if its support $\mathcal{L}_k \subset \Gamma$ where Γ is the whole domain boundary (cf. Fig. 5.2) [108].

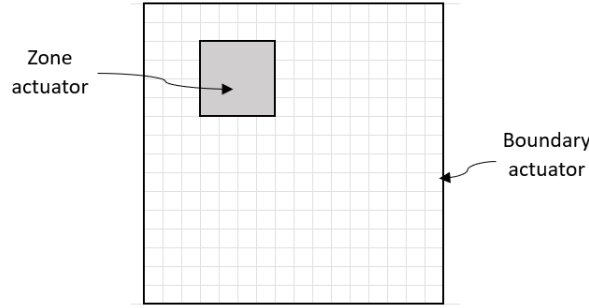


FIGURE 5.2 – Types of actuators

Definition 5.9 (Control in cellular automata) Let us recall some useful notions related to the definition of control in CA. The application of a control on CA is formalized by a global control operator G that defines the way the control excites the CA through the cells of \mathcal{L}_k (cf. Eq.(5.10)).

$$\begin{aligned} G &: \mathcal{U} \rightarrow \mathcal{S}^{\mathcal{L}} \\ u &\mapsto Gu \end{aligned} \quad (5.10)$$

Where \mathcal{U} is the control space defined in Eq.(5.8). G is an operator that transforms the physical actions u to a realization Gu in the configuration space. Its action on cell c at time t is denoted as $g(u_t(c))$. It defines the way how the control is applied to the cellular automaton through the k cells of \mathcal{L}_k .

$$Gu_t(c) = \begin{cases} g(u_t(c)) & \text{if } c \in \mathcal{L} \\ 0 & \text{elsewhere} \end{cases} \quad (5.11)$$

The controlled CA can be locally defined by the triple defined by Eq.(5.12).

$$\mathcal{A}_c = (f, g, \mathcal{N}) \quad (5.12)$$

where f and g are respectively the local transition and control functions and \mathcal{N} is the neighbourhood.

The CA are then considered as a controlled system, defined by the local transition function f in Eq.(5.13) :

$$s_{t+1}(c) = f(s_t(\mathcal{N}(c))) + g(u_t(c)) \quad (5.13)$$

The global evolution of a controlled CA is described in the linear case by Eq.(5.14).

$$\begin{cases} s_{t+1} & = & F(s_t + Gu_t) \\ s_0 & \in & \mathcal{S}^{\mathcal{L}} \end{cases} \quad (5.14)$$

Where F is the global transition function of CA and G is the global control function.

The continuation of our work involves to make an area \mathcal{G}_1 reach a desired state thanks to an area \mathcal{G}_2 that we can control (cf. Fig. 5.3). Formally, we consider CA $(\mathcal{L}; \mathcal{S}; \mathcal{N}; f)$ where \mathcal{L} is the cellular space, \mathcal{S} the set of cell states, \mathcal{N} the neighbourhood set and f is the transition function. Let T be a given time and $\{0, 1, \dots, T\}$ is a discrete time set, \mathcal{G}_1 and \mathcal{G}_2 sub-parts of space \mathcal{L} which include respectively $n_{\mathcal{G}_1}$ and $n_{\mathcal{G}_2}$ cells (cf. Fig.5.3). Let $s_d \in S^{\mathcal{G}_1}$ be a desired configuration on the space \mathcal{G}_1 and s_T the configuration of the space \mathcal{G}_1 at time T . Let λ_s be a measurement on a configuration s of $S^{\mathcal{L}}$.

We define on the space of configurations $S^{\mathcal{L}}$ a distance Δ by Eq.(5.15)

$$\forall (s_1, s_2) \in S^{\mathcal{L}} \times S^{\mathcal{L}}, \Delta(s_1, s_2) = |\lambda_{s_1} - \lambda_{s_2}| \quad (5.15)$$

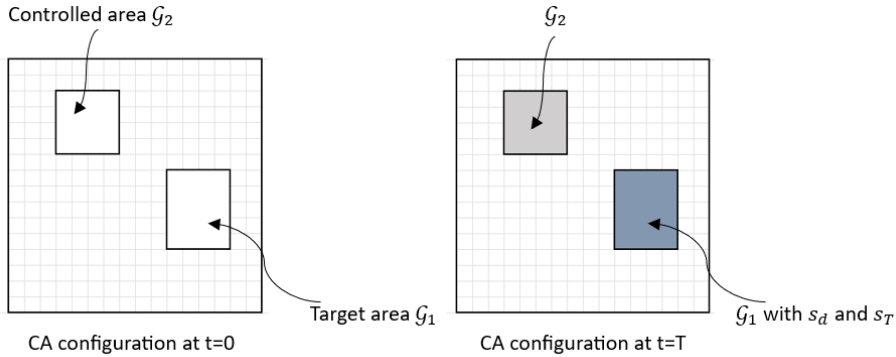


FIGURE 5.3 – Control problem

Definition 5.10 (Exactly regionally controllability) [108] *The CA $(\mathcal{L}; \mathcal{S}; \mathcal{N}; f)$ are exactly regionally controllable if, for $s_d \in S^{\mathcal{G}_1}$, there is a control u to apply T times on \mathcal{G}_2 to lead \mathcal{G}_1 towards a configuration s_T . Thus, Eq.(5.16) is verified.*

$$s_d = s_T \text{ on } \mathcal{G}_1 \quad (5.16)$$

Definition 5.11 (Weakly regionally controllability) [108] *The CA $(\mathcal{L}; \mathcal{S}; \mathcal{N}; f)$ are weakly regionally controllable if, for $s_d \in S^{\mathcal{G}_1}$ and $\varepsilon \geq 0$,*

there is a control u to apply T times on \mathcal{G}_2 to lead \mathcal{G}_1 towards a configuration s_T . Thus, Eq.(5.17) is verified.

$$\Delta(s_d, s_T) \leq \varepsilon \text{ on } \mathcal{G}_1 \tag{5.17}$$

The study of the controllability of CA will enable us to influence the desertification process through a control parameter that needs to be identified. The section below will focus on determining this control parameter, recognized as a predominant factor on which action can be taken to prevent or halt land degradation.

5.3 Studying the sensitivity of the built-model to the emergence of a predominant factor

In this section, the sensitivity of the *Enhanced Model of Desertification* is tested to bring out a factor that has the greatest influence on the whole system. It consists of studying and analyzing the impact of the factors in our model among the four main ones namely : soil, vegetation, climate and management. Finding the predominant one will enable to act efficiently on the system. Thus, positive actions on this factor should slow down or stop the land degradation process and lead the system to the regeneration or stability process. Negative actions are expected to worsen the deterioration.

5.3.1 Methodology of the study

To observe the impact of the main factors on the desertification process, we launch simulations from the same initial state illustrated in Fig. 5.4 representing the studied area. It is divided into three parts delimited by a road (in black), a river (in blue) and residential areas (in white). One parameter is chosen as a studied parameter and its index is set constant over time and space. Thus, the bottom right part corresponds to a random distribution of indexes of the three other (*non-constant*) factors, the top right part corresponds to low indexes of these non-constant factors and the top left part corresponds to high indexes of these non-constant factors. All the factors are assumed to have the same weight $\alpha_i = 1$ in order not to influence the predominance. The considered neighbourhood is Moore's one with radius 1. The parts of the study area are considered to be exploited : the exploitability factor index is equal to 1 for all cells.

More formally, the chosen parameter $x \in \{l, v, w, m\}$ is set constant by giving a constant value to $f_x(\xi_t(\mathcal{N}(c)))$ in the transition function defined by Eq.(4.16). We let the other factors evolve normally in time and space.

5.3.2 Results and discussion

In Fig. 5.5 and Fig.5.6, the index of the studied factor is set at low and constant over time for the case (a), at moderate and constant for the case (b) and high and

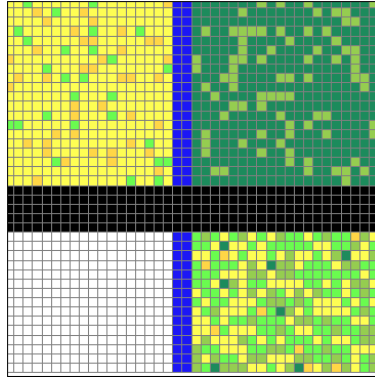


FIGURE 5.4 – Initial state of studied area divided into three parts delimited by a road(in black), a river(in blue) and residential areas(in white)

constant for the case (c). The first column shows the ongoing impacts of management, the second, third and fourth columns present the constant impacts of climate, soil and vegetation on the study area respectively. We can see the evolution of the cells at time $t = 20$ in Fig.5.5 and the distribution of the cell states in Fig.5.6.

The Fig.5.5(a) and Fig.5.6(a) analysis shows that low indices for each factor taken separately constant are sources of regeneration for degraded cells and improvement for cells in good condition and cells in moderate condition. In Fig.5.5(b) and Fig.5.6(b), moderate indexes of each factor taken constant are stabilization sources of the cell states. Indeed, moderate values of the management degrade the cells in good condition to a moderate state and improve the states of the degraded cells to a stable states. This situation is also observed for moderate indices for soil and vegetation. However, moderate indexes of the climate do not lead to significant improvements in degraded cells. This is explained by the fact that these moderate climate indexes modestly influence human actions. In Fig.5.5(c) and Fig.5.6(c), high and constant indexes for each factor accelerate the degradation of cell states. This degradation is more accentuated for the climate and management and less pronounced for the soil and vegetation which have practically the same effects. However, extreme climate indexes correspond to arid areas which are not concerned by the desertification process.

Management has a more significant impact in a shorter time. Low management index leads to a considerable improvement of the study area condition. In fact, this low management index consists in reducing considerably land use level and also in adopting and in applying land protection policies. A low management considerably improves the quality indexes of the other factors and therefore strongly contributes to the improvement of the overall area condition while high management index, which consists in not controlling human actions, leads to its degradation. A high management index is a degradation source of land parameters and strongly contributes to its extinction. A moderate management index improves the degraded cell states to moderate, deteriorates slightly the good cell states and stabilizes them

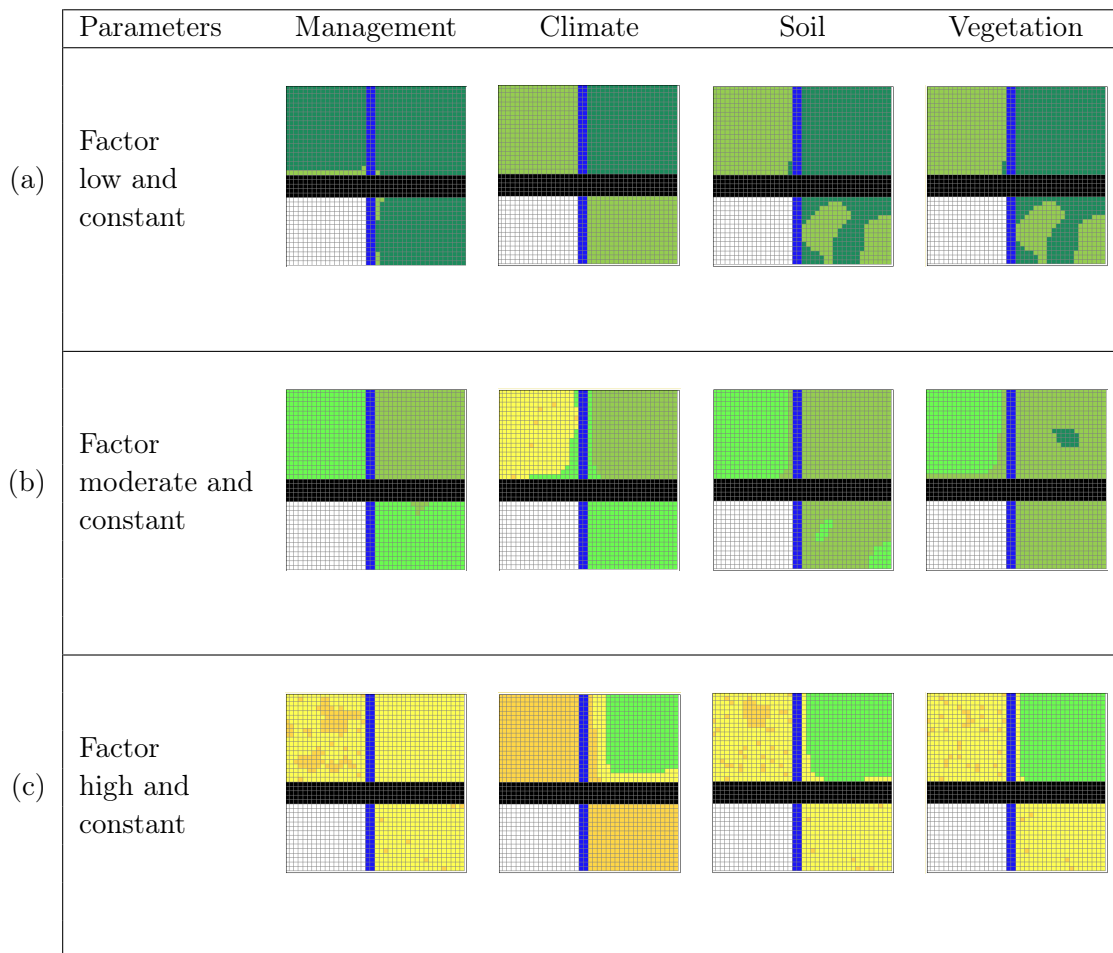


FIGURE 5.5 – Evolution of an area with constant factor index at $t=20$.

to the moderate states. Also, the states of the study area for moderate and high management converge to a stable state. This stability is due to the fact that the management index is chosen constant, the additional pressures due to the loss of the land quality state are implicitly neglected for the moderate and high values.

To complete the analysis, in Fig.5.7 and Fig.5.8 is added a third dimension representing the value of the constant parameters. On this axis the value is incremented by step of 0.1 that helps to understand the impact of all possible values of the studied factor index in the desertification process. In this way, the predominant factor between soil, vegetation, climate and management factors which impacts the elementary processes of land degradation, namely regeneration, stability and degradation is highlighted.

Through Fig.5.7(a), we can see that the number of cells in good states (low and moderate) is increased for low management indexes, but also for moderate ones until stabilisation obtained from 1.2 to 1.4. Subsequently, this number undergoes a rapid fall for high indexes (from 1.4) of the management until it is canceled out for

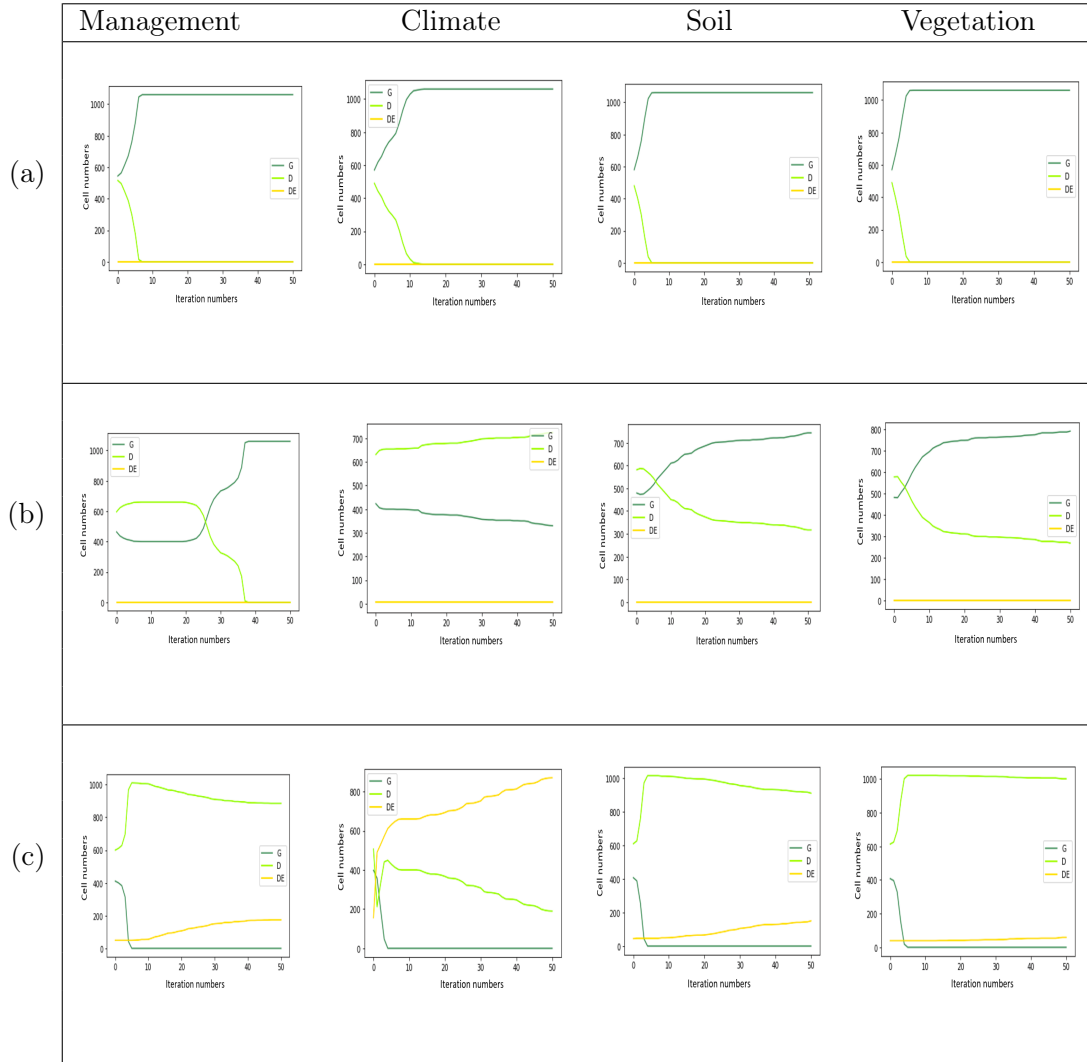


FIGURE 5.6 – Evolution of the number of cells in good, moderate and degraded states depending on iterations number. (a), (b) and (c) are described in the same way as in Fig. 5.5

very high management indexes. Thus, for low management indexes, the numbers of degraded and *desertified* cells are practically zero. This confirms the fact that low management indexes improve all cell states by improving indexes of other factors. The number of degraded cells is growing rapidly from a management index set at 1.3. Indeed, cells in good condition begin to degrade at moderate management indices and these deteriorations increase with increasing management indices. As for the number of *desertified* cells, it begins its growth from 1.4 with a slight growth and a rapid evolution beyond 1.7. This is because the number of cells in good condition has dropped to zero. Thus, these cells in good states passed through the class of degraded cells for a high management index and died out for very high management

indices.

Through Fig.5.7(b), we see that the number of cells in good state (low and moderate) is growing for low and moderate indexes of the climate until reaching 1.4, decreases thereafter until canceling from a climate index equal to 1.6. Indeed, high climate indexes cause weakening of cells in good states and thus contribute to their degradation, while good climate indexes improve the condition of these cells. For low climate indexes, the numbers of degraded and *desertified* cells are practically zero. This is because low climate indexes improve the condition of all cells by improving indexes of other factors. The number of degraded cells undergoes rapid growth from a climate index set at 1.4. Indeed, cells in good states begin to be degraded when the climate indexes are high and this degradation becomes more and more accentuated with the growth of this index. As for the number of *desertified* cells, it begins to grow from high climate indexes. This is because the number of good cells fell to zero for these extreme climate indexes. These good cells passed through the degraded cell class and subsequently died out. These remarks are identical in case of Fig.5.8(c) and Fig.5.8(d).

At the end, each of the factors taken separately has a degradation or improvement influence on the system according to its index. Indeed, for a chosen factor, low indices kept constant over time are improvement sources of the other factors over time while high indices contribute to the degradation of all the factors and therefore of the entire system. This degradation is more accentuated in the high index case and extreme for the climate factor. High climate indexes correspond to arid areas which are not concerned by the desertification process. Moderate indexes on different factors improve degraded cell conditions and low indexes improve all cell conditions. However, the improvement of cell states is more accentuated for the management indexes which remains the main source of cell degradation. Acting on management allows to slow down the degradation evolution and improve the overall index of the area studied. Indeed, its low and moderate indexes significantly improve the overall quality of the study area and high indexes cause its degradation. This situation is explained by the fact that management impacts all the factors of desertification. By acting on management, we act indirectly on all these factors.

5.3.3 An example of management application as predominant factor

Through this study, it is clear that the management has a strong impact on desertification process. Now, we want to study the influence of a small management controlled area over the neighbourhood. To do so, constant index management is only imposed on central area over time. Soil, vegetation and climate factors are evolving normally according to the transition function. In Fig.5.9, the evolution of the studied area according to the different management trends (*low, moderate and high*) is simulated.

On the first line of Fig.5.9 and Fig.5.10, the constant management is *weak*. One can see an improvement of the states of its non-desertified neighbouring. However,

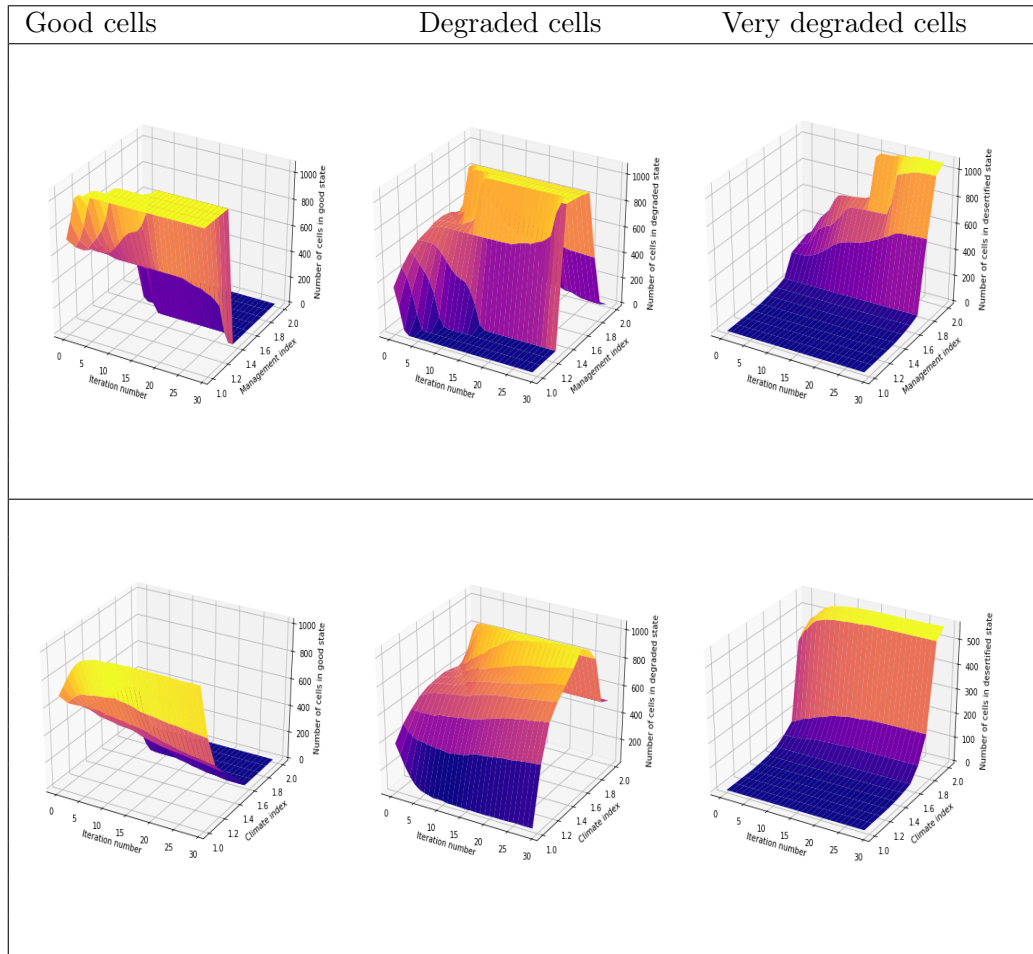


FIGURE 5.7 – Evolution of the number of cells in good state, in degraded state and in *desertified* state according to the iteration numbers and the chosen factor index : (a) corresponds to Management constant and (b) to climate constant

the other factors of the cells in this central area are degraded by the *desertified* neighbouring cells located in the upper left. Thus, the central *desertified* neighbouring cells are degraded over time from the upper left. On the second line, the *moderate* state of some central cells is degraded by their *desertified* neighbours. Furthermore, the *moderate* central cells gradually degrade their *good* neighbour states but improve the states of their *degraded* neighbours. On the third line, the *degraded* state of some central cells becomes *desertified* by their *desertified* neighbours. Furthermore, the *degraded* central cells gradually degrade their neighbours in *good* states and in moderate states.

The comparative analysis of Fig.5.5 to Fig.5.9 highlights the role of border areas (roads, watercourse and housing). These border areas prevent the spread of the desertification phenomenon. Without a border zone, the degradation is a little more accelerated because the practices are diffused according to the surrounding areas.

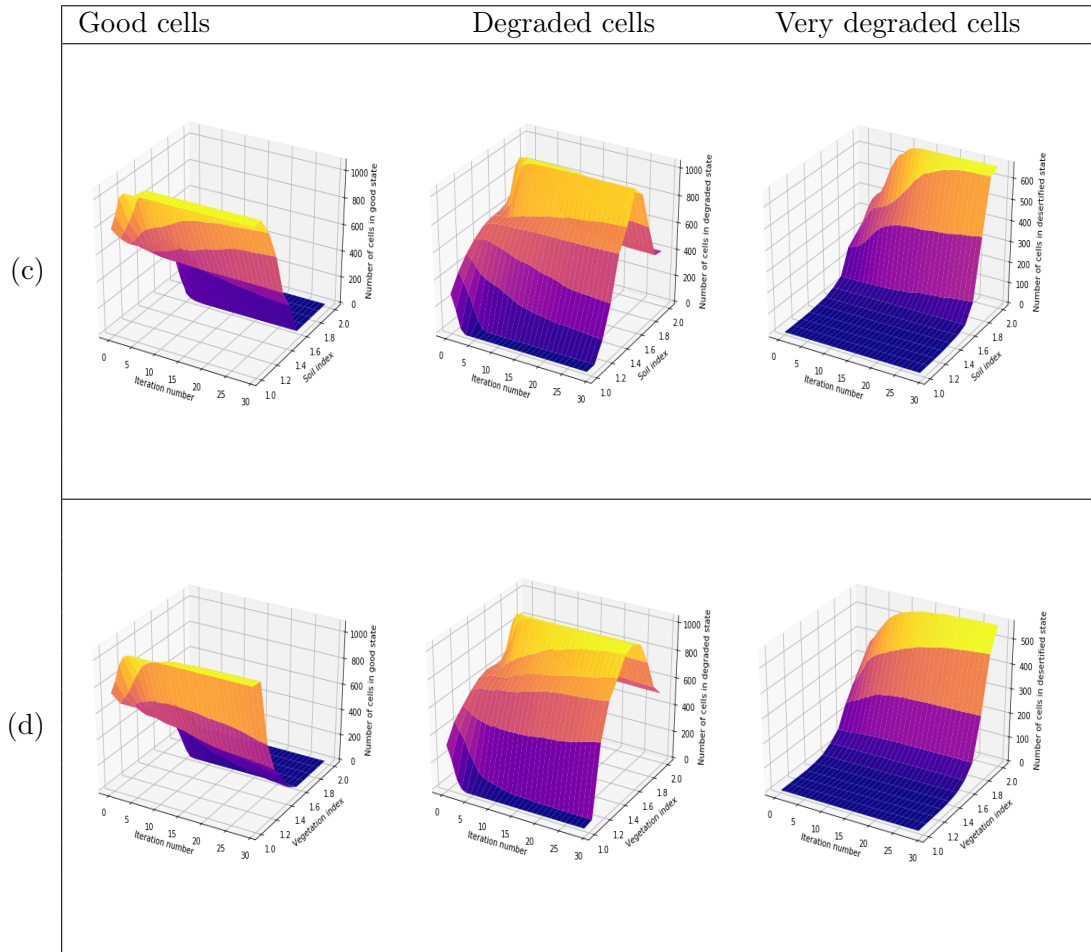


FIGURE 5.8 – Evolution of the number of cells in good state, degraded state and *desertified* state according to the iterations number and the chosen factor index : (c) corresponds to soil constant and (d) to vegetation constant

After highlighting management as a predominant factor, the next objective is to apply the controllability theory to the desertification issue by acting on management. This application is achieved by combining the concepts of controllability and *GAs*, which are defined in the next sections and followed by their application.

5.4 Genetic Algorithms

5.4.1 Definition and principles

Genetic Algorithms, in short *GAs*, are numerical optimisation algorithms inspired by both natural selection and natural evolution in genetics [29] with biological terminologies of natural selection, crossover and mutation [61]. *GAs* are defined by the following concepts and steps [88].

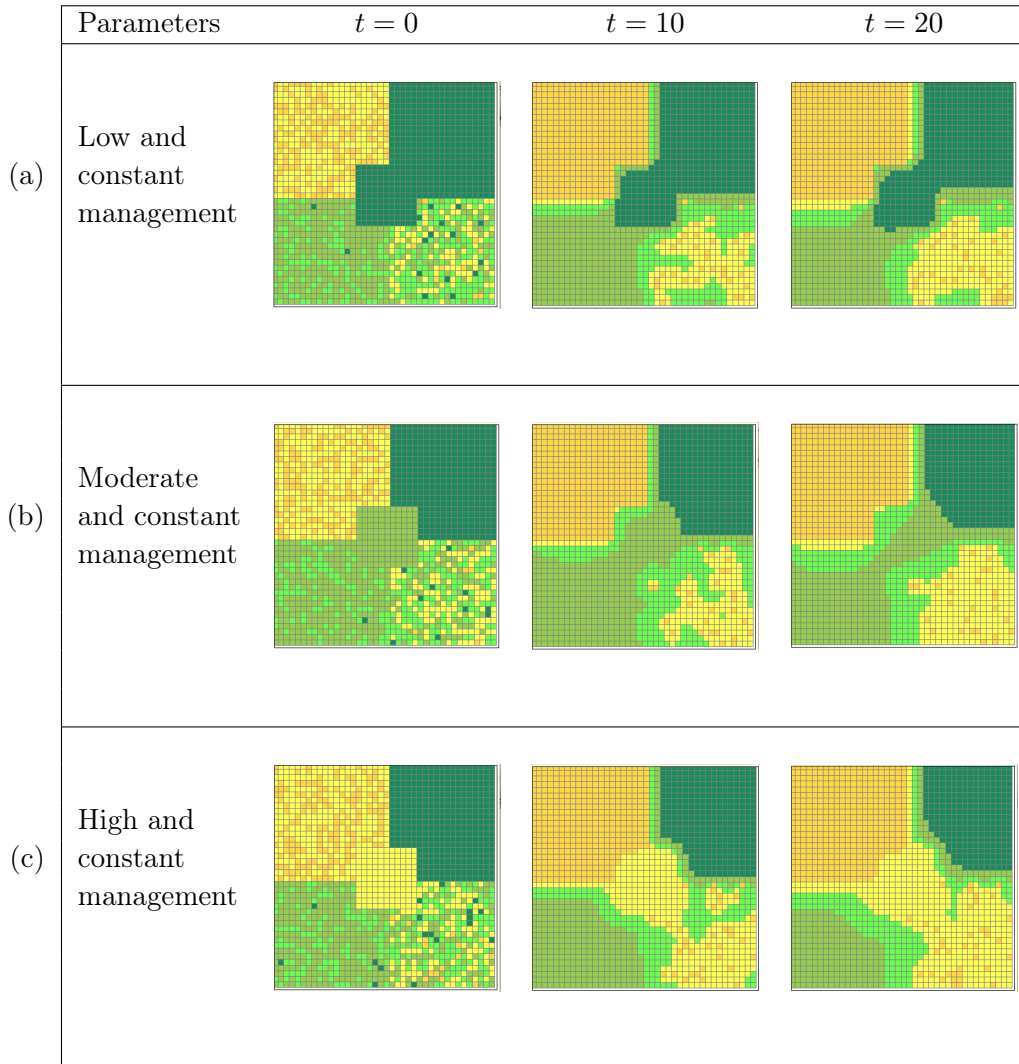


FIGURE 5.9 – Evolution of a middle area with constant management index in different areas.

Individual or chromosome This is a potential solution of the problem to solve. A chromosome or a individual A of length L is a sequence $A = \{A_1, A_2, \dots, A_L\}$, $\forall i \in \llbracket 1, L \rrbracket, A_i \in \{0, 1\}$. A chromosome A is therefore a sequence of bits in binary coding, also called a binary string.

Population GAs search by simulating evolution, starting from an initial set of solutions or hypotheses called initial population and generating successive generations of solutions [121]. A population is composed of individuals.

Fitness function The fitness score of a sequence A is a positive value denoted $\delta_1(A)$, where δ_1 is typically called the fitness function. The fitness function δ_1 de-

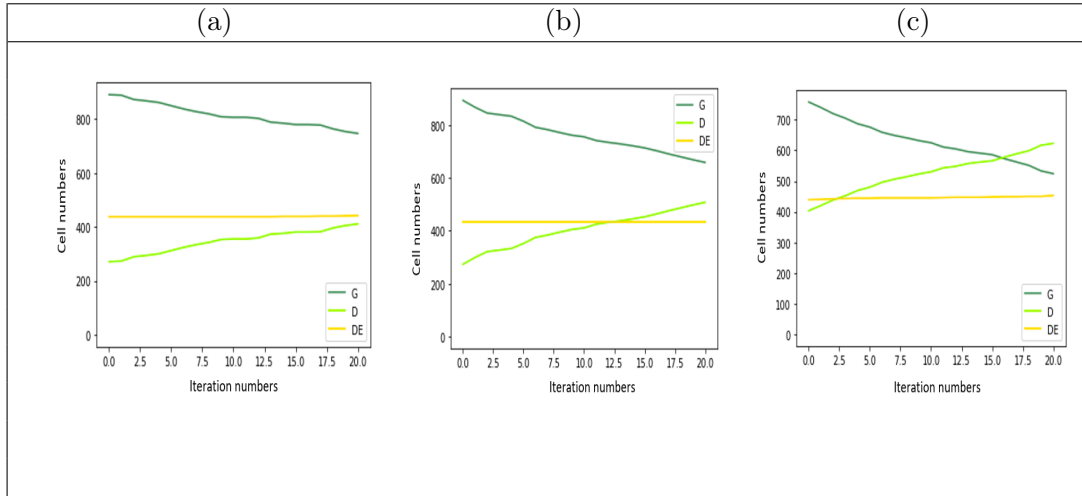


FIGURE 5.10 – curves of cell numbers according to the number of iterations in case (a),(b) and (c)

termines the ability of an individual A to compete with other individuals in the current population [62]. A decoding function $\delta_2 : \{0, 1\}^L \rightarrow R$ is used to convert from a binary string to a real-valued digit. The fitness function δ_1 is then chosen to transform this value into a positive value, i.e. $\delta_1 : \delta_2(\{0, 1\}^L) \rightarrow R_+^*$. The principle of GAs is to find the sequence that maximizes or minimizes the fitness function δ_1 [88].

Selection The probability that an individual will be selected as parent for reproduction is based on its fitness score [124]. It creates a new population of chromosomes by using an appropriate selection method (minimum, or maximum)[88].

Crossover This genetic operator takes more than one parent solution and generates children solutions. Genes from parent chromosomes are taken, and a new offspring is produced (see Fig. 5.11). In detail, the operator selects a random crossover point. Everything in the binary string from the first chromosome before this point is copied and everything after this point from the second chromosome is copied to generate a new offspring [29].

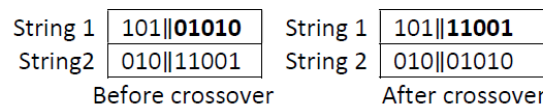


FIGURE 5.11 – Crossover operation

Mutation In certain new offspring formed, some of their genes can be subjected to a mutation with a low random probability. This implies that some of the bits in

the bit string can be flipped [124].

Termination After that selection, crossover and mutation have been applied to the initial population, a new population is formed and the generational counter is increased by one. These processes of selection, crossover and mutation continue until a fixed number of generations is reached or convergence criteria are met [29].

5.4.2 Advantages of GAs

The main advantages of GAs using which have made them immensely popular are :

- GAs do not require any derivative information which may not be available for many real-world problems ;
- GAs are faster and more efficient as compared to the traditional methods ;
- GAs have very good parallel capabilities ;
- GAs optimizes both continuous and discrete functions and also multi-objective problems ;
- GAs provide a list of “good” solutions and not just a single solution ;
- GAs always get an answer to the problem, which gets better over the time ;
- GAs useful when the search space is very large and there are a large number of parameters involved.

5.4.3 GAs limitation

Like any technique, GAs also suffer from a few limitations. These include that GAs are not suited for all problems, especially problems which are simple and for which derivative information is available. Fitness value is calculated repeatedly which might be computationally expensive for some problems. Being stochastic, there are no guarantees on the optimality or the quality of the solution. If not implemented properly, the GAs may not converge to the optimal solution.

5.5 Application to desertification issue

The management factor is identified as being the predominant parameter [13] in *Enhanced Model of Desertification* built from the coupling of the MEDALUS model and cellular automata with continuous states enriched by anthropogenic parameters [12]. Acting positively on the management factor means acting indirectly on the other desertification factors in order to interrupt the degradation sources and slow down or stop land desertification [13]. The application of the controllability theory described above is achieved from the management parameter. The aim is therefore to determine its intensity on a given area to be able to control a desired area. To do so, we have designed GAs which components are described below.

5.5.1 Intensity of management calculated by GAs

The index of each desertification factor is in the interval $[1, 2[$. Thus, each management value is a real number whose integer part is 1. The intensity of management depends on the value of its decimal part. The GAs developed in this present work consist in determining the decimal part of the management which is aggregated to the value 1 to form the management index. Normally, the decimal part of the management is between 0 and 99 corresponding respectively to 0 and 1100011. So the decimal part has seven digits. For the developed GAs, each individual (or chromosome) is composed of seven genes and each gene is either 0 or 1.

5.5.1.1 Initial population

The initial population \mathcal{P} is composed of 10 individuals drawn uniformly at random. For each individual $y_i \in \mathcal{P}$, a management m_i index is associated by Eq.(5.18). Let r_i be the decimal corresponding value of the individual y_i and k the number of digit of r_i :

$$m_i = \begin{cases} 1 + \frac{r_i}{10^2} & \text{if } k = 1 \text{ or } k = 2 \\ 1 + \frac{r_i}{10^k} & \text{else} \end{cases} \quad (5.18)$$

5.5.2 Fitness function

The fitness is based on applying an appropriate management value within a region \mathcal{G}_2 of the lattice \mathcal{L} to attain the desired state at a specific time T within another region \mathcal{G}_1 of the same lattice. The management value m_i corresponds to the i -th individual y_i obtained through the utilization of Genetic Algorithms (GAs).

Let $ds_0^*(\mathcal{G}_1)$ be the desired *DSI* average of the part \mathcal{G}_1 and $ds_T(\mathcal{G}_1)$ its final *DSI* average obtained by applying T times the management m_i of the i -th individual y_i of the GAs in the part \mathcal{G}_2 (cf. Fig.5.12).

The fitness function ψ is defined by Eq.(5.19).

$$\begin{aligned} \psi & : [1, 2] \rightarrow [0, 1] \\ m_i & \mapsto |ds_T(\mathcal{G}_1) - ds_0^*(\mathcal{G}_1)| \end{aligned} \quad (5.19)$$

5.5.3 Selection operation

At each iteration, three parent individuals are retained and these individuals verify Eq.(5.20).

$$\min_{m_i} \psi(m_i) = \min_{m_i} |ds_T(\mathcal{G}_1) - ds_0^*(\mathcal{G}_1)| \quad (5.20)$$

5.5.4 Crossover operation

The crossover is done with a proportion of 0.9, that is to say with a rate of 90%. For each pair of individuals resulting from the selection process, this consists

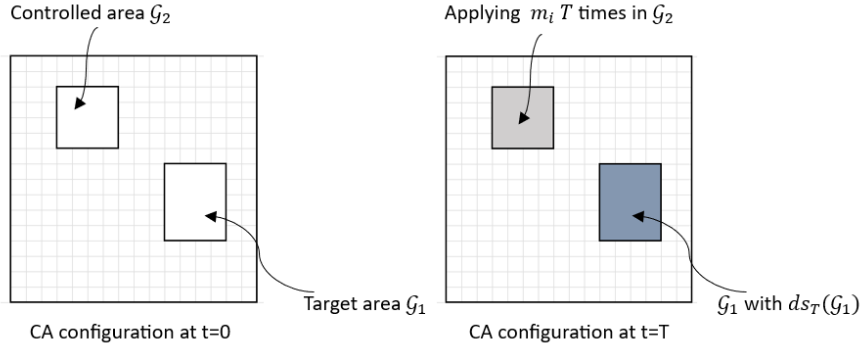


FIGURE 5.12 – Developed control problem

of randomly choosing a real number between 0 and 1. If the chosen number is less than 0.9, the two individuals concerned undergo a crossover from a random crossing point.

5.5.5 Mutation operation

Some individuals resulting from the crossover carry out a mutation with a rate of $\frac{1}{k_0}$ where k_0 is the number of bits of each individual y_i . The bit j of the new individual obtained by mutation from individual y_i is given by Eq.(5.21).

$$y_i[j] = 1 - y_i[j] \quad (5.21)$$

5.5.6 New population generation

At each iteration, a new population \mathcal{P} is generated with individuals successively resulting from the processes of selection, crossing and mutation. Indeed, the individual numbers of each population generated vary according to the number of individuals retained after the selection process and according of the individual numbers resulting from the crossover and the mutation.

5.5.7 GAs termination

The modelled GAs termination is based on the theory of controllability within CA. The control parameter is the predominant factor namely the management identified through our studies.

The idea involves applying an appropriate management value within a region \mathcal{G}_2 of the lattice \mathcal{L} to attain the desired state at a specific time T within another region \mathcal{G}_1 of the same lattice. The management value m_i corresponds to the i -th individual y_i obtained through the utilization of Genetic Algorithms (GAs).

The used actuator of control is thus defined by a couple (\mathcal{G}_2, h_m) . h_m is defined by setting management values to m_i in the support of control \mathcal{G}_2 except for the *desertified* cells. Eq.(4.15) is then modified in Eq.(5.22). It is a zone actuator.

$$h_m : [0, 1]^9 \times \mathcal{S}^{n+1} \rightarrow [1; 2]$$

$$h_m(\alpha, \xi_t(\mathcal{N}(c))) = \begin{cases} m_t(c) & \text{if } ds_t(c) \in I_5 \text{ (Irreversibility)} \\ m_i & \text{otherwise} \end{cases} \quad (5.22)$$

The controlled CA in our study is characterized by $\mathcal{A}_c = (f, h_m, \mathcal{N})$ where f is the transition function of *Enhanced Model of Desertification* as described by Eq.4.16. \mathcal{N} represents Moore's neighbourhood of order 1.

The convergence criterion of GAs developed in this study depends on the type of controllability that we want to implement.

- The designed CA are exactly regionally controllable if, for desired state $ds_0^*(\mathcal{G}_1)$, there is an individual $y_i \in \mathcal{P}$ with a management index m_i such that applied T times on \mathcal{G}_2 gives $ds_T(\mathcal{G}_1)$ a *DSI* average on the part \mathcal{G}_1 , where Eq.(5.23) is verified.

$$\psi(m_i) = 0 \quad (5.23)$$

where ψ is defined by Eq.(5.19) and y_i is given by GAs previously defined.

- The designed CA are weakly regionally controllable if, for desired state $ds_0^*(\mathcal{G}_1)$, there is an individual $y_i \in \mathcal{P}$ with a management index m_i such that applied T times on \mathcal{G}_2 gives $ds_T(\mathcal{G}_1)$ a *DSI* average on the part \mathcal{G}_1 , where Eq.(5.24) is verified.

$$\psi(m_i) \leq \varepsilon \text{ with } \varepsilon \geq 0 \quad (5.24)$$

Thus, the convergence criterion of the designed GAs is defined by Eq.(5.23) or Eq.(5.24) according to the type of controllability implemented.

5.5.8 Initial configuration

The simulations are achieved from the same initial configuration as Fig.5.13 representing the studied area. It is divided into four parts where the bottom right part corresponds to a random distribution of desertification factor indexes. The bottom left corresponds to moderate indexes, the top right corresponds to low indexes of the factors and the top left corresponds to high indexes. The cells in red color correspond to the controlled area. It corresponds to the part of CA grid on which a control is applied through the management factor. The central cells to the reds correspond to the affected area i.e the target area. It corresponds to the part of CA grid where the impact of the control is observed. Thus, in the controlled area, different land protection measures will be applied through the management factor index. These measures will have indirect effects on the target area. In the case of our study, the target area will be isolated from other parts of the study area through the controlled area. This choice is motivated by the fact that the cells directly affected by the control area are, in fact, the immediate neighbours of that area. These cells will, in turn, influence their respective neighbors. As a result, the changes introduced into

the system through the control action will propagate into neighbouring areas, and this propagation will enable the achievement of the intended goal. All the factors are assumed to have the same weight $\alpha_i = 1$ in Eq.4.16 in order not to influence the predominance. The considered neighbourhood is Moore's order 1. The parts of the study area are considered to be exploited : the exploitability factor index is equal to 1 for the all CA cells.

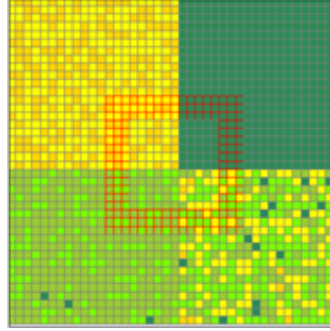


FIGURE 5.13 – Initial state of the studied area

5.5.9 Results and analysis

In Fig.5.14, the initial state of the target area is given by the average *DSI* index $ds_0(\mathcal{G}_1) = 1.41$. It corresponds to the geometric mean of all cells in the target area. The objective of the study is to search a management value m , using our *GAs*, to be applied to the control area in order to reduce the degradation process of this target area. The average *DSI* indexes $ds_T(\mathcal{G}_1)$ of the target area should subsequently be lower by its initial value after this control process and must approach or reach a desired value $ds_0^*(\mathcal{G}_1)$ during $T = 100$ times.

In Fig.5.14(a), the desired mean *DSI* is $ds_0^*(\mathcal{G}_1) = 1.3$ and this value must be approximated to $\varepsilon = 0.15$. The implementation of the *GAs* allows to reach this value from $t = 100$ with a management value on the control area $m = 1.15$. Thus, the fitness functions reaches $\min_{m_i} \psi(m_i) = 0,12 < \varepsilon$. This corresponds to a weakly regionally controllability case. The *GAs*, responsible for determining the value of the control, converges after one iteration. The difference between the desired state and the initial state of the study area is not large enough. Thus, the weakly regionally controllability allows to improve the state of the area. Indeed, by putting protective measures around an area, the conditions of the central area have been improved and mitigate its degradation process.

In Fig.5.14(b), by choosing $\varepsilon = 0.01$, the desired state is approached at $t = 100$ and that from 2 iterations of *GAs*. Thus, the value of the fitness function is 0.003 for a management value $m = 1.02$. This corresponds practically to an exactly regionally controllability. Indeed, protective actions in the controlled area allows to positively improve the condition of the target area and achieve the desired state.

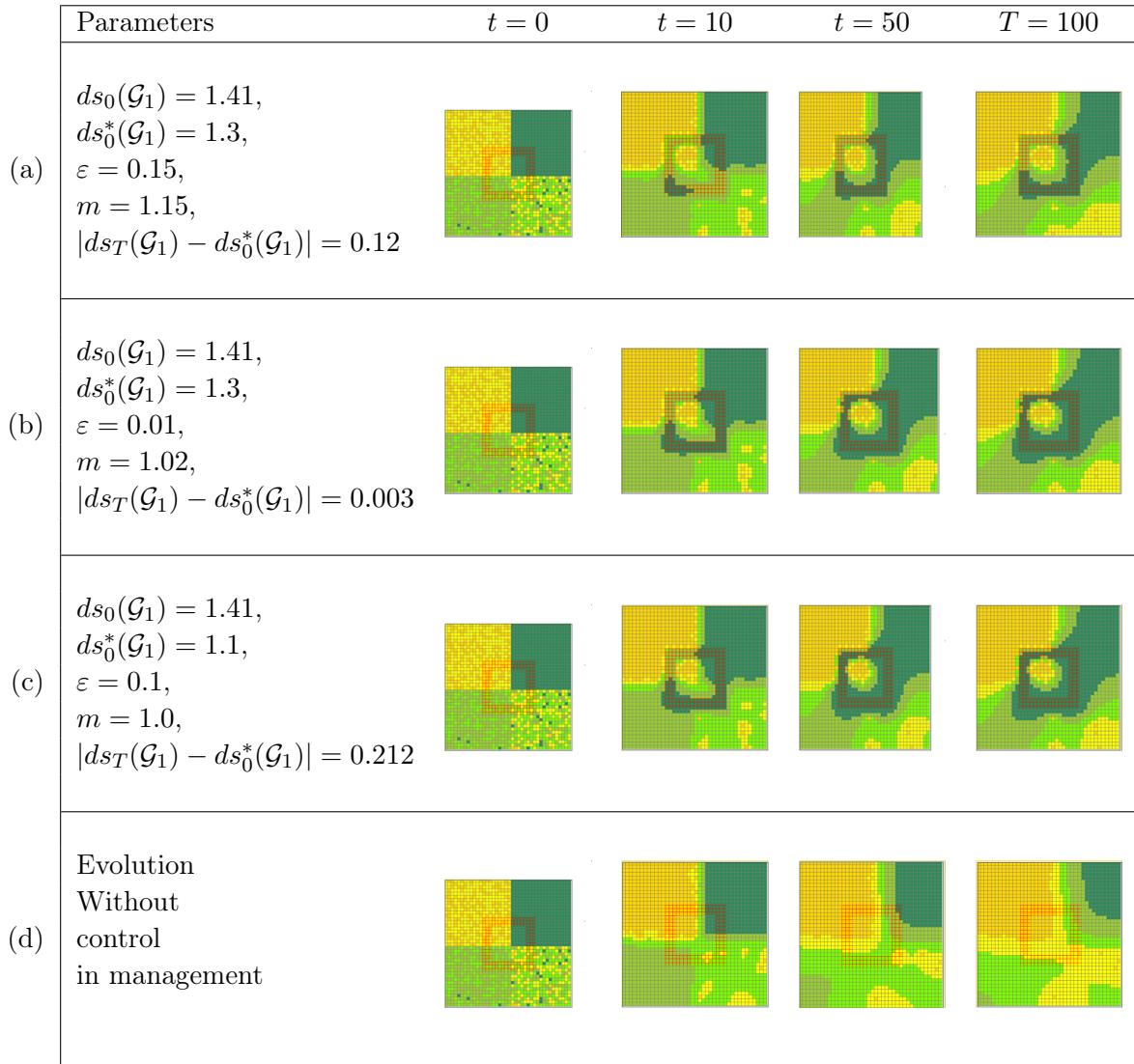


FIGURE 5.14 – Evolution of the same area with the management as control parameter

This improvement is done without changing the state of the *desertified* cells which is the degradation threshold. The other cells undergo the positive impacts of the controlled area and improve their condition through the neighbouring effects.

In Fig.5.14(c), the desired mean *DSI* is $ds_0^*(\mathcal{G}_1) = 1.1$ and this value must be approximated to $\varepsilon = 0.1$. From $t = 100$, the *GAs* reach the minimal value of management $m = 1.1$ and converges to the corresponding value of the fitness function $\min_{m_i} \psi(m_i) = 0.212$. Beyond $t = 100$, the algorithm has almost converged and the values of the fitness function remain identical. This is explained by the fact that the target area contains *desertified* cells whose conditions cannot be improved by simple control actions. In fact, neighbourhood actions cannot have any real impacts

on these cells. In this context, it is necessary to act directly on these cells through restoration or rehabilitation actions. The minimum management value, given by GAs, corresponds to the introduction of strong measures in the control area. This has a positive impact on non-desertified cells in the target area and other neighbouring areas. At the end of this process, the mean index of the CA grid is improved. However, the convergence of the GAs does not make it possible to reach the desired mean index in the target area but it allows to reach it at a certain value of ε . In this case, it is a weakly regionally controllability situation.

In the first three cases of the figure presented in Fig.5.14, the study of controllability is achieved by the action on non-desertified cells. Indeed, the states of the cells in the target area are improved from the states of neighbouring cells located in the controlled area. Thus, the neighbourhood effects improve cell states and subsequently improve the average state of the target area. Although the aim of the study is not the improvement of their states, the areas not located in the target area and in the controlled areas also see their states improved when the control value is low.

The control imposed favorable human activities in the controlled area, which effects resonated in the target area and surrounding areas. As a result, the cells present in this control support and target area have states that are in a continuous improvement process, except for some *desertified* cells which are in an irreversible state. In Fig.5.14(d), no control has been imposed on management factor. In this figure, we can observe that the area is in a continuous degradation process. indeed, the *desertified* cells contribute to a significant degradation of their surroundings. Consequently, the desertification process spreads across the study area and, in the long term, it will contribute to its complete desertification. It is therefore necessary to slow down or prevent this expansion.

5.5.10 Conclusion and perspectives

This study emphasizes the influence of management, specifically human actions, on the process of desertification. It has been confirmed that desertification is spreadable in measure. In fact, intervening in management implies implicit intervention in all factors contributing to desertification, either slowing down or accelerating its progression. Management actions can effectively interrupt the land degradation process before it reaches an irreversible state, thereby maintaining its stability or even improving its condition. This approach enables the integration of actions into the achieved desertification model by adjusting the management intensity.

This study introduces the concept of controllability into the achieved modelling. When the difference between the desired state and the initial state of an area is not too significant, achieving controllability is possible. Indeed, control actions allow us to reach the desired state and enhance the average desertification condition of an area. This makes sense only if we aim for a slight improvement in the state of the study area by implementing protective measures in its neighbourhood. As a result, non-*desertified* cells see their conditions improved and will contribute to the achievement of the improvement objective. However, the control process cannot

enhance the conditions of *desertified* cells. For these *desertified* cells, it is necessary to act directly through actions of rehabilitation, restoration, and reassignment which require enormous means.

At the end, this study shows that GAs are a good candidate for determining the intensity of the control. They are easy to use and, through different tests, they are able to determine the intensity of the desired management which represents the control operator. However, the *desertified* cells lead to the convergence of the algorithm after a number of iterations because their states cannot be modified and contribute to stabilize the mean state of the study area.

Also, the determination of a low state for the study area requires the implementation of the GAs for a long time.

In terms of future prospects, it is possible to optimize the constructed GAs to discover a distinct and more relevant m_i at each stage, facilitating quicker convergence towards the desired solution.

CONCLUSION AND PERSPECTIVE

The main objective of this thesis is to develop models for understanding and simulating the process of desertification. Two models have been proposed and discussed in this research.

The first model associates **CA** to the study area by dividing it into cells. It models the evolution process of desertification by coupling **CA** and the **MEDALUS** model. The states of the cells evolve from its neighbours states. This modelling has the advantage of being simple and easy to implement and also integrates the properties of irreversibility, combination of factors and stress. However, it does not take into account the transfer of activities from a land to another.

The first model incorporates **CA** approach to represent the study area by dividing it into cells. It simulates the evolution of desertification by combining the **CA** with the **MEDALUS** model. The states of the cells evolve based on the states of their neighbouring cells. This modelling approach is advantageous due to its simplicity and ease of implementation, while also considering properties such as irreversibility, the combination of multiple factors, and the impact of stress. However, this model does not account for the transfer of activities between different areas.

To address this limitation, a second model called the *Enhanced Model of Desertification* has been developed. This model offers a more comprehensive approach by incorporating additional anthropic factors into the **MEDALUS** model. These factors include exploitability, land ownership, and land use type, enhancing the simulation capabilities and improving the realism of the model.

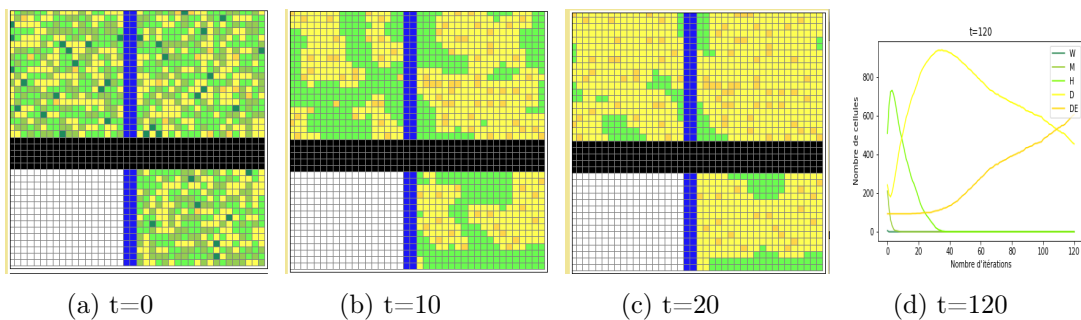
The results obtained from the *Enhanced Model of Desertification* were utilized to create a simulation tool called **DESERTICAS**. This tool, based on the **CA** approach and implemented in Python, enables the simulation of the evolution of a given area by adjusting various parameters such as initial data, neighbourhood radius and factor weights.

The accomplished studies have demonstrated the expansion of desertification and the significant influence of human activities, specifically called management, over other factors. Depending on the objective, the optimal value of management required to reverse or halt the process of land degradation spread is determined through the employed **GAs**. The management value thus established enables the implementation of control operations in an area. This control approach introduces an additional form of land protection, involving the application of positive management

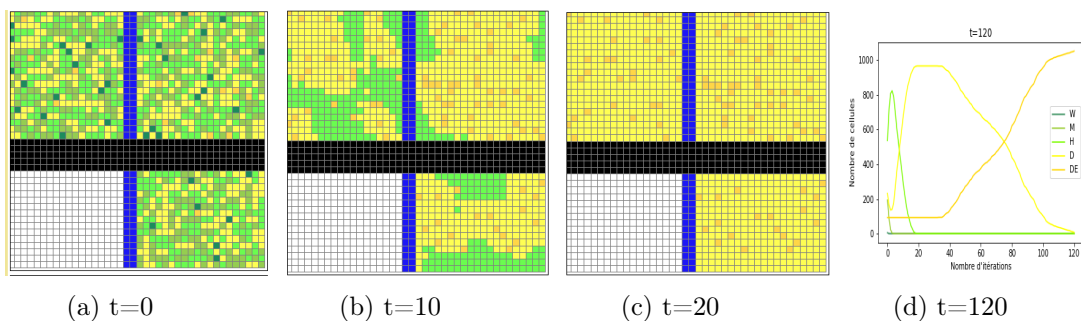
actions in one area to enhance the conditions of neighbouring areas. However, *GAs* suffers from its long execution time. As perspective, the developed model can be optimized to overcome this insufficiency.

Lastly, it is important to emphasize that the simulations were conducted on an artificial study area featuring structured heterogeneity. Future work will focus on applying the models to real-world situations in Saharan Niger, where desertification is a significant challenge. This will provide valuable insights into addressing the desertification phenomenon in practical scenarios.

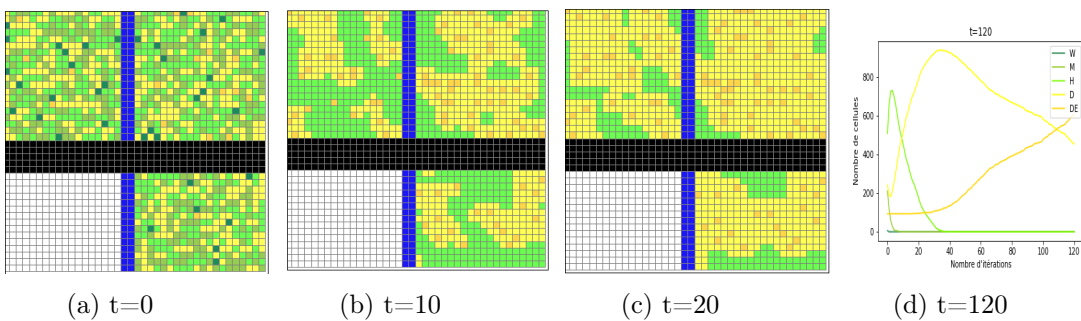
Appendix



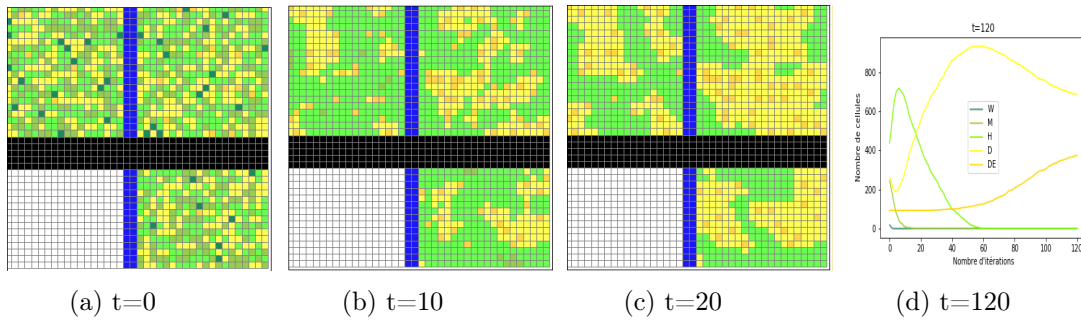
Appendix 1 : Evolution of an area in DESERTICAS with standard parameters $\alpha_l = (1; 1; 1)$, $\alpha_v = (1; 1; 1)$, $\alpha_w = (1; 1; 1; 1)$, $\alpha_m = (1; 1)$ and $r = 1$



Appendix 2 : Evolution of an area in DESERTICAS with standard parameters : $\alpha_l = (1; 1; 1)$, $\alpha_v = (1; 1; 1)$, $\alpha_w = (1; 1; 1; 1)$, $\alpha_m = (1; 1)$ and $r = 2$



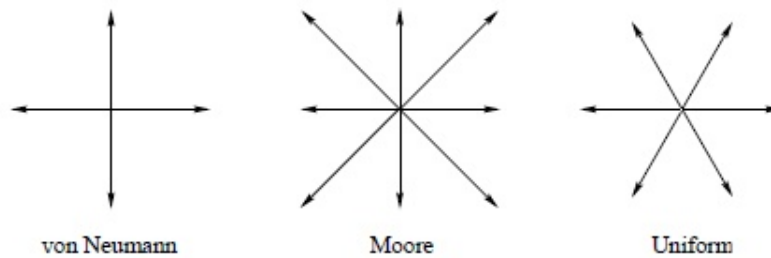
Appendix 3 : Evolution of an area in DESERTICAS with chosen parameters $\alpha_l = (2; 1; 1)$, $\alpha_v = (2; 1; 1)$, $\alpha_w = (3; 1; 1; 1)$, $\alpha_m = (1; 1)$ and $r = 1$



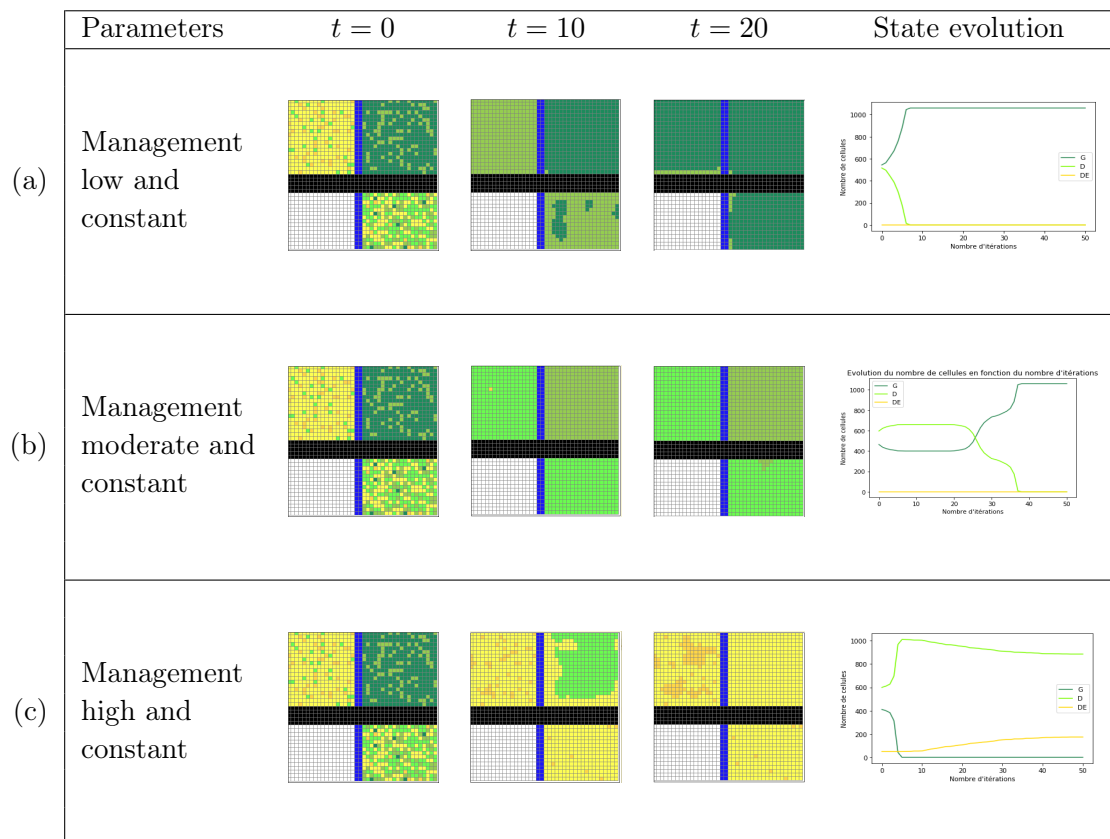
Appendix 4 : An area evolution in DESERTICAS with chosen parameters $\alpha_l = (3; 1; 2)$, $\alpha_v = (3; 1; 2)$, $\alpha_w = (5; 1; 2; 2)$, $\alpha_m = (2; 1)$ and $r = 1$

Process	Cell state at time t	Neighbourhood state at time t	Cell state at time $t + 1$
Degradation	Weak	High	Moderate
	Moderated	Degraded	High
	Degraded	Very degraded	High
	High	Very degraded	Degraded
Regeneration	Degraded	Moderate	High
	High	Weak	Moderate
	Degraded	Weak	Moderate or high
Preservation	Weak	Weak	Weak
	Moderated	Moderated	Moderated
	High	High	High
	Degraded	Degraded	Degraded

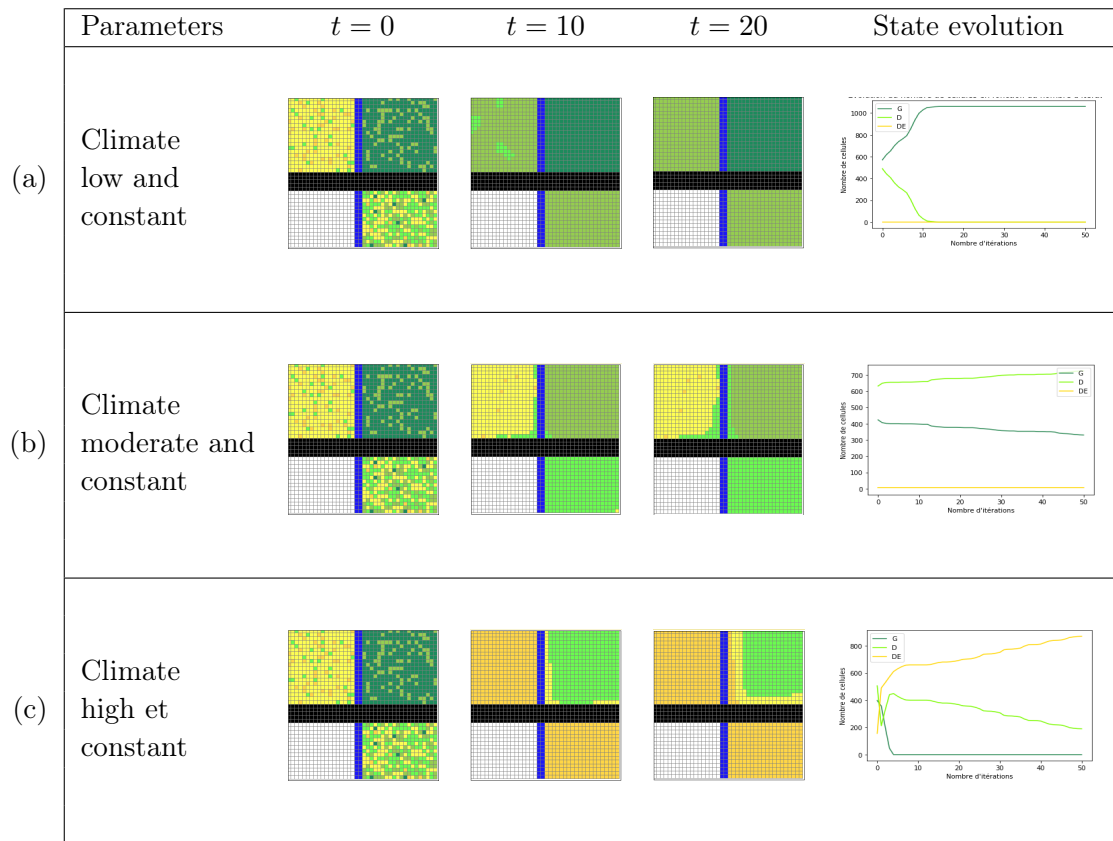
Appendix 5 : Table of rules : Examples of applying the transition function in DESERTICAS



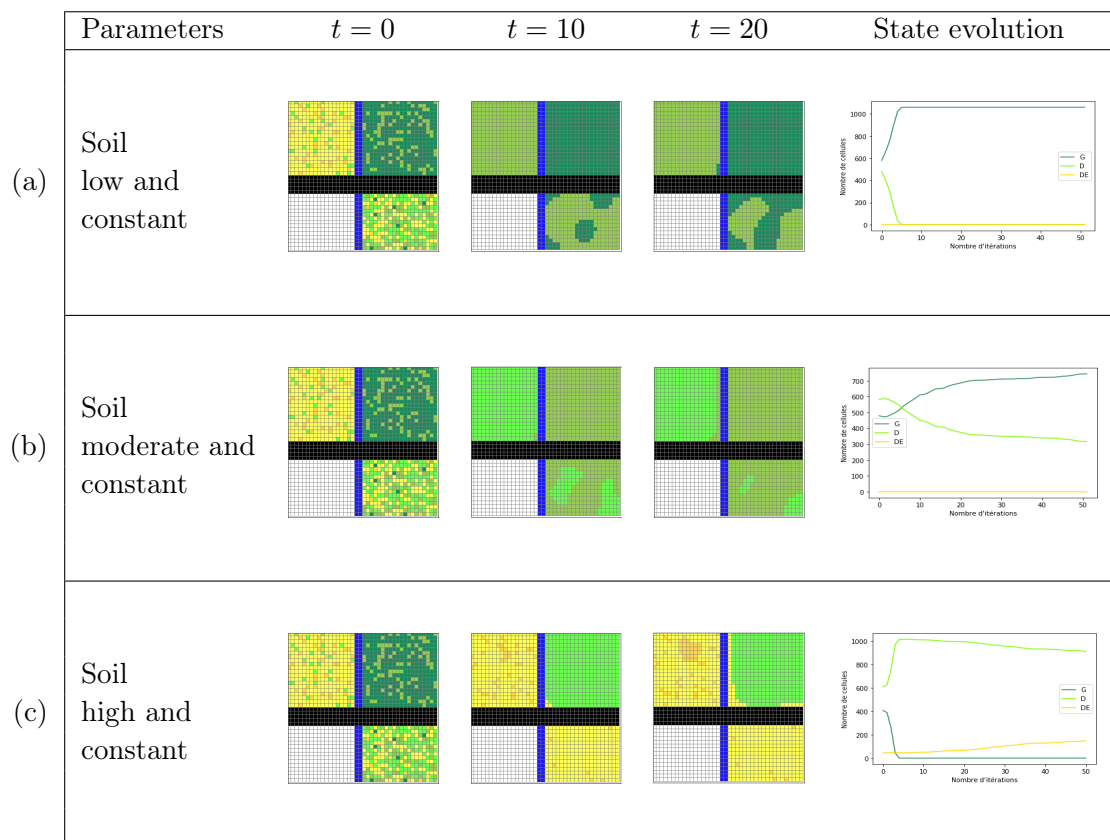
Appendix 6 : Main types of neighbourhood



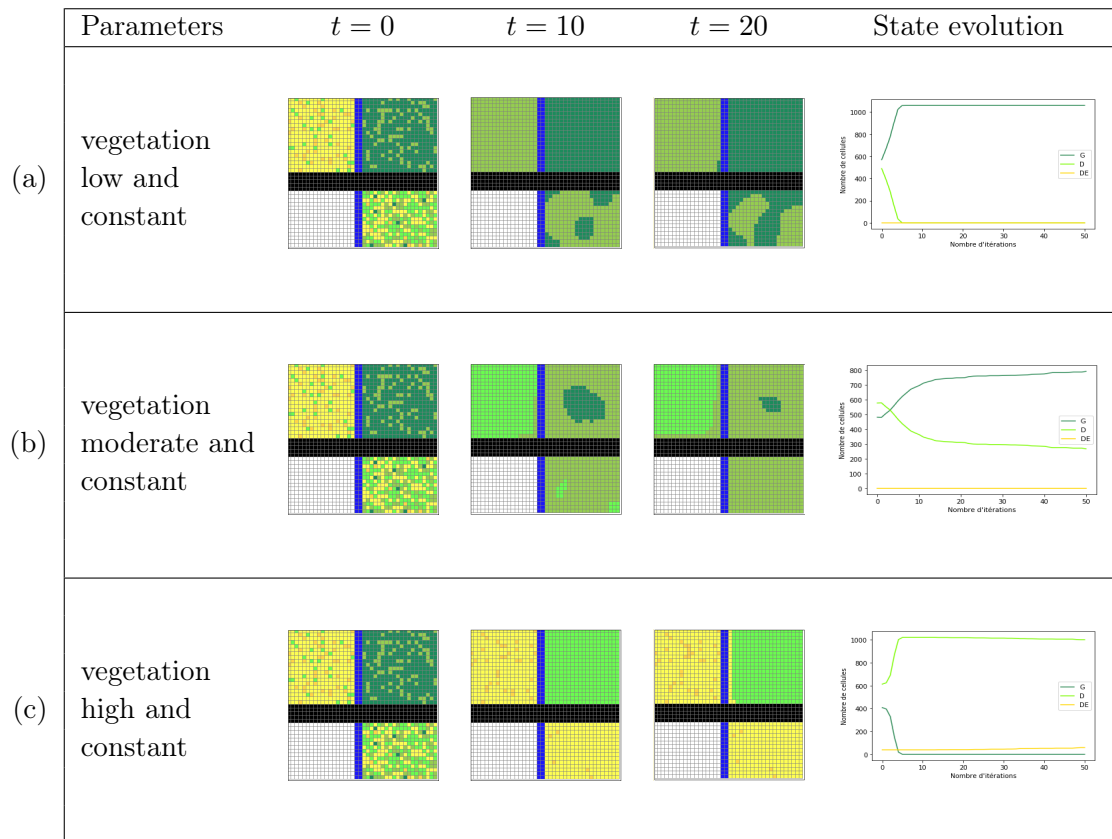
Appendix 7 : Evolution of an area with constant management index in DESERTI-CAS



Appendix 8 : Evolution of an area with constant climate index in DESERTICAS



Appendix 9 : Evolution of an area with constant soil index ind DESERTICAS



Appendix 10 : Evolution of an area with constant vegetation index in DESERTICAS

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