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Achieving Sustainability in the Argane Forest, Morocco

Master's Thesis

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Abstract

The Argane forest is home to the unique Argane tree specie (*Argania Spinosa*) in the southwest of Morocco. There, it plays a central role in the ecology, the economy, and social life of the local population. It is vital to preserve the Argane forest for its value, but also because it acts as a barrier against desertification coming form the Sahara desert. However, the argane forest is experiencing an alarming decline due to human activities induced by internal and external factors. Internally, population growth and the growth of the cattle associated with it induce a high pressure on the resources inducing deforestation. Externally, the introduction of the intensive irrigated agriculture disturbs the equilibrium of the forest region as it leads to deforestation and loss of soil due to salinization. The irrigated agriculture also catalyses a higher growth rate of the local human population, thus further aggravating the pressure on the forest. These internal and external factors disturbed the equilibrium of the Argane forest, and the forest system is expected to collapse within the next 20 years. Yet, sustainability in the Argane forest can still be approached by introducing measures for regenerating the forest, reducing the economic dependence on the irrigated agriculture by valuing forest products, and limiting population growth.

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I. Introduction

I.1. Scope and objectives

The paper studies the dynamics of the Argane forest system in the region of Taroudant. This system is in no terms dissociable from the rural economic and social systems of the region. The study attempts in a first stage to define the main causes of the unsustainability of the system. The second stage is to identify possible measures susceptible of achieving ecological, economic, and social sustainability in the Argane forest.

The region of Taroudant comprises 40% of the total Argane forest area, 36% of the rural population living in the Argane forest, and 36% of the animal population grazing in the Argane forest (Agroforest, 1997). The region of Taroudant also experiences a rapid rate of agricultural intensification. Conclusions reached for the region of Taroudant are applicable to the remaining of the Argane forest. The study covers a time period from 1990 to 2030. The work is restricted to the rural sector of the region, thus excluding the urban areas.

I.2. Methodology

The study started by a theoretical formulation of the problem faced by the Argane forest due to overexploitation engendered by internal as well as external factors. The initial view of the system was formed from personal knowledge and experience, but with no accuracy. The next step was to collect information about the Argane forest system on the field. Information concerning the natural condition of the Argane region and the human activities there was gathered in Rabat (Ministry on Agriculture, University Mohamed V), Agadir (Direction de la Region Hydraulique Souss Massa Draa), and Inzgane (Natural Reserve of Souss Massa), all in Morocco. The numerical information available was mostly concentrated in the study made by Agroforest for the Ministry of Agriculture in Morocco in the year 1997. However, the report by Agroforest does not cover the period ulterior to 1997, and the data it includes is incomplete in certain cases. Data about the rainfall was drawn from hydrologic records of the "Direction de la region hydrolique du Souss Massa Draa" covering the last 40 years. The descriptive information was drawn from the works by Benzyane et al (1998), Charrouf (1998 and 1999), and Aarab (1999). Conversations with Dr. Charrouf (Mohammed V University, Rabat, Morocco) and Mr. Benzyane (Ministry of Agriculture, Rabat, Morocco) were helpful. Furthermore, literature about the application of systems' dynamic to sustainability was reviewed. This was carried out in Lund, Sweden. The information sought in this category concerned the application of system dynamics to economic and natural modeling, and modeling of decision making for achieving sustainability.

The system was next redefined and the initial theoretical speculation revised. The new view of the system's actors and interactions is presented in the problem definition (section III.). Numerical data tables were translated into graphs and attempts to draw relationships between the data were made. These relationships were later used in building the system model. Following was the concentration on studying the dynamics of the system, building a model of the system in parallel. Finally, the work went into an analysis of the impediments to the durability of the system and propositions about how to modify it to achieve sustainability[1]. For the purpose of this paper, sustainability refers to a stable system behavior that lasts in the future and that fulfills three conditions. First, the human population is stable at an optimal size, and is not forced to decline due to resources scarcity. Second, the human population' revenues are high enough to ensure a reasonable standard of living. Third, the forest regenerates, stops declining, and ultimately increases in area.[2] The given definition of sustainability evolves around these three key elements of the system as will be investigated throughout the paper.

The paper starts with a background relating the Argane forest problem to other similar issues. Afterwards, the paper gives a more detailed presentation of the Argane forest, its importance, its uses, and the threats it faces. Then, a more thorough study of the system is carried out following systems' dynamics thinking, and a computer model of the system is built progressively[3]. Once the dynamics of the system are comprehended, scenarios of the future development of the forest system are simulated under different conditions of rainfall. Thereafter, the paper defines the main causes of the system instability. Finally, based on the conclusions from the former scenarios, suggestions for a more sustainable future are suggested and scenarios run to evaluate them. The paper is annexed by the list of equations concluded in section IV and the model developed.

I.3. Background

The Argane forest was implanted in Morocco when this part of the African continent was part of a subtropical climate in the tertiary era. The climatic change of the quaternary era engendered higher rainfall and lower temperature in North Africa, thus confining the Argane forest to a very limited area in the southwest of Morocco (Benzyane et al., 1998). The Argane tree has been known to mankind since the time when the Phoenicians settled in the region of Essaouira on the Atlantic coast of Morocco more than 2000 years ago (Agroforest, 1997). The uses of the Argane tree were first recorded by Arab geographers and scientists such as Ali-Ibn-Rodhouan in the 10th century and later Ibn-Al-Baytar in the 13th century (Benzyane et al., 1998).

The Argane forest is at the center of the local rural population's life. It also supports a unique ecology and a fragile economy in a semiarid to arid region. In the beginning of the 20th century, however, due to an increased pressure from the human activities, the forest regressed dramatically by 200,000 hectares between the years 1918 and 1924 (Benzyane et al., 1998). Nowadays, the forest is still regressing at an average rate of 600 hectares per year (Charrouf, 1998). The disappearance of the Argane forest would cause the desertification of its environment and the collapse of the social and economic systems related to it.

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[1] Probably, the most often quoted definition of sustainable development is the one given by the World Commission on Environment and Development in its 1987 report *Our Common Future*, where sustainableility is defined as the ability of development "to insure that it meets the needs of the present generations without compromising the ability of the future generations to meet their own needs" (The World Commission on Environment and Development, 1987).

[2] The conditions adopted for defining sustainability will be argued for during the analysis of the paper.

[3] The model is constructed using Stella 5.1.1 software, by High Performance Systems Inc., Hanover, NH, USA.

This study illustrates the problem of land deterioration and desertification[4] due to human pressure in arid and semiarid climates. Mainguet makes a distinction between desertification and land degradation, as she notes that desertification causes irreversible loss of the biological land potential, while land deterioration offers a more optimistic possibility of recuperating the land (Mainguet, 1991). The phenomena of desertification and land degradation are arguably a consequence of natural conditions and/or human pressure on the natural resources, mainly the vegetation cover and the animal population dependent on it (Ibid.).

In the case of the Argane forest, the study supports the thesis that intensive extraction of the forest resources (arable land, wood, tree fruits) along with the intensive animal grazing, destroy the natural potential of the forest system including the biological and abiotic resources. Moreover, based on historic data of the rainfall and future scenarios developed in this study, the climatic conditions are not a primary cause of the loss of the forest. The distinction whether the result of the loss of the natural potential of the forestland is desertification or land degradation will be made in the paper. Besides, the forest is not the only overexploited resource of the system studied. The extraction of the aquifer water is another element that illustrates "the tragedy of the commons"[5]. The water belonging to no one, or to everyone, is extracted carelessly, thus reducing its positive impact on the ecological environment and accelerating its depletion. Moreover, the revenues extracted from the Argane system are not restituted to it. The forest is continually grazed, the forestland converted to agricultural land, and the aquifer water extracted, but no investments are made to preserve the potential of the region.

However, the problem in hand is not unique to the Argane region. Mortimore analyses the case of Northern Nigeria, where land exploitation and overgrazing increased the pressure on the land greatly (Mortimore, 1989). However, as Mortimore puts it, "trade made fortunes in Nigeria, rather than land or productive investments" (Ibid.). In fact, the Nigerian trade then based on agricultural production was beneficial for only a small portion of the population, and its revenues were not put back into the production system to improve it. This is similar to viewing the system as a one way flow where resources are extracted linearly from the land, but their revenues are not put back in the land to compensate for the extraction. This flow will ultimately result in the depletion of the land potential and could be irreversible. The negative impact of overexploiting the land is further aggravated by the irregular and low rainfall in the semiarid to arid regions.

Mainguet reports the drastic effects of overgrazing, overcultivation, and deforestation in the Sahel and the semiarid and dry regions of Africa (Mainguet, 1991). Some land degradation is irreversible, as the top soil was lost due to erosion and dune settlements. Mainguet supports that pastoral people try to maximize their revenues through maximizing the size of their herds. Moreover, when the pastoral

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[4] Desertification was defined in 1977 by the United Nations Conference on Desertification as "the diminution of the biological potential of the land, and can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystems, and which has diminished or destroyed the biological potential, i.e., plants and animal production, for multiple use purposes at a time when increased productivity is needed to support growing populations in quest of development" (cited in Mainguet, 1991).

[5] Paper by G. Hardin, presented in Nelissen et al. (Nelissen et el., 1997). Hardin argues that the common goods are subject to overexploitation and ultimately exhaustion.

people are able to compensate for forage deficits during drought they disturb the equilibrium between the natural vegetation cover and the animal population. On the other hand, overcultivation of the land and deforestation are magnified with an increase in the human population. As a result, the human and animal population living on the land surpass its natural carrying capacity. Mainguet concludes that "when the rainfall deteriorates, there are no mechanisms to painlessly reduce the population to a level which the land can then support" (Ibid.). Mainguet also shows that the problem of land degradation concerns a wide range of regions in the worlds, including the Sahel, Egypt, China, Russia, Australia, and North America. According to Mainguet, all the land degradation in these regions is due to increased human pressure on the land and aggravated by drought (Ibid.). From Mainguet's conclusion, we can in turn conclude that it is not the natural conditions that are the primary cause of land loss in many regions. The natural drought is instead a complement to the human population pressure on the land which causes its degradation.

II. Introducing the Argane forest system

The Argane forest covers 828,000 hectares in the southwest of Morocco, just north of the Sahara desert (figure 1). It is principally composed of Argane trees (*Argania Spinosa*)[6]. Geologically, the forest grows in plains as well as in mountain hills, within altitudes between sea level and 1550 meters (Benzyane et al., 1998). The climatic conditions in the Argane forest are diverse, with rain falls raging from 50mm/year to 500mm/year (Direction de la Region de l'Hydrolique Souss Massa Draa). Although fossil traces of other *sapotaceae* relatives of the Argane tree were found in southern Spain and the north of Morocco, the Argane tree specie is nowadays confined exclusively to the forest in the southwest of Morocco and two isolated populations: one near Oujda in the northeast (800 hectares) and the other near Rabat (30 hectares) in the northwest as indicated on the map (Aarab, p.4).

Figure 1: the geographical distribution of the Argane populations

[6] Belongs to the *Sapotaceae* family. It is also referred to as *Argania Sideroxylon*, *Sideroxylon Spinosum*, and *Elaeodendron* Argane (Benzyane et al., 1998).

However, the importance of the Argane forest does not lie only in its uniqueness. The forest is the backbone of an exceptional and fragile ecological, economic, and social system. Ecologically, the forest ecosystem is conditioned by the remarkable adaptation properties of the Argane tree to the local soil and climate. Economically, the forest supports a dual agricultural system made of traditional agriculture and intensive agriculture. Socially, the Argane forest is at the center of the local population's traditional pastoral and agricultural system, sustaining the lifestyle of one and a half million people in rural areas (Charrouf, 1998; Agroforest, 1997). The loss of the argane forest would inevitably lead the destruction of the ecological, economic, and social systems based on its existence. The loss of the forest would in fact mean the desertification of the land, thus losing the ecology related to the former.

II.1. The ecological importance of the Argane forest

The Argane tree is probably the most original and well-adapted specie in its habitat. The tree resembles the olive tree and the height of an adult tree can vary from eight to over ten meters according to the climatic conditions. The treetop is very dense and wide with persistent foliage. In case of drought however, the tree can decelerate its metabolic rate and drop its leaves entirely or partly in order to reduce its evapotranspiration[7]. The tree can recover its foliage rapidly when water is available, thus regaining a normal metabolic rate. The trunk of Argane is very vigorous and short. It is usually made up of many interlaced individual stems. The root system is very well developed as it grows broad and deep to optimize the water uptake (Benzyane et al., 1998).

The simplest function of the Argane trees is the protection of the soil and young seedlings from the sunshine, which can be damaging in arid climates (Benzyane et al. 1998). The Argane also work as a “water pump” in the forest, as its deep roots extract the underground water that is partly restituted to the ground surface through evapotranspiration and atmospheric condensation[8] (Ibid.). This water can then be used by the vegetation in the forest. In mountain areas, the forest protects the soil from hydrologic erosion in slopes and favors the infiltration of rainwater to refill the underground water reservoirs. In the plains, the forest is vital for countering wind erosion. In fact, the location of the Argane forest on the immense plain of Souss[9] protects the soil from the very menacing wind erosion.

II.2. The economic and social roles of the Argane forest

Traditionally, virtually every part of the Argane trees and the forest space are used for subsistence (figure 2). First, the Argane wood is used for cooking and heating fire and also for craft works. Second, the Argane fruit produces edible oil for

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[7] Loosing water as it evaporates and escapes from openings in the leaves called stomata.
[8] Benzyane states that it is not rare to witness the water condensation mainly at nigh (Benzyane et al., 1998).
[9] The plain of Souss extends between the High-Atlas to the north and Anti-Atlas Mountains to the south in the southwest of morocco. It contains only a part of the Argane forest (about 1/3 of the total forest area), but it also comprises the most intensive and profitable agriculture in the forest. Because of its large area and location open on the ocean to the west, the plain of Souss is subject to strong winds (Benzyane et al., 1998).

the humans, pulp and press cakes as animal forage[10], and shells used as supplement for firewood in cooking (Aarab, 1999). Third, the foliage and grasses of the forest are used as forage for the animal herds. Finally, the forestland is used for traditional agriculture that takes place within the forest, thus making use of the trees for providing shade, holding humidity, and protecting from wind erosion.

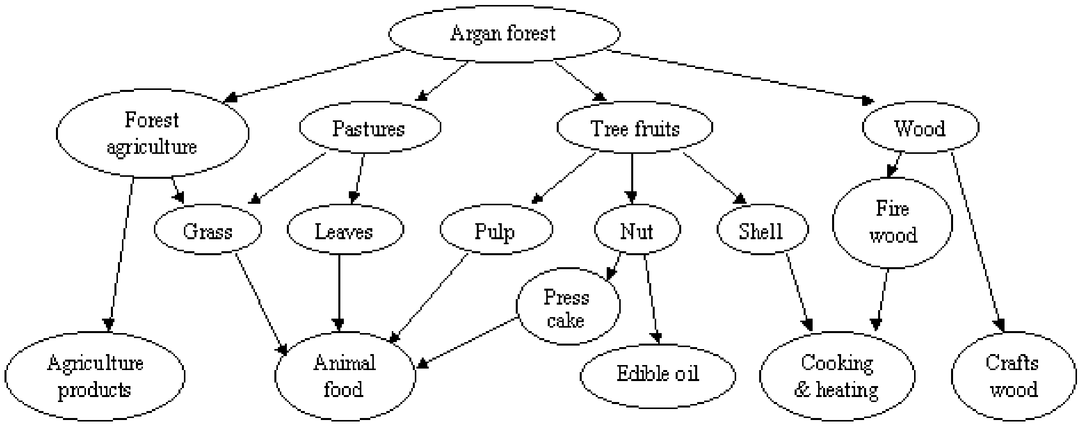

Figure 2: the uses of the forest in supporting the local population (Aarab)

II.2.1. Wood and fuel source

The high density (between 0.9 kg/l and 1.1 kg/l) and hardness of the Argane wood make it very praised for charcoal production and agricultural tool, and use within architectural structures (Benzyane et al., 1998). In terms of energy content, the biomass in one hectare of Argane forest with a medium density of 300 Argane trees per hectare has an energy content of 221 million kcal, equivalent to 31.6 tones of coal or 138 barrels of crude oil (Ibid.). In the beginning of the century and under the French and Spanish protectorate in Morocco, some 20,000 hectares of forest were being lost annually for the production of charcoal for national urban markets and rural consumption (Ibid.). Nowadays, however, the production of combustibles and craft wood products is legally limited to the rural population needs, thus making up 13% of the national combustible wood production (Ibid.).

[10] The press cake is the residue from the Argane fruit after extracting the oil.

II.2.2. Edible and cosmetic oil source

Yet, a more important value of the Argane forest resides in the Argane fruit. The fruit is composed of a pulp and a nucleus made of a hard shell covering the seeds[11]. The seeds are used to produce a highly nutritive edible oil, while the pulp and the press cake are used as forage for the animal. The Argane oil contains 47% of oleic acid and 33% of linoleic acid, which is higher than the content in these unsaturated fatty acids in woman milk, cow milk, meat, and fish (Charrouf et al., 1999). The unsaturated fatty acids represent no digestion or assimilation problems for the human metabolism. Besides, pharmaceutical studies carried out by P. Fabre Laboratories showed that the activity of the Argane oils have considerable skin protective properties (Ibid.).

II.2.3. Forage source

The fruit is as well important for forage production through the pulp and press cakes. However, the fruit forage products are only complementary to forage provided by foliage and forest grasses. In fact, the Argane forest is vital for the local bovine, ovine, and mainly caprine, equidae, and cameline populations. The role of the forest is even more critical in drought periods for both the local animal herds and the immense herds of nomads coming from the Sahara seeking pastures in the Argane forest (Benzyane et al., 1998). The different animal species are able to share the forest resources: while the sheep and cows are restricted to graze on the ground grasses and bushes, camels are able to reach the lower part of the treetops, and the goats are even able to climb the tree thus grazing on the leaves of the tree crown (Ibid.). The grazing of the herds is done collectively within one tribe, as the right of exploiting the pastures is commonly owned, but not the pastures themselves (this will be further investigated in section II.3.). However, during the fruit-gathering period, the forest is fragmented into a multitude of small enclosures within which individuals have individual rights to harvest the fruits (Ibid.).

II.2.4. Agricultural source

Finally, the forest space is used for agriculture. Traditionally, the agricultural activity is mainly based on rainfall with occasional irrigation using gravity flow drainage[12]. The traditional agriculture actually takes place within the forest. In fact, the traditional plowing techniques are able to spare the trees' roots (Benzyane et al., 1998). For this purpose, the forest density is reduced from an average of 300 trees per hectare in the wild forest to between 40 and 150 stands per hectare (Ibid.). However, due to the increase in the size and needs of the human population, the agriculture starts to develop at a rapid rate, sometimes on the detriment of the forest as repeated clear cutting of the forest has been witnessed (Ibid.).

In addition, the intensive irrigated agriculture appeared in the Argane forest twenty years ago, mainly in the plains (Souss) (Benzyane et al., 1998). The intensive irrigated agriculture is mainly directed towards external markets, both national and to

[11] The number of the seeds can very from one to three or four per nucleus.

[12] Gravity flow drainage consists in directing water to flow over the ground surface to the targeted areas to irrigate. This method is very inefficient in using the water as 40% to 50% of the water is lost (Miller, 2000).

a large extent for export. Actually, the yearly production of this new agricultural type averages a value of 2 billion DH[13] or $200 million US, 70% of which is directed towards export (Agroforest, 1997; Benzyane et al., 1998). Due to the high profitability of the intensive irrigated agriculture, there is an increasing demand of this land exploitation. However, considering the high cost of investment in the intensive irrigated agriculture which the local population can not afford, the land is usually rented to nonmembers of the region for very low prices (Benzyane et al., 1998).

However, the intensive irrigated agriculture is damaging to the Argane forest in three aspects. First, the intensive irrigated agricultural method requires covering uninterrupted land areas for building greenhouses and using machines. Yet, this is not possible within the Argane forest, which means that the natural vegetation is cleared to give place to the intensively irrigated cultures (Benzyane et al., 1998). Second, this agricultural type causes the impoverishment of the soil mineral nutrients and the increase of soil salinity[14] (Ibid.). Particularly, the local farmers claim that the productivity of tomato cultures drops by 60% if harvested on the same location in two consecutive years (Ibid.). The soil impoverishment and salinization result in partial or even complete sterilization of the soil (Ibid.). Third, the irrigation causes a drop of 5 to 10 meters in the level of the aquifer. Considering the fact that the Argane tree relies greatly on underground water to draw water, the lowering of the later' level has negative implications on the growth and existence of the former (Ibid.).

II.3. Land tenure and legislation

The land tenure forms in the study region differ between the forestland and the agricultural land.

The agricultural land tenure falls within five categories shown with their consecutive ratios in figure 3:

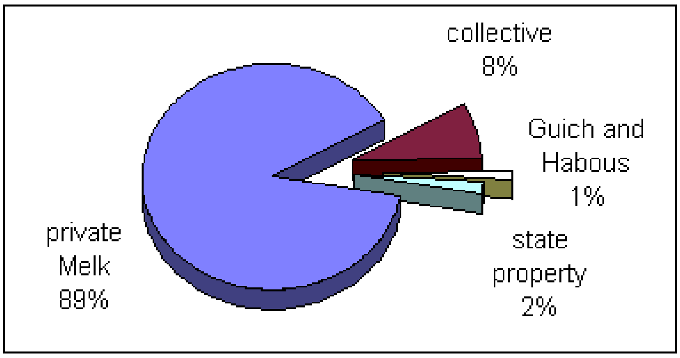

Figure 3: the composition of the agricultural land tenure forms

1. First, 89% of the agricultural land is privately owned[15] (Agroforest, 1997). The private property, locally referred to as "Melk"[16], gives full

[13] Dirham (DH) is the currency of Morocco, it fluctuates actually around $ 0.1 US.
[14] Irrigation in arid climates is subject to high rates of evaporation of the waters. Thus, a high concentration of salts from the evaporating water accumulates of the superficial layers of the soil (Benzyane et al., 1998).
[15] The numbers given here for the land tenure are from one limited region (region of Tiznit) within the study area. However, the trends presented here can apply to the rest of the area study (Agroforest, 1997).

exploitation rights to its holders who can be one individual or a group of persons.

2. Second, the collective lands represent 8% of the total agricultural area (Ibid.). The collective land status was originally the only land tenure form, considering the social and economic characteristics of the first rural populations in the region who lived in communities of common destiny and low standards of living, and for which it was too hazardous to individualize the land (Ibid.).

3. Third is the “Guich”[17] land status. The lands of the “Guich” belong to the state, and have been attributed the right of exploitation by the sultans of Morocco to certain tribes for services or support the tribes provided to the state, mainly in times of war (Ibid.). The lands of the “Guich” are managed by the Ministry of Interior of the country, according to the local customs.

4. Fourth is the status of “Habous” which represents 1% of the land along with the “Guich” status. The status of “Habous” is an institution of the Islamic law that designates a good that can not be traded and is only exploited for the benefit of a religious establishment.

5. Fifth, 2% of the agricultural land is owned by the state.

On the other hand, the forestland is owned by the Moroccan State, but the right of usage is legally insured to the local population. The right of usage of the forest resources for the local population was first founded by the Dahir[18] of the 10th of October 1917 relative to the conservation and exploitation of the forest areas (Benzyane et al., 1998). However, due to the extensive degradation of the Argane forest during the period between 1917 and 1925, a new Dahir was issued on the 4th of March 1925 (Ibid.). This legal document is the effective basis of the Argane forest legislation. The legal decree gives exclusive exploitation rights to the local population of the Argane forest. The Dahir states that the local population has the right to:

1. Gather dead wood, in all times, for domestic use. However, the needy can sell the dead wood with the condition that the transport is carried out on human or animal back.

2. The harvest of Argane fruit, with the permission to install enclosures around the trees during the harvest.

3. Free animal grazing without limit except on land that has been burned or exploited since less than six years.

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[16] Melk in Arabic means ownership.
[17] “Ghuich” refers to the Arabic word “Jaych” which means army.
[18] A Dahir is a royal legal decree. The Dahirs can deal with the legislation of different issues in different fields, and are considered as legal references in the Kingdom.

4. Cultivating, without payment, the forestland except land that has been burned of exploited since less than two years. However, cutting the trees on cultivated land is illegal.

5. Extract without payment but with the authorization of the services of forestry, wood for heating, making charcoal, and building or making tools for domestic use.

6. Cutting tree branches necessary for making enclosures.

7. The extraction from specific locations of soil and construction stones for domestic use at only 20% of their market price.

Moreover, legislation issued in the years 1951, 1957, and finally 1976 gradually directed the entirety of the revenues from forestry throughout the Morocco to the local rural communes. The Dahir of the 20th of September 1976 requires that 20% of the forestry revenues received by the rural communes be directed towards insuring the sustainability of the forest areas (Benzyane et al., 1998).

Despite these legal measures, however, the use of the Argane forest remains regulated by the local populations' practices. The forest is implicitly distributed between its traditional users mainly in the more populated areas such as the plains. For instance, the Argane trees themselves obey the law of heritage (Ibid.). Moreover, due to the increasing need of the growing population, the legislation concerning the forest is rarely obeyed. This problem is engraved by the development of the intensive irrigated agriculture. In fact, this type of agriculture occupies the traditional space, which pushes the animal herds and the traditional cultures deeper into the forest.

To face the failure of the existing legal measures to insure the durability of the Argane forest, the national Ministry of Agriculture issued a final text in 1983 to specify the terms of the conversion of the forestland to agricultural land. The acquisition of a new parcel to cultivated was conditioned by the payment of an initial 100 DH/hectare (less than $10 US) and a yearly 50 DH/hectare. Moreover, the beneficiary is bound to conserve the existing Argane population on the land. Besides, the farmer has the right to abandon the acquired parcel after three years of exploitation and to take on a new parcel from the forestland. In fact, it is after three years that the intensively irrigated land loses its productivity due to the loss of the soil nutrients and the increase of its salinity (Benzyane et al., 1998).

The legislation of the Argane forest presents a close analogy to Hardin's “tragedy of the commons” (Nelissen et al., 1997). Hardin argues that the common wealth is overused by individuals in an attempt to maximize their individual profits. Exploiting the resources in this way results in an accelerated an inevitable deterioration of the resources. In the Argane forest, the forestland is not commonly owned, but the right to exploit it is. This makes subject to the tragedy of the commons as will be shown later throughout the paper analysis.

III. Problem definition

The Causal Loop Diagram (CLD) in figure 4 illustrates the actors and dynamics of the Argane system.

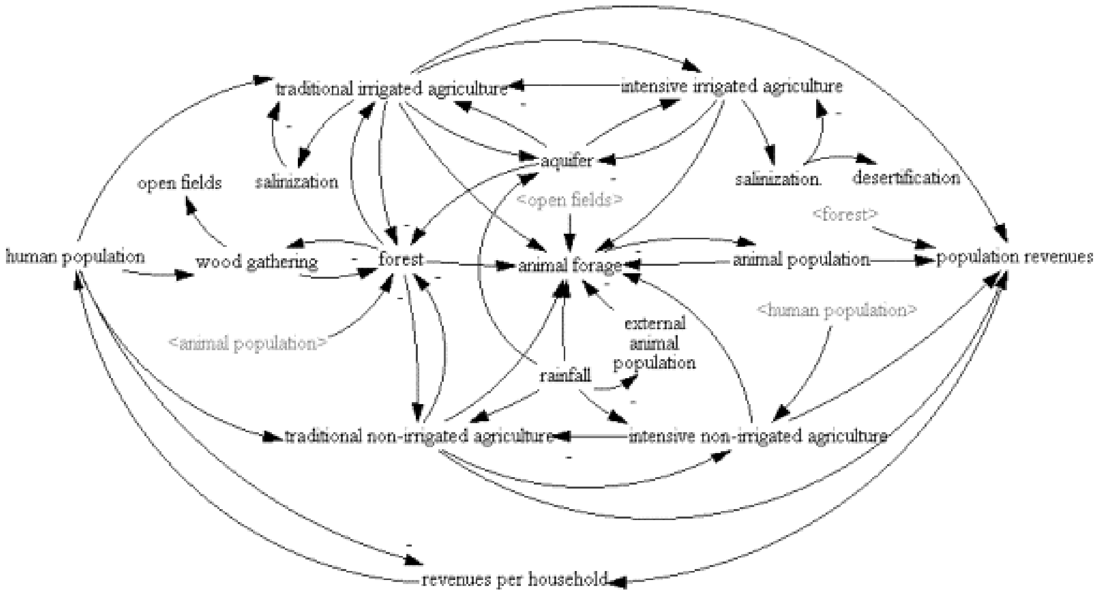

Figure 4: CLD summarizing the Argane forest system

The human population affects the forest in two ways. First, the human population increases the gathering of wood, which in turn reduces the forest. This reduction can be either in density or area. However, we will assume that only the surface area of the forest changes (assumption n1). Thus, instead of arguing that the density of one hectare of forest decreased by a certain fraction, we will assume that the forested area decreased by the same factor while the density of the remaining forested area stays the same. The forestland lost for wood production transforms into open fields[19].

Besides, the growth of the human population also drives an increase in agricultural land area on the expense of the forestland. The CLD in figure 4 illustrates the four different types of cultivation land use:

1. Traditional agricultural land which includes two types:
   - Traditional rain based or non-irrigated agriculture
   - Traditional irrigated agriculture.
2. Intensive or mechanized agriculture which also includes two types:
   - Intensive rain-based or non-irrigated agriculture
   - Intensive irrigated agriculture.

According to the legislation of the Argane forest, traditional agricultural land can be drawn from the forestland. However, the intensive agriculture can only be converted from existing traditional land. In fact, because the intensive agriculture requires plain uninterrupted areas, it can legally not take place within the forest nor convert forestland into agricultural land. Yet, the existing traditional agricultural land

[19] Open fields refer in this paper to land, which has a non woody vegetation cover but still supports a vegetation.

is for the most privately owned, and so bound by no legislation about the method of exploitation. (Why they rent for cheap then?) We will then assume that the intensive irrigated agricultural land is derived from existing traditional irrigated[20] land due to closer access to the irrigation water (assumption n2). As well, the intensive rain-based agriculture is acquired from existing traditional rain-based agriculture[21] (assumption n3).

Both the traditional and intensive rain-based agriculture depend on the rainfall. The production of the non-irrigated agriculture increases with the rainfall and decreases with drought. On the other hand, both the traditional and intensive irrigated agriculture are limited by the availability of irrigation water. In fact, the volume of the aquifer is actually decreasing due to the extraction of water for irrigation (Benzyane et al., 1998; Agroforest 1997). Besides, the aquifer decrease has a negative impact on the forest. The Argane trees use the aquifer as a supplementary water source to the rainwater. Benzyane et al. report that the Argane trees retain their foliage in the beginning of the drought period (late spring to early autumn) and start growing new burgeons weeks before the first autumn yearly rains (Benzyane et al., 1998). This suggests that a lowering of the underground water level will delay the appearance of burgeons and precipitate the fall of the foliage. Moreover, a reduction in the aquifer will also mean a decrease in the water pump function of the Argane trees, which implies a reduced vegetation cover in the drought period of the year. Following these arguments, we will assume that a decline in the aquifer volume reduces the amount of forage and Argane fruits provided by the forest, and thus increase the dependence of the forest biological potential on the rainfall (assumption n4).

In addition, both modes of irrigated agriculture cause salinization and impoverishment of the soil, which limits their expansion. The lost land from the intensive irrigated agriculture is desertified, while the land used for traditional irrigated agriculture is subject to limited and reversible damage due to its exploitation. Yet, the agriculture compensates for the loss of surface area through converting more land as explained in previously (4th paragraph of this section). The land lost from the intensive irrigated agriculture becomes the origin of sand dunes. Actually, the sandy composition of the local soil makes it very vulnerable to wind erosion, mainly caused by the western winds. In fact, dunes are already appearing on abandoned agricultural land (Benzyane et al., 1998). Thus, we will assume that the abandoned intensive agricultural land undergoes irreversible damage due to it exploitation and become sterile land (assumption n5).

The development of the agricultural land has a second less obvious but no less important impact of the forest. When more traditional agricultural land is specified for intensive agriculture, the traditional practices are forced to search for resources deeper inside the forest. Thus, even more forestland is converted into traditional agricultural land, which means a decrease in the forestland and pasture space. Moreover, pasturing becomes more intensive as the area reserved or it decreases.

The forest and agricultural land provide forage for the animal population. However, the forage availability varies depending on the composition of the land use.

[20] Land that has not been derived from the forest.
[21] Land that has not been derived from the forest.

In fact, since the animal forage comes from various sources, and since these sources have different productivity values, the total amount of forage will vary as the land organization changes. This will be further investigated in section IV.3.1. Moreover, the forage availability for the local animal herds is reduced by the arrival of external herds. The external herds are affected by the amount of rainfall, as bigger numbers arrive when the rainfall is low, and less when the rainfall is high. The rainfall also affects the availability of forage, as more rain produces more forage. This means that in drought periods more external herds are coming into the forest while less forage is available, which aggravates the negative impact of the grazing animals on the forest. In fact, the animal population affects the forest inversely as intensive grazing reduces the regenerative capability of the forest. The caprine, equus, and cameline are able to graze on young tree seedlings, thus destroying the latter before they grow into mature trees.

The revenues of the human population are supported by the forest products, the agriculture, and the animal population, but not the intensive irrigated agriculture (Benzyane et al, 1998; Agroforest, 1997). The revenues then affect back the human population. At this stage, the population is adjusted by the amount of revenues per household. In fact, if the revenues per household are low, the population growth decreases and can even become negative. However, if the revenues per household are high, the population growth increases. The flexibility of the human population growth is actually due to the high rates of migration between the rural world and the urban centers. The high rates of rural exodus imply an increased pressure on the urban centers. However, this paper does not investigate the human migration beyond the fact that it allows the flexibility of the growth rate, thus disregarding the effects of migration outside the system (assumption n6). The human population will be studied further in section IV.1.

From the CLD in figure 4 we can predict that the forestland will decrease since there is no compensation to the pressures caused by the gathering of wood and Argane fruits, the grazing of the animals, and the expansion of the agricultural land. It also appears that the irrigated agriculture will come to an end as the irrigation water gets exhausted. However, we can not at this point predict accurately the dynamics of the population revenues, the animal population, and the human population.

IV. Studying the driving variables of the system

IV.1. The human population

Figure 5 shows the development of the rural population in the region between the years 1960 and 1994 (Agroforest, 1997)[22].

[22] There is actually no data about the human population available after the year 1994.

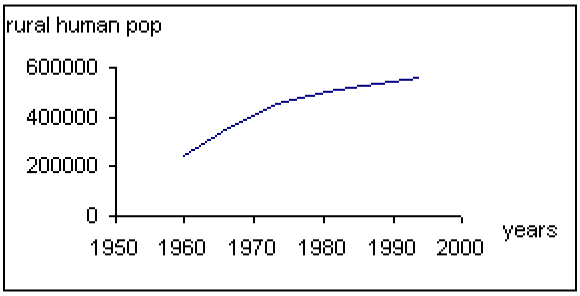

Figure 5: the evolution of the rural population

The rural population increases over time at lower rates as time passes (figure 5), which indicates that the growth rate is stabilizing at lower values (0.8% in 1994) as time increases. Yet, in the same year of 1994, the total population (urban and rural) growth rate equaled 2.2% and the urban population grew by 20.1%. The large difference between the rural and urban growth rates is explained by the high rate of rural exodus towards the urban centers (Agroforest, 1997).

The high migration phenomenon indicates the existence of limiting factors to the expansion of the rural population. In fact, the major constraint on the rural population lies in the decrease in revenues per household as the population increases (figure 6, part of the CLD in figure 4). Notice that the intensive irrigated agriculture is not part of the CLD in figure 6, since it does not contribute into the formation of the population revenues.

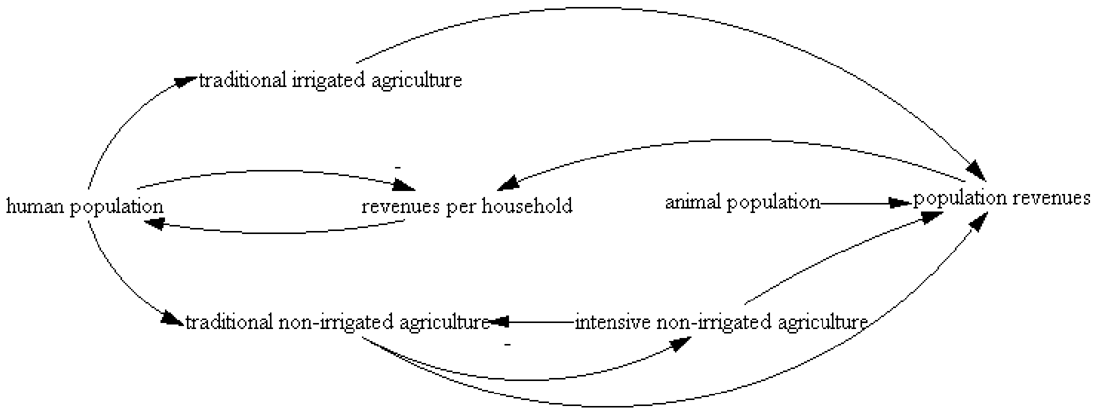

Figure 6: the formation of the human revenues and its interaction with the human population

Actually, the human population increases the land cultivation, which together with the forest products and the breeding of animals forms its revenues. However, the increasing human population decreases the revenues per household, thus limiting its own growth. Studying the formation of the revenues of the local population is then important.

First, the agricultural production excluding animal breeding contributes to 20% in the revenues of rural households (Agroforest, 1997). There are two complementary conditions for the agricultural production to follow the change of the human population size. First, the Useful Agricultural Area[23] (UAA) should expand with the evolution of the human population. Second, the traditional production mode has to be shifted to the more profitable mechanized method. However, between the years 1960 and 1994, the UAA increased by 34% whereas the UAA/household dropped by 55% (from 3.6 ha/household to 1.6 ha/household) (Agroforest, 1997). This means that although the overall UAA expanded, it developed slower than required by the evolution of the human population as the UAA/household decreased considerably. The compensation for the deficit of the UAA/household comes from the mechanization of the agriculture and the introduction of the irrigated agriculture. This will be investigated in the next section dealing with the land dynamics (section IV.2)

Second, animal breeding is the second pillar of the rural population subsistence. Each household owns in average 18 Ovine Equivalent Individuals of cattle[24] (OEI) (Agroforest, 1997). The cattle cover 31% of the households' revenues (Ibid.). Yet, as illustrated in figure 6, the human population does not affect the size of the animal population (Benzyane et al, 1998). In fact, the animal population reached the carrying capacity of the land and can only grow depending of changes in the carrying capacity (Ibid.). We will address this question later on in section IV.3.1.

Third, the forest is as well a considerable mean of support for the rural population. Implicitly, the forest contributes to providing the animal forage and space for agricultural exploitation. Explicitly, however, products from the forest, such as wood, honey, and Argane fruits products, represent 5% of the households' revenues (Agroforest, 1997).

Fourth, the most important source of income of rural households comes from external resources. In fact, transfers from workers in the urban areas and foreign countries to their families insure 44% of the rural population income (Ibid.). The external income is not part of the system and is excluded in the CLD in figure 6. We will make the assumption that the external income to rural households will steadily cover 44% of the income (assumption n7). We will study how the remaining 56% evolve and impact on the population.

Thus, to study the evolution of the revenues of a household, we will define a Unit of Value[25] (UV) which represents the financial needs of one household in one-year period produced internally within the rural sector. The internal revenues of the rural population are composed from 55% from the animal production, 36% from land cultivation, and 9% from forest products.[26] In the year 1994 for instance, the rural population produces internally a total of 85,834 UV (the equivalent of the number of

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[23] Throughout this paper, the Useful Agricultural Area refers to the share of the land area that is used for agricultural exploitation.
[24] The Ovine Equivalent Individuals is a measure that compares species of the animal herd to ovines on the basis of forage needs per year. The forage need for one ovine over one year is evaluated to 350 kg of barley grain. In this measure, 1 bovine individual is equivalent to 5 ovine, 1 caprine to 0.80 ovine, 1 cameline to 7.2 ovine, and 1 equidae to 2.5 ovine (Agroforest, 1997).
[25] One unit of value corresponds to 18,125 Dirhams (March 1997 number) (Agroforest, 1997).
[26] To calculate these percentages, we exclude the external revenues and deal with the remaining 56%. Thus, the animal production insures 31% of the total revenue, or 0.31/0.56 = 0.55 of the total rural production.

households). We deduce that one OEI provides 0.03 UV per year.[27] As well, one hectare of wild forest provides 0.015 UV[28] per year, one kilogram of grain is worth 1.65E-4 UV[29], and one hectare of irrigated agriculture returns 2.47 UV[30] per year. From this we can calculate the amount of UV produced each year (please refer to appendix 1 for the equation).

IV.2. The land:

The increase in the human population drives an increase in the agricultural land and in wood gathering (figure 7, part of the CLD in figure 4). The gathering of wood inversely affects the forestland (section II.2.1). In fact, the wood gathering is only legal for domestic use (Benzyane et al., 1998). Still, the yearly needs of wood for each rural household amount to 4,300 kg (Agroforest, 1997) while one hectare of Argane forest contains in average 50,000 kg of wood (Benzyane et al. 1998). Besides, the legislation of the Argane forest (section II.3) implies that the forestland is the source of the new traditional agricultural land, which in turn is the source of intensive agricultural land.

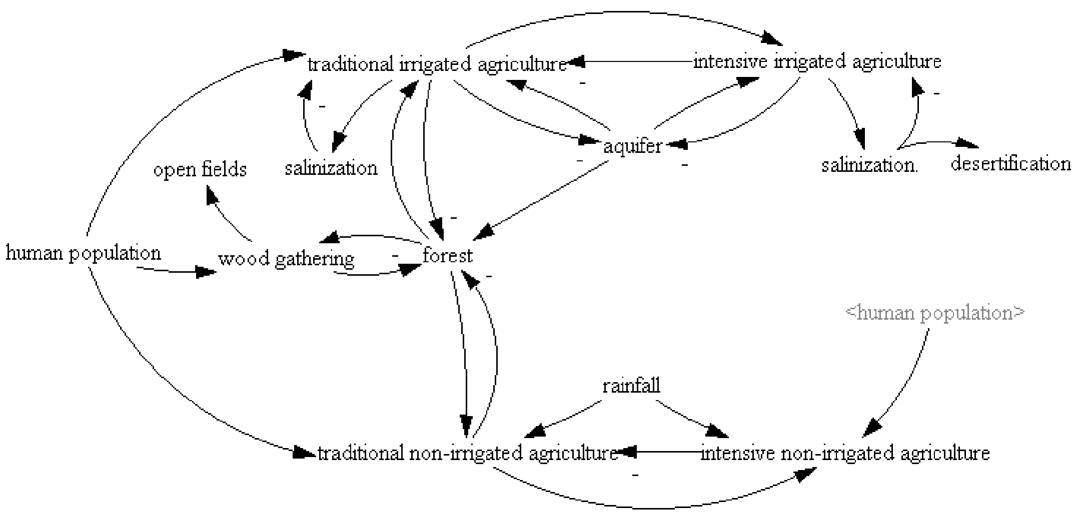

Figure 7: the factors of the land composition

The traditional agriculture takes place within the forest and makes use of the existing Argane stands. In addition, the traditional plowing techniques are not harmful to the trees, specially the roots. On the other hand, the mechanized plowing is destructive for the trees (Benzyane et al, 1998). The intensive agriculture requires clear-cut land and so considers the density of the forest as disturbing (Ibid.).

Because of the differentiation between the intensive and traditional agriculture in productivity, usefulness for the local population, and effect on the forest, we need

[27] The value of one OEI = (the value of the total animal population / the animal population) and the value of the animal population = 55% of the total UV needed by the human population. Then, the value of one OEI = 0.55*85,834/1,550,884 = 0.03 UV.
[28] 528,215 hectares providing 9% of the total 85,834 UV needed.
[29] This is calculated on a basis of 1kg of grain costing 3 DH. Then, the value of 1kg grain = 3/18,125 Dh/UV = 1.65E-4.
[30] This is calculated on the basis of one hectare of irrigated land produces a value of 44,838 Dh/year (Agroforest, 1997).

to determine the share of each one of them. The intensive irrigated agriculture occupies 42% of the total irrigated agricultural land (Agroforest, 1997). Moreover, the intensive irrigated agriculture is two to three time more productive than the traditional mode (Ibid.). However, There are no estimations concerning the proportions of the intensive and traditional non-irrigated agriculture. Yet, we can find an indicator when looking at the fluctuations of the cultivated land area for grain production[31] (figure 8).

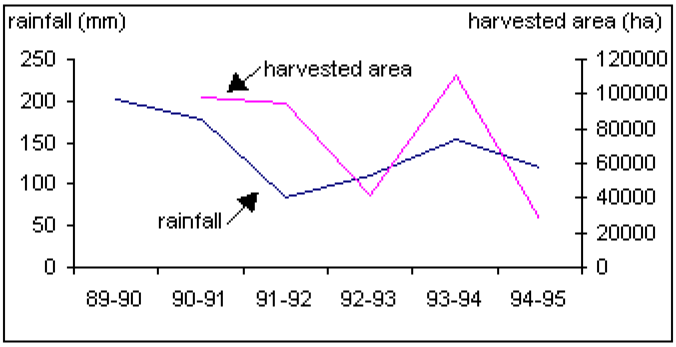

Figure 8: harvested grain land and rainfall fluctuations (Agroforest, 1997)

During the first three years (90-91, 91-92, 92-93), the harvested grain area follows the rain pattern for the previous years. The area is unusually large in the fourth year and unusually small in the fifth year. The behavior of the cultivated land area during the first three years can be explained according to the following assumption (assumption n8): as farmers have no predictions about the rainfall for a certain year, they can only assume it would be similar to the previous year. Then, farmers harvest depending on the previous year's precipitation. On the fourth year (93-94), farmers try to compensate the very low harvest of the previous year, and encouraged with an increased rainfall pattern for the same previous year, harvest a large area. On the fifth year (94-95), although the previous year was reasonably rainy, traditional farmers harvest less land for grain production. Indeed, traditional agriculture harvests the land in cycles between grain and other productions in order to preserve the land fertility.

From the first three years on the graph in figure 5, we will assume a logarithmic dependence of the cultivated area for grain production in a given year on the rainfall on the previous year (assumption n9) (please refer to appendix 1 for the equation). A logarithmic function requires that the dependent changes rapidly for small values of the variable, and more slowly as the variable increases. In fact, the harvested area increases rapidly with the increasing rainfall in order to maximize revenues rapidly. However, for higher values of the rainfall it is harder to expand the harvested land more because of the physical limitation imposed by the land availability. The logarithmic dependence of the harvested grain area upon the rainfall of the previous year will be true except for the following situations:

- If at a given year the rainfall is reasonably high and the cultivated area low, the cultivated area in the following year will be 80% higher than

[31] Grain production occupies 90% of the non-irrigated harvested land. Then, it is taken as an indicator for the non-irrigated agricultural production (Agroforest, 1997).

expected, within the limits of the arable land (in accordance with the data in figure 8).

- If in a given year the cultivated area is larger than expected from the logarithmic contingency, the harvested area for the following year will be 33% lower than expected (in accordance with the data in figure 8).

The flexibility of the harvested area is primarily due to the fact that because of their low standards of living, the small farmers[32] do not risk their capital in cultivating the land unless they have some certainty that their harvest will be successful. Besides, the only indicator the small farmers can base their judgement on is the rainfall.

The dual agricultural system also implies a variation in productivity between the traditional and intensive modes. We anticipate the productivity of the non-irrigated intensively harvested land to be higher than the non-irrigated traditional cultivation productivity. Figure 9 shows that when the agricultural area decreases, the productivity of the land increase, independently from the rainfall.

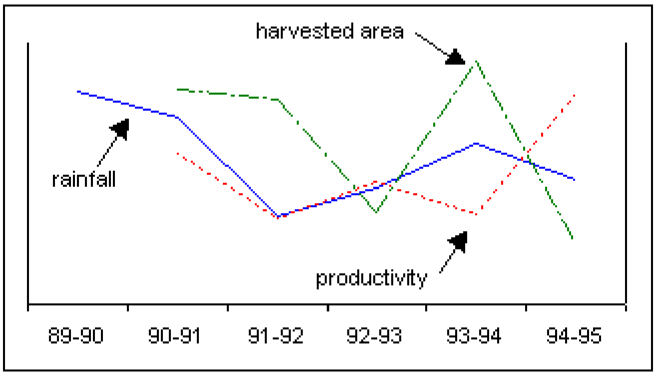

Figure 9: Variations in rainfall, cultivated area, and productivity (Agroforest, 1997)

Combining the information in figure 8 and figure 9, we conclude that the mechanized non-irrigated agriculture occupies approximately 25 % of the non-irrigated agricultural land (assumption n10) [33]. Yet, while the traditionally harvested land fluctuates depending on the rainfall and land cycling, the mechanized agricultural area is fixed (assumption n11) [34]. As a result of these two assumptions, the productivity of the mechanized harvest is calculated to be about four times higher than the traditional culture (average of 2000 kg of grain per hectare for the intensive against 500 kg of grain per hectare for the traditional (assumption n12)). The different productivity values will affect the revenues from agriculture. However, opting for the intensive agricultural mode instead of the traditional will have negative effects on the forest.

[32] The small farmers with parcels of < 4 ha make up 79% of the total local farmers, and farmers with parcels < 7 ha make up 96% of the total local farmers (Agroforest, 1997).
[33] This assumption comes from the fact that when the total harvested surface area is the lowest, corresponding to 25% of the total non-irrigated agricultural land, the productivity is the highest.
[34] The statement of this assumption is based on two facts. First, the non-irrigated intensive agriculture uses fertilizers to compensate for nutrients' loss in the soil and so is less affected by land cycling. Second, the intensive private cultivators and cooperatives have more income than the small farmers, and so can risk their capital in a more invariable rate than do the small framers.

The conclusions above concern the existing agricultural land[35]. However, as the human population evolves, the land chart also changes. We will assume that the ratio of the UAA per household will remain fixed at the rate of 1994 (assumption n13). We will also assume that the shares of the intensive agriculture with respect to the traditional agriculture will remain the same to the limits of the convertible land[36]. Moreover, the irrigated land share of the total agricultural land will remain fixed at 43%[37]. Yet, this land use will only grow to the limit of the available irrigation water. Then, if the irrigation water is exhausted, the irrigated land will be directed towards non-irrigated agriculture (assumption n14). Besides, we will keep in consideration that the irrigated agriculture causes land degradation after three years of exploitation. However, since only the intensive irrigated agriculture requires clear-cut land, we will assume that only the intensive irrigated land is changed into irrecoverable desertified land after three years of exploitation, while the traditional irrigated land goes back to the forest after three years of exploitation (assumption n15) [38].

IV.3. The Agricultural system

IV.3.1. Animal breeding

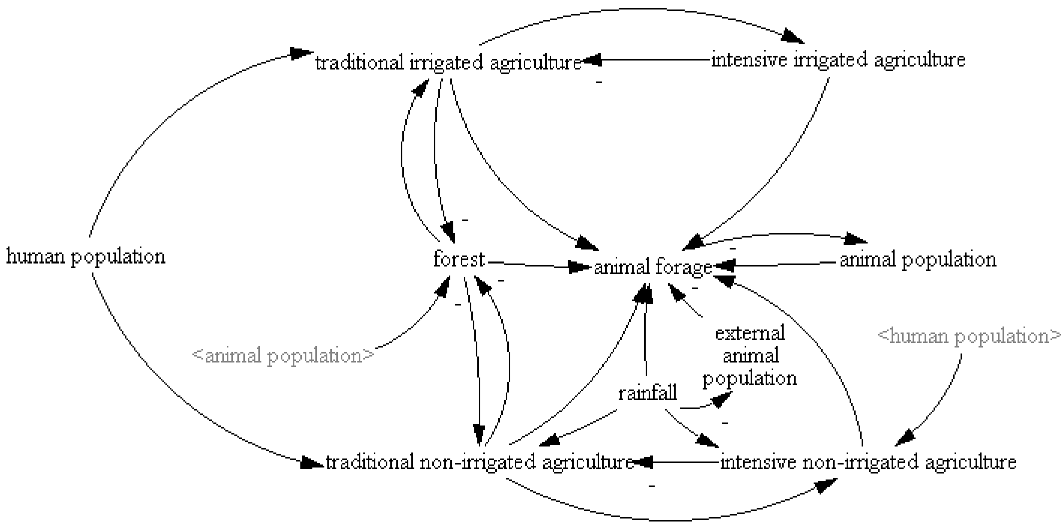

Figure 10: the factors affecting the animal population

The animal population is not affected by the size of the human population. In fact, the latter tries continually to increase the size of the former. However, because the animal population reached the limit of the carrying capacity of the land, it is unable to grow following the inducement from the human population (Benzyane et al., 1998). Instead, the animal population grows according to the forage availability

[35] Land which is part of the land tenure statuses listed under "agricultural land" in section II.3.. This land excludes land which has been converted from the forest and which remains the property of the state.
[36] The convertible land is the land that can be transformed into intensive cultures, which is the privately or commonly owned agricultural land.
[37] In 1994, the total agricultural land in the region Taroudant was 175083 ha, within which the non-irrigated cultures covered 99173 ha and the irrigated used 75370 ha (Agroforest, 1997).
[38] We keep in consideration that the density of the traditional irrigated land in one third that of the wild forest. According to assumption n1, two thirds of the traditional irrigated land will transform into open fields.

(figure 10, part of the CLD in figure 4). In fact, all the forms of the land produce forage for the animals. The rainfall also affects the availability of the forage positively. On the other hand, the external animal population affects negatively the local animal population as it reduces the forage availability (Benzyane et al., 1998).

Figure 11 shows a plot of animal population in OEI and annual rainfall as a function of time.

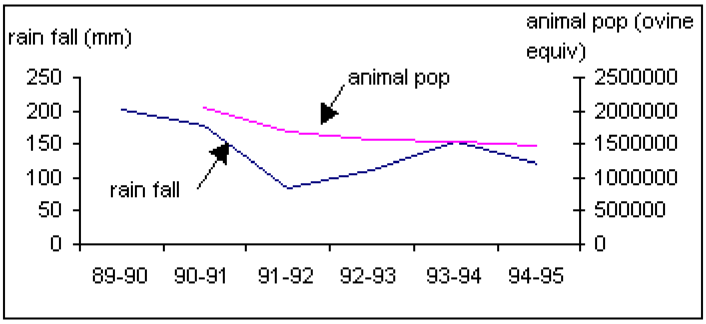

Figure 11: Parallel evolution of animal population and rainfall

From the graph in figure 11 it can be noted that the animal population follows the overall trend of the rainfall. However, the animal population's response to a drop or increase in rainfall is not instantaneous as could be expected. The explanation lies in the composition of the animal herd and the properties of its species, and the constitution of the animals' diet.

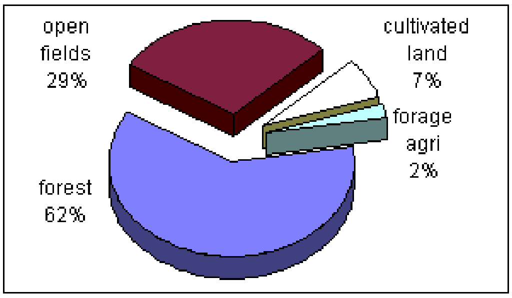

Figure 12: constitution of the animal forage in FU (Agroforest, 1997)

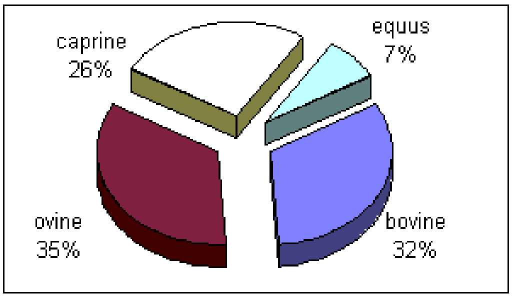

Figure 13: composition of the animal herds in OEI (Agroforest, 1997)

The data in figure 12 represents traditional forage production modes, which cover only a part of the animal herds needs. In fact, 50% of the bovine forage and 20% of the ovine forage are provided by purchased forage (Agroforest, 1997). Moreover, during the four years between 1990 and 1994, the animal forage recorded a deficit of 25% in the region of Taroudant, while it reached 50% in other regions (Ibid.). This deficit is compensated for trough commercial forages. We will then assume a 50% deficit in the animal forage is allowable (assumption n16).

Figure 12 shows that 91% of the animal diet is drawn from the forest and non-cultivated open fields. The local vegetation, namely the Argane tree, being itself very well adapted to drought, the animal species that graze in it will resist more comfortably to variations in the rainfall. The equus and caprine are very well adapted to arid climates, even more that they have the ability to graze on young trees and bushes, and trees' leaves in the case of the caprine. On the other hand, 50% of the bovine food comes from industrial cow food not included in figure 12 (Agroforest, 1997). This factor makes the bovine population less sensible to fluctuations in the availability of forage but more dependent on external production and market systems instead.

However, unlike the caprine and equus populations, the ovine herd is not very good adapted to the forest pastures. The ovine can only graze on grasses, which considerably decrease in drought periods. In addition, local shepherds occasionally cut down tree branches for the sheep to graze on the foliage in periods of drought (Benzyane et al., 1998). Still, the ovine population is subject to large and rapid fluctuations related to rainfall. For instance, the ovine population decreased by 37.7% between the years 1991 and 1992[39], while the caprine and equus decreased respectively only by 9.8% and 7.9%, and the bovine even increased by 6.2% over the same period (Agroforest, 1997).

The animal population size depends on the rainfall, which generates vegetation for forage, and the grazing land, which is the support of the vegetation. First, when analyzing animal population and rainfall data, it was concluded that the animal population of one year is directly linked to the sum of rainfalls of previous years. This makes sense considering the margin of deficit allowed, the high resistance of the pastures to drought, and the completion of forage needs using commercial forage. Figure 14 shows the plot of the animal population as a function of the sum of preceding four years' rainfalls.

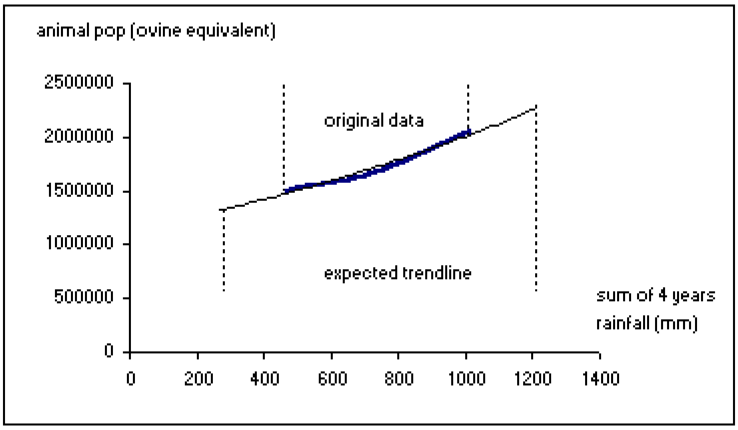

Figure 14: Animal population as a function of the sum of the last four years' rainfall

The expected trend of the animal population shows an exponential increase with accumulation of rainfall for four years (please refer to appendix 1 for the equation). However, the animal population can obviously not grow infinitely. In fact, the dependence of the animal population on the rainfall excludes the limit imposed by the available land, which will be discussed later in this section. Besides, the exponential growth over time is characteristic of a population under no resources constraints (Miller, 1999). In fact, a certain population produces a larger population in time, which in turn produces a larger population, thus reaching the exponential growth. The same reasoning is applicable to the evolution of a population as a function of growth resources instead of time. Thus, a certain population produces a

[39] In the year 1991-1992, the rainfall dropped to a very low total of 83.7 mm for the entire year (Direction de la Region Hydrolique Souss Massa Draa, Rainfall data at Taroudant, 2000).

larger population if resources are available, which in turn produces a larger population if resources increase, thus achieving an exponential growth.

In reality, however, the animal population is also a function of the land available per ovine-equivalent individual. As illustrated in figure 8, the traditional animal forage comes from the forestland, the open fields, the cultivated land, and the forage cultures. In a sufficiently rainy year, 1 ha of agricultural land generates 100 Units of Forage (UF)[40], against 300 UF from 1 ha of forest, 80 UF from 1 ha of open fields, and 1000 UF from 1 ha of forage cultures (Agroforest, 1997). As the need of one OEI is evaluated to be 350 UF/year, we can conclude the following for each year:

- 1 ha of forest is necessary to feed 300/350=0.86 OEI
- 1 ha of open field can feed 0.23 ovine unit
- 1 ha of agricultural land can feed 0.28 ovine unit
- 1 ha of forage cultures can feed 2.8 ovine units

We can then calculate the upper limit of the animal population (corresponding to the carrying capacity of the pastures) in figure 10 as a function of the land composition according to the ratios above (please refer to appendix 1 for the equation). We will thus assume an exponential growth of the animal population depending of the accumulation of the rainfall of four years, limited by the carrying capacity of the pastures, which in turn depends on the land composition (assumption n17).

Finally, the local animal population is affected by the arrival of external herds mainly in drought periods. In normal years, the external herds enter the Argane forest in the month of July when the vegetation in the south is insufficient and leave the forest in the month of September. However, in dry years, these herds can get to the Argane forest earlier by the month of March (Benzyane et al., 1998). We will assume a fixed number of the external animal population. However, we will assume the time period the external herds graze in the Argane forest is inversely dependent on the rainfall (assumption n18).

IV.3.2. Non-irrigated agriculture

Non-irrigated agriculture covers 60% of the total UAA, and amounts to 99713 hectares (year 1997 numbers) (Agroforest, 1997). Within this area, 90% of the land is allocated for grain production. Grain production will then be taken as indicator for the non-irrigated agricultural production. The production depends both on the area and the rainfall. The mechanized and traditional cultures determine the total area. We stated in assumption n12 (section IV.2) that the mechanized agriculture is four times more productive than the traditional. We will also assume that for the four years between 1991 and 1995 the mechanized agriculture covers a stable area of 25000 ha (assumption n19) [41].

[40] 350 Forage Units correspond to the forage needs of one ovine for a period of one year. 1 UF is equivalent to 1 kg of barley grain (Agroforest, 1997).
[41] Assumption n18 will be used only for the purpose of this section (IV.3.2) to simplify the study of the non-irrigated agricultural production.

Figure 9[42] in section IV.2. shows that the harvested area during the years 90-91 and 91-92 remains closely fixed. The average productivity on the other hand changes considerably between the same two years. This is due to the drop in rainfall during the same period. We will then assume a linear relationship between the average non-irrigated agricultural productivity and the rainfall (assumption n 20) (please refer to appendix 1 for the equation). We can also calculate that the traditional agricultural productivity is equal to 4/7 of the average productivity and the intensive agricultural productivity equal to 2 times the average productivity.[43] We will also assume an upper limit of 3000 kg/ha for the mechanized agriculture[44] (assumption n21). Thus the traditional agriculture takes an upper limit of 750 kg/ha. Finally, we can draw the direct relationships between the traditional agriculture and the rainfall, and between the intensive agriculture and the rainfall.

IV.3.3. Irrigated agriculture

The irrigated agriculture covers an area of 75370 ha (year 1997 number), and uses between 5500 m^3 to 7000 m^3 of water per hectare (Agroforest, 1997). Within this land, 32278 ha are exploited with intensive green house farming, while the remaining 43092 ha are cultivated using traditional methods (Ibid.).

The irrigation water is provided by an aquifer reserve containing 50 billions m^3, of which 8 billions m^3 potentially exploitable (Agroforest, 1997). However, the aquifer recorded a decrease over the last thirty years, with a yearly rate between 155 millions m3 and 260 millions m3 (Direction de la Region hydraulique du Souss Massa et Draa, 2000). This deficit causes the aquifer level to lower at a rate of 1 to 3 meters per year depending on the regions (Ibid.). Besides, two major dams[45] provide a total of 86 millions m^3/year (Ibid.). The dams are also used to artificially recharge the underground reserves at a rate of 120 millions m^3/year (Ibid.).

V. Future scenarios

The analysis in section IV resulted in the construction of a model of the system, which will be used in this section to make predictions about the future trend of the system under different conditions. All of the system actors are dynamic and interdependent, except the land area, the initial amount of underground water, and the rainfall pattern. Among these fixed factors, the land surface area and the initial amount of underground water are fixed and known. However, the rainfall trend might change unexpectedly. We will then study the system under three main conditions: 1)

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[42] Variations in rainfall, cultivated area, and productivity.

[43] Total production = Traditional production + intensive production. In turn, total production = average productivity * total area = traditional productivity * traditional area + intensive productivity * intensive area, and intensive area = 25000 ha (assumption n18), intensive productivity = 4 * traditional productivity (assumption n12). With a total area equal to 100,000 ha, we conclude that traditional productivity = average productivity * (total area / (traditional area + 4*intensive area)) = 4/7 * average productivity.

[44] This is the productivity of irrigated grain production (equivalent to an optimal rainfall) (Agroforest, 1997).

[45] The dams are Aoulouz on the river Souss, and Abdelmoumem on the river Issen (Direction de la Region Hydraulique du Souss Massa Draa, 2000).

expected rainfall data similar to the historic trend[46]; 2) expected rainfall data 30% higher than historic data; and 3) expected rainfall data 30% lower than historic data.

V.1. Steady rainfall pattern

The graph in figure 15 shows the trend of the human population, the forestland, and the revenues per household development over the period of the study under rainfall similar to the historic trend of the last forty years.

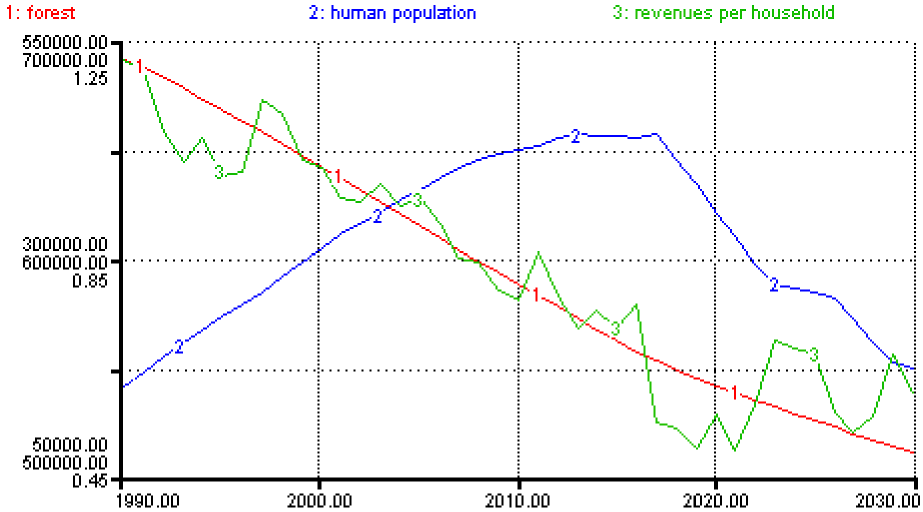


Figure 15: the change of the forestland, the human population, and the revenues per household.

Figure 15 illustrates that the forest area will decrease dramatically over the next thirty years by nearly 85%. The human population, on the other hand, will increase until the year 2013 to reach nearly 657,000 (21% increase from the 1990 value), then it will stabilize around this values until the year 2017 when it will start to drop. The limit in the human population growth will be due to a decrease in the revenues per household as the population increase, and then a sharp drop in the revenues that will cause the population to start the decline at the year 2017. This sudden drop is in turn caused by the exhaustion of the irrigation water, and thus the collapse of the irrigated agriculture (figure 16). The irrigation water is unable to support the irrigated agriculture by the year 2015, which induces a drop in the latter. Yet, in the year 2016, the aquifer refilled slightly after not having being used in the previous year, and the irrigated agriculture increases again. This latter increase will be limited, since by the year 2017 the underground water table level drops again, and with it the irrigated agriculture. For the years to follow, the irrigated agriculture will fluctuate around a low harvested area following the occasional availability of the irrigation water.

[46] The historic rainfall is drawn from records of the “Direction de la Region Hydraulique du Souss Massa Draa” for the last 40 years.

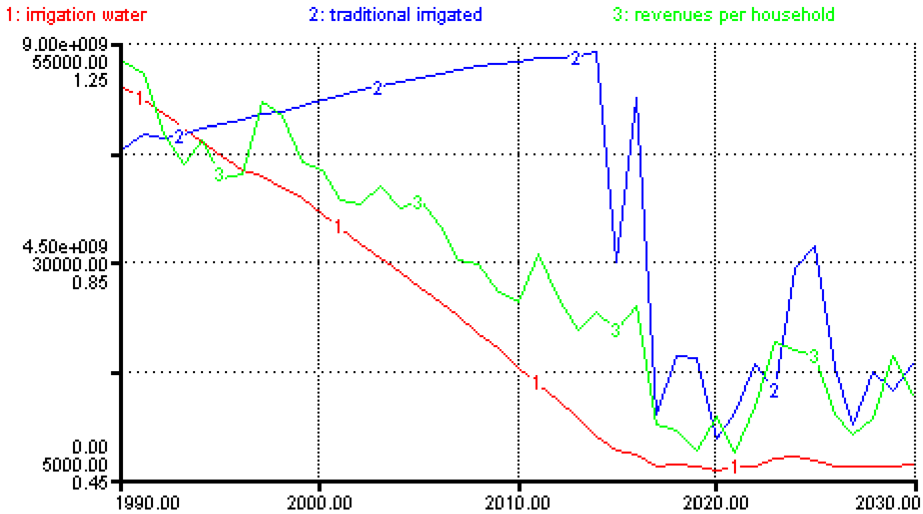


Figure 16: the change of the irrigation water, the irrigated agriculture, and the households' revenues

Besides the important loss of revenues for the local population from loosing the traditional irrigated agriculture, the intensive irrigated agriculture will collapse as well. This will result in an important handicap for the export business, and, within the Argane system, in the loss of job opportunities for farm workers. Besides, this will also result in more labor force for other sectors, but this is out of the scope of this paper.

The drying out of the irrigation waters is not the only cause of the collapse of the revenues for the population. We can see on figures 15 and 16 that the revenues per household trend will be decreasing before the fall down of the irrigated agriculture, thus causing the human population to level off before the year 2015. This is partially due to the increasing human population before the year 2015, but also because the composition of the revenues that did not follow the population growth.

In fact, the forestland will decrease (figure 15) due to land conversion for agricultural use and to deforestation for wood production. The fact that the forest has no natural regeneration exacerbates the problem. Yet, the Argane tree will still participate in the population income as a disperse trees population still exists in the traditionally harvested land. The revenues from trees on the traditional agricultural are three times lower than the wild forest revenues, as the trees stand with an average density four times lower in the harvested land than in the forest.

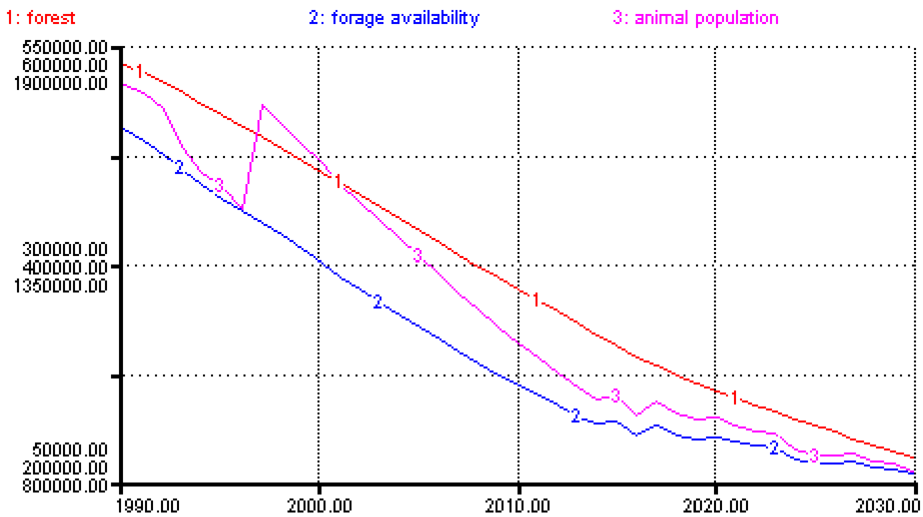


Figure 17: the change of the forest, the forage available, and the animal population

The animal population as well does not follow the change in the human population (figure 17). Due to a decline in forage availability because of pastures loss (mainly forestland), the carrying capacity of the land for the animal population weakens. We can also see that the rate of decline of the forage availability decreases after the collapse of the irrigated agriculture. This indicates that the forage productivity of the forest declines as the aquifer diminishes, and then stabilizes at a lower value when the aquifer is depleted. As a direct result of the animal population decline, the revenues of the population are negatively affected. Besides, as the traditional pastoral land decreases to the profit of agricultural land, the composition of the animal stock is expected to change. Practically, when the diet of the animal population shifts to a more produced or traded forage, instead of the natural pastoral forage, the animal herds will most probably be more composed of bovine and ovine, which require less grazing space on open fields and forestland. However, producing more forage requires more pressure on agricultural land, which means a mechanization of the agriculture since the traditional expansion in forestland is no more possible due to land scarcity. In turn, mechanizing the agriculture means destroying the remaining tree stands on the traditional land.

The rain-based agriculture contributes greatly to the formation of the population revenues. However, because it is based on the rainfall, its productivity is unstable, and so are its revenues (figure 18). Still, The overall trend of the non-irrigated agriculture is increasing. Yet, it is after the year 2015 that we can notice a first sharper rise in the rain-based agriculture, and a second even more important in the year 2017. This is due to the conversion of the irrigated land into non-irrigated cultures after irrigation is no more possible.

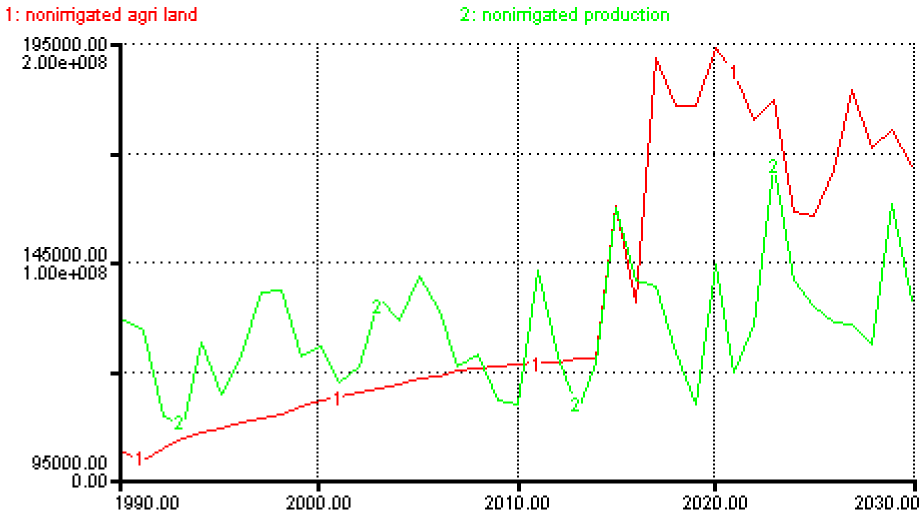


Figure 18: the change of the non-irrigated agricultural land and production

Under usual conditions, then, the system is clearly unstable and directed towards collapse. Ecologically, the loss of the forest will induce losses of the biodiversity it supports. Furthermore, the soil protection and buffering against drought effects provided by the forest will also be subject to change. The effects of the loss of the buffering effect of the forest is obvious when looking at the animal population decrease and the big variations in revenues. The loss of the buffering effect of the forest is even more sensed after the year 2017 (loss of irrigated agriculture) when the agricultural system's dependence and more rapid response to the changes in rainfall are more expressed.

Socially, the standard of living of the population will decrease as well, notably after the year 2016 as the revenues per household will drop. Besides, the role played today by the animal herds and the forest in the population's life style will also be attenuated because of their decline. To this adds up the breakdown of the irrigated agriculture, which implies an increased dependence of the population on the market for acquiring products such as vegetables, fruits, and other irrigated foods. Thus, the population will be more subject to changes in market prices, and will probably afford less for purchased irrigated products.

Economically, the diversification of the population revenues will be limited more and more to the non-irrigated agricultural production. Thus resulting in a more unstable revenues' pattern. The economic effects of the system behavior will also be greatly experienced outside the system boundaries. This will be expressed in higher rural exodus to the cities to relieve the pressure on the rural area. Another important aspect will be the crash of the irrigated agricultural products export industry, causing important deficits in the convertible capital of the entire country.

V.2. 30% decrease in the rainfall pattern

In this section, we assume that the rainfall for the future thirty years will be 30% lower than it has been during the past ten years. The graph in figure 19 shows the evolution of the human population, the forest area, and the revenues per household in this case.

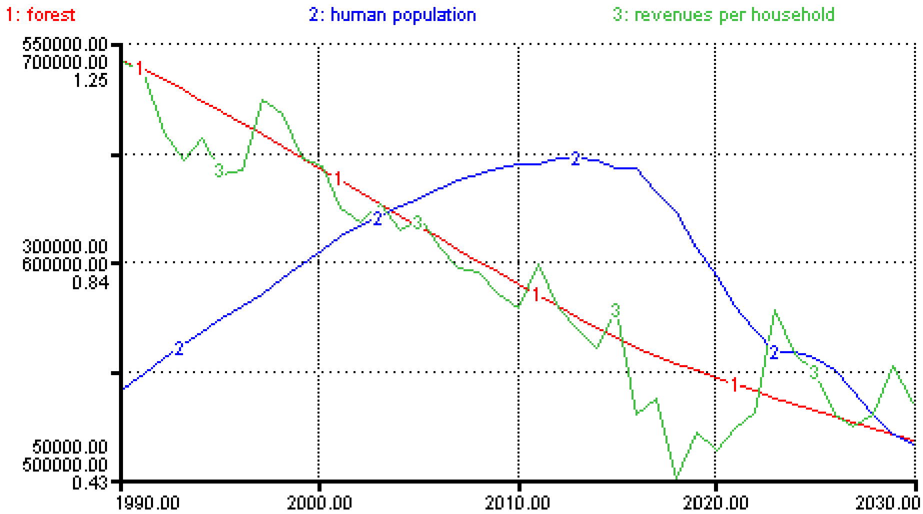


Figure 19: the evolution of the human population, the forestland, and the revenues per household under lowered rain pattern

The general behavior of the system under limited rainfall is similar to the evolution expected under normal rainfall trend. Yet, it can be noted that the population drop occurs one year earlier than under normal rainfall conditions. Moreover, the human population reaches a maximum size smaller than the one reached under usual rainfall conditions. This is due to the lower population growth rate under drought conditions. In fact, lower rainfall means lower productivity of the land and a lower recharging rate of the aquifer. These two facts in turn imply a decrease in the population revenues, which limits the population growth.

On the graph in figure 19, we can also see that the revenues per household are smaller than in the previous section after the year 2000 (before the year 2000 the rainfall is unchanged and based on historic data). This is partially due to the decrease in rain based agricultural production due to lower rainfall, and partially to the decrease in the animal population which in turn depends on the forage availability. The decrease in the animal population is actually engraved by the augmented arrival of nomads' herds from the south due to the drought.

The decrease in rainfall then means a degradation of the revenues per household, engendering lower standards of living. This will most probably drive the population to put more stress on the existing natural products to compensate for the economic deficit. This implies a more severe degradation of the forest and the natural environment. Besides, the difference between the maximum population and the population supported after the system collapse will be greater than under unchanged rainfall pattern (figures 15 and 19). This suggests that more population will be forced to migrate out of the rural area, thus putting more stress on the migration destinations.

V.3. 30% increase in the rainfall pattern

The graph in figure 20 shows the development of the forestland, the human population, and the revenues per household under a rainfall patter 30% higher than the historical trend.

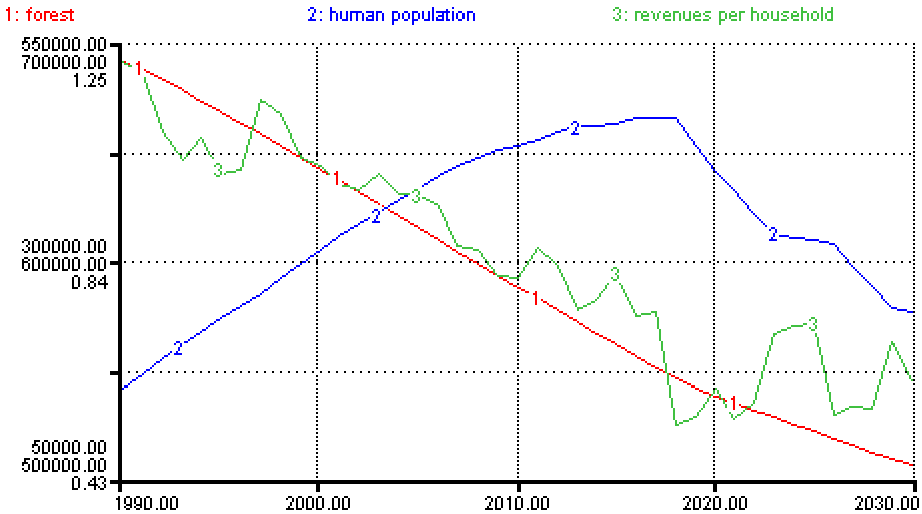


Figure 20: the change of the forestland, the human population, and the revenues per household under increased rainfall trend

The graph in figure 20 shows that the human population grows faster to reach 665,000 by the year 2017 and then start a steady decrease. The difference between the maximum population and the population supported after the system collapse is smaller than in the two previous cases of rainfall. This is because of an important non-irrigated agricultural production due to the higher rainfall which can support more population than before and thus attenuate the population drop. The rain-based agriculture is important during the years before 2017, and then increases more after the irrigated land is transferred to non-irrigated land. Yet, the non-irrigated agricultural production is not high enough to ensure a steady value of the revenues per household after the collapse of the irrigated agriculture. Besides, the positive effect of the increased rainfall on the aquifer is not important enough to compensate for the irrigation demands, and so the aquifer is depleted, engendering a decrease in the productivity of the forest although lower than in the previous two cases.

V.4. Defining the key bottlenecks of the system[47]

From the three scenarios based on changes in the rainfall patterns, we conclude that the system is unstable independently of the rainfall. As illustrated in figures 15, 19, and 20, the rural population's revenues drop dramatically after the inevitable exhaustion of the irrigation water, and so the end of the irrigated agriculture. In fact, the scatter graph in figure 21 illustrates that the total population revenues fluctuate around 100,000 UV, and then fall to around 45000 UV when the irrigation water is exhausted. Figure 21 also shows that the revenues decline with the reduction of the aquifer even before its depletion. This is due to the fact that the aquifer is necessary for the productivity of the forest, and its reduction leads to a decline in the revenues drawn from or based on the forest vegetation.

Moreover, the fact that the irrigation agriculture sustains a high income for the farmers causes a disproportional growth of the population. In fact, the high revenues during the period before the collapse of the irrigated agriculture disturb the natural equilibrium between the land and the human population. This illustrates the problem

[47] From this point on we consider a rainfall similar to the historical trend.

of induced growth caused by a non-durable factor[48]. We can then identify the exhaustion the irrigation water as one major cause of the system collapse, suggesting that the irrigated agriculture is a non-sustainable activity in the system.

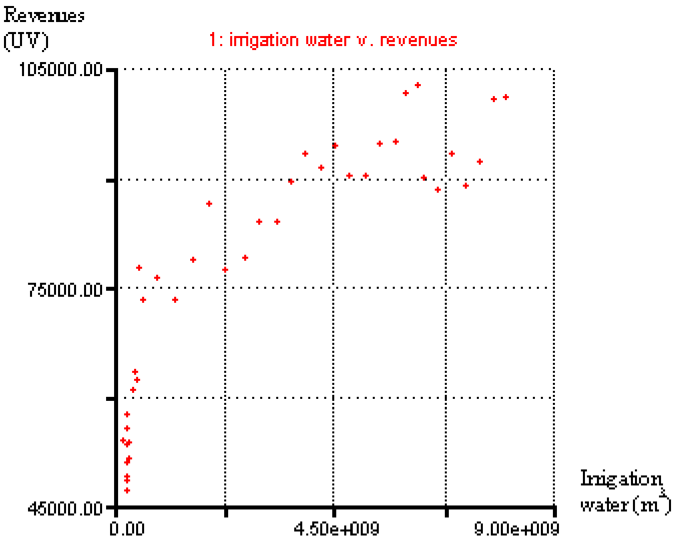


Figure 21: the total revenues of the rural population as a function of the irrigation water

Furthermore, figure 22 shows that the human population causes the decrease of the forestland through collecting wood, grazing, and also converting the forestland to agricultural land. The graph in figure 22 shows that even when the human population decreases (due to the failure of the irrigated agriculture) the forestland keeps on decreasing. The decrease in forestland engenders a decrease in the animal population, and so the revenues of the human population.

Yet, after the fall of the irrigated agriculture, forestland is no more converted to agricultural land, as the previously irrigated land is then harvested on a rainfall basis. In fact, the reason behind the decay of the forest is the absence of regeneration of the forest, which means that there is no compensation for the loss of the forest due grazing and the collecting wood, which continue as long as there is a human population. We can then define two requirements for the system stability. First, there is a need for limiting the effect of the population on the forest. Second, reforestation is absolutely needed.

[48] Cases like this can be noted in the Sahel region (sub-Sahara in Africa) for instance. In the Sahel, the human and population were induced to grow higher than the carrying capacity of the land due to the digging of additional wells by the UN in the region. The increased availability of the water encouraged population growth, but the carrying capacity of the land was push to the limit. Ultimately, the natural equilibrium was broken (Svensson, 1999).

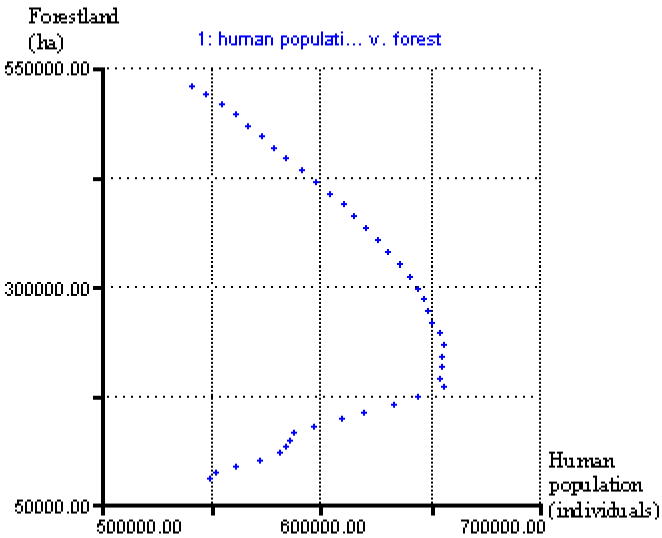


Figure 22: scatter graph of the human population vs. the forestland

We can then identify three main key actors causing the instability of the system, namely the irrigated agriculture, the growing human population, and the absence of regeneration of the forest.

VI. Propositions for future development

VI.1. Alleviating the pressure from and dependence on the irrigated agriculture

In the previous section we concluded that the irrigated agriculture, along with the human population and the absence of forest regeneration, is a major cause of the instability of the system in the medium time scope. As seen before, the irrigated agriculture can be classified as traditional and intensive. The traditional irrigated agriculture is essential to the local population as a component of their revenues and subsistence. It is then difficult to practically eliminate the practice of traditional irrigated agriculture. Besides, it is also unsound to assume that the intensive irrigated agriculture can be eliminated from the system for its national economic importance in the short term. However, it is reasonable to attempt to increase the efficiency of irrigation, thus reducing the consumption of water.

However, there is virtually no cost for using the water (besides the extraction costs). Complementarily, the amount of dam-collected water used for irrigation is negligible, and so is the cost related to it. For this reason, there is no incentive for the farmers to reduce the amount of water used for irrigation. This is a major obstacle towards reducing the consumption of underground water resources. To this adds up the high cost of installing more efficient irrigation techniques.

Actually, the vast majority of the farmer use the inefficient gravity-flow irrigation that can result is loses of 40% to 50% in the amount of the water used (Miller, 2000). Assuming we can increase the efficiency of the irrigation to a theoretically possible 95% (Ibid.), the system will behave as shown in figure 23.

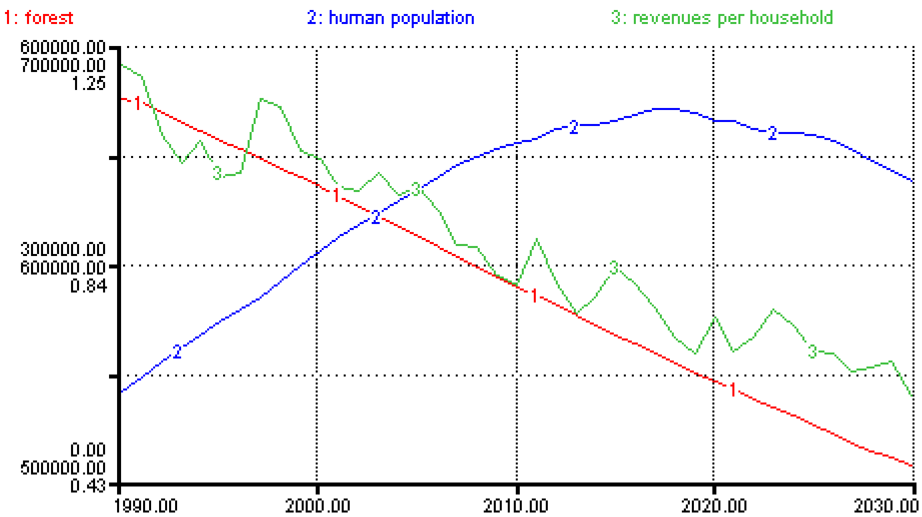


Figure 23: the change of the human population, the forestland, and the revenues per household under increased irrigation efficiency

Figure 23 shows that with perfecting the irrigation methods, the human population will still decline within the study period. The forestland and the revenues per household, on the other hand, will steadily decrease. The decline in the human population is initially due to the rapid decrease of the forestland and with it the population revenues. This decline will be accelerated in the year 2029 when the aquifer will be depleted. Thus, increasing the irrigation efficiency will only result in delaying the collapse of the system.

The pressure imposed by the irrigated agriculture surpasses the capacity of the system. To limit this pressure, one option is to stop the growth of the irrigated agriculture. This can be achieved through legally prohibiting further conversion of land to irrigated cultures. Yet, such a decision is politically very sensible due to the economic importance of the irrigated agriculture. Still, when investigating the case of no growth in the irrigated agriculture (figure 24), it appears that the system is still aimed to failure.

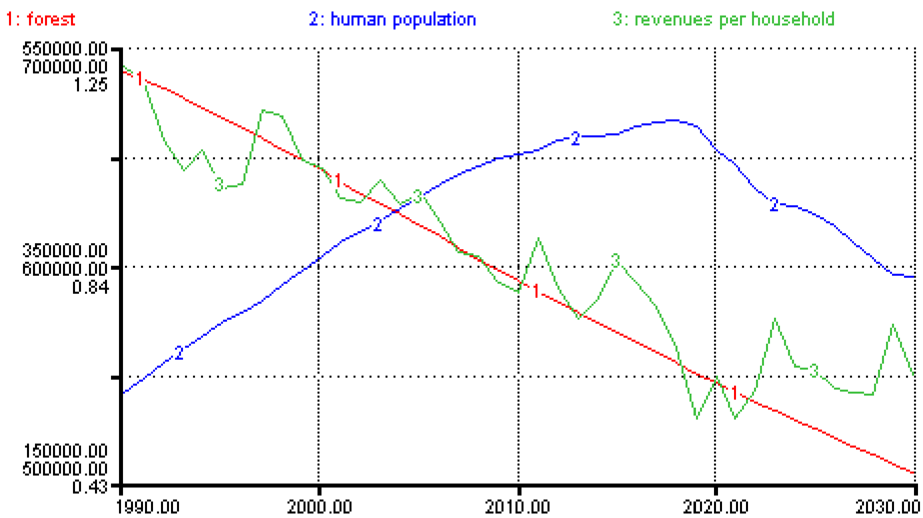


Figure 24: the evolution of the system under no growth of the irrigated land area

The exhaustion of the irrigation water and its leading to a crisis illustrates the typical growth dependent on limited non-renewable natural resources open to unrestricted usage. This type of growth is obviously not sustainable as the resource is depleted. The solution is then to shift the dependence away from the nonrenewable resource. This can not be achieved radically, but can possibly be developed overtime.

One way to decrease dependence over the irrigation agriculture is to further value other local products. While agricultural and animal products face competition from similar products produced elsewhere, the forest products are distinctive for the Argane region. Efforts are already being made in this sense through the development of cooperatives in the Argane region (Charrouf, 1998). The cooperatives' members collaborate in producing Argane goods, namely the oil and its derivatives, labeling the products, and marketing them.

The production is carried out through improved traditional methods, with more emphasis on hygiene and quality. In fact, traditionally the Argane fruit is given to chew to the goats that expel out the seed after chewing the pulp (Benzyane et al., 1998). This method is avoided because it transfers undesired odors to the Argane oil. Instead, the pulp is removed manually after drying the fruit in the sun. The seed shells are then smashed manually to extract the almonds, which are then press mechanically to produce the oil. With the help of research, the oil products are labeled with their composition and nutritional values. Finally, the Argane products are packed in an elegant manner, thus favoring their marketing. The products range from comestible oil to cosmetics, and are sold up to four times higher than the ordinary price in expanded urban markets. The new markets and the improved image of the Argane products can result in a 400% increase in its price (Charrouf, 1998). Applying a theoretical increase of 400% in the value of the forest products to our system results in the behavior in figure 25 bellow.

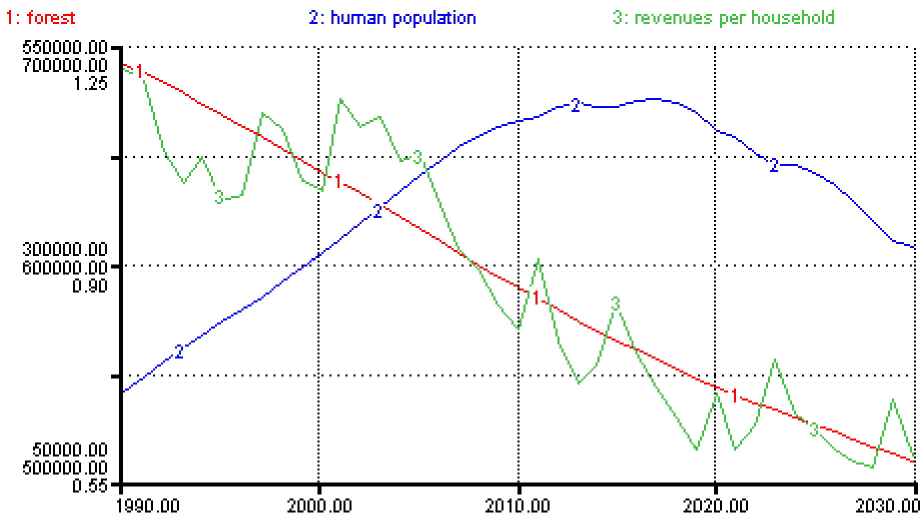


Figure 25: the system change under increased forest products' value and stopped growth of the irrigation agriculture

Adding up the valuation of the forest products to the fixed irrigation agriculture still can not avoid the collapse of the system. However, these modifications insure a higher value of revenues per household than before. The difference between the maximal human population and the population after the system collapse is also smaller. Still, the forest area and the revenues per household keep on declining. Moreover, the human population will actually drop and the underground water resources will be depleted by the year 2019. These two facts and the decline of the forestland indicate the instability of the system. It is then crucial to tackle other problems besides the non-sustainable irrigation.

VI.2. Insuring forest regeneration

Even with a stable population, the forest area will decrease due to the deforestation engendered by gathering firewood and grazing pressures. It is then vital to insure the forest regeneration. While the forest does not regenerate naturally[49], it is proven that the Argane seeds can germinate with no difficulty. An applied traditional method consists in leaving the grains in the water until the germination starts, then transfer them to the soil, with watering during the early years (Benzyane et al, 1998). Experiments showed that special treatments of the seeds with chemicals is not necessary, since it only allows to keep the dormant grains for a longer period without them decaying (Ibid.).

Regenerating the forest is then not a costly operation, since grains are plentiful and the method very rudimentary. Other methods, such as test tube cloning, are also in use to produce Argane trees but to a limited extent (Benzyane et al, 1998). Cloning can prove very efficient in producing large amounts of trees with specific characteristics such as high fruit productivity or more developed root systems. In fact, the Argane tree survives the dry climate of the region by the virtue of its well-developed root system, which can reach aquifer water reserves underground (Ibid.). However, the water resources may be the limiting factor to the forest regeneration and possibly even existence. In fact, records from 1969 have already reported that due to intensive exploitation of the underground water resources in the plain of Souss resulted in a deficit in the aquifer balance at least every three years out of four (Ibid.).

However, existing experience of a community benefiting from the valuation of the Argane oil shows that the cooperative[50] involving more than one hundred women replants ten hectares of forest each year (Charrouf, personal conversation, 2000). This suggests the possibility of replanting an average of one hectare for every 10 households every year. The newly planted forest can grow on the exiting and expanding open fields, thus avoiding conflict with the agricultural land. For a sustainable equilibrium of the forested area, the reforestation rate should reach a value of one hectare for every 11.6 households[51], which is bellow the rate of regeneration achieved by the existing Argane cooperatives.

Figure 26 bellow shows the behavior of the system with a reforestation rate of 1 hectare for every 10 households. The replanting is taken to start on the year 2001. However, the Argane trees take 15 years to maturate and become productive. We will then delay the usefulness of the replanted forest by 15 years. In addition, Figure 26

[49] The natural regeneration of the forest is inhibited by the harvest of the fruits and the use of the seeds, plus the grazing of the animals on the small growths (Benzyane et al, 1998).
[50] This is the cooperative of the region of Tamanar to the north of Agadir.
[51] The 1 hectare per every 11.6 household actually compensates for the deforestation rate caused by wood gathering, excluding the growth of agricultural land.

takes into consideration a valuation of the argan products with 400%, but no modifications affecting the irrigated agriculture.

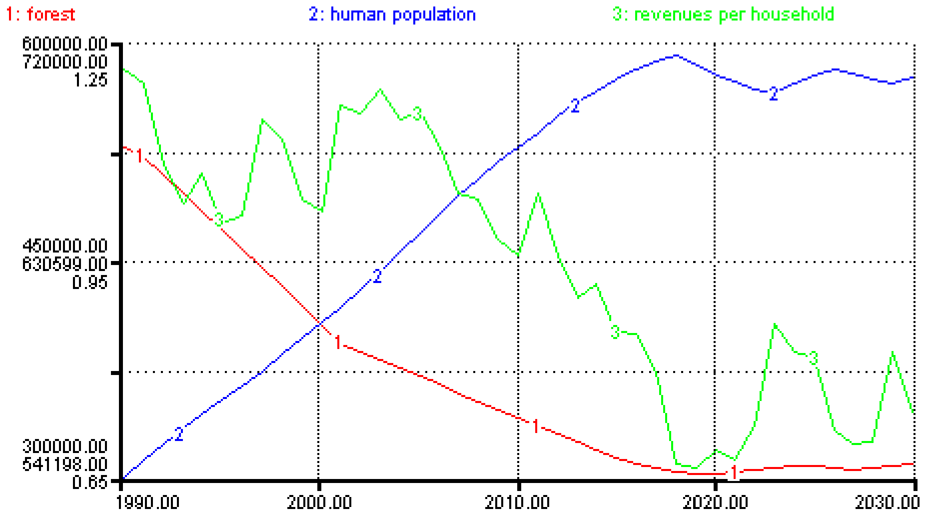


Figure 26: the change in the human population, the forestland, and the revenues per household under conditions of reforestation and increased forest products value.

Figure 26 shows that the system is more stable when the forest is regenerated and the forest products valued. The human population increases rapidly until the year 2018 when the irrigation agriculture collapses as seen before (section V.1.). The human population will then fluctuate around a fixed value (710,000 individuals), imposed by the revenues generated from the land. In fact, the high revenues from the forest, supported by a regenerated forest keep the revenues per household high enough for the human population not to fall. Besides, delaying the enterprise of regenerating the forest will cause a larger decrease in the human population growth rate. In fact, the model simulation shows that starting to regenerate the forest after the year 2010 will result in an important decrease of the human population after the collapse of the irrigated agriculture. The forest will regenerate and stop declining, and it will actually increase as time passes. A reforestation rate higher than 10 hectares per household will accelerate the recovery of the forest. Still, considering the studies assumptions, the human population stops growing only because it is able to migrate out of the rural areas. This implies that the system is not yet sustainable.

VI.3. Limiting population growth

From the previous discussions, we can sense that the growing human population puts more stress on the environment. Indeed, the increasing human population requires more land to harvest, larger animal stocks, more wood for energy and other purposes, and more water for irrigation. From the scenarios above, it appears that the optimal carrying capacity of the system under the initial condition can support a human population around 700,000 people. For the system to be stable in the long run, this population can not be exceeded. Hopefully, the actual size of the population (around 540,000 people) leaves a reasonable margin to control the population size before reaching its limit.

However, the social structure of the region is not permissible towards accepting a population limit policy. In fact, the farmers need labor for the farm work and the animal grazing. Yet, the most important catalyst for sustaining a large family size (6.5 individuals per family) is due to the fact that there is no insurance other than family support for the farmers. As farmers grow old and unable to work, or in case of physical disability due to disease for instance, their families are the only resource for them to survive.

For this matter, the formation of farmers' cooperatives can be useful. If we consider the valuation of the Argane forest products discussed above, the cooperatives are able to generate supplementary income for the farmers. Part of this income can be used to create a saving account for social welfare. Farmers would contribute into the savings, and when in need they could have recourse to the account. Yet, any measures to reduce the population growth can not be successful if the people are not educated about the urgent need to respect them. Surprisingly, the local people prove to be very receptive to new ideologies susceptible of improving their future.[52]

However, as far as how the system structure for this paper is concerned, we assumed a dynamic development of the population depending on the revenues per household (based on historic data). Yet, this assumption is true when taking into account the very high rates of migration and population movement mainly from rural to urban areas. A controlled population growth will mean less pressure due to migration, which means a more stable overall system including the system herein studied.

VII. Conclusion

From our analysis it is appears that the natural equilibrium of the Argane forest was disturbed. This disturbance goes back to internal and external factors. Internally, the human population growth and the mode of life of the population put enormous pressures on the forest. The local population pressure resulted in the loss of the forest natural regeneration due to harvesting the fruits and grazing the large animal herds. Besides, using the forest as a source of fuel induces a very high rate of deforestation, which increases with the increasing human population.

Externally, the introduction of the irrigated agriculture for market production also disturbs the equilibrium of the system. The intensive irrigated agriculture has a negative impact on the land in two aspects. First, it causes soil salinization and loss of nutrients on clear-cut lands, which then become nuclei for continental dunes and desertification. Second, because the intensive agriculture continually requires new land that it derives from traditional agricultural land, the traditional agricultural practices including cultivation and pasturing are pushed more into smaller forest areas. As a result, the pressure on the forest is amplified, thus causing this latter to decline steadily.

On the other hand, the traditional irrigated agriculture encourages a rapid population growth, which affects more the forest. Moreover, the collapse of the irrigated agriculture will result in a social crisis, as the revenues per household will

[52] The experience from newly created Argane cooperatives showed that rural men are more open to the local women thoughts and opinions after these latter showed their talent in managing the cooperatives. The women, on the other hand, proved to be more receptive to lectures about family structuring and childbirth limiting.

drop dramatically thus producing a massive migration movement away from the rural areas in study. This trend is expected independently of the rainfall pattern in the future.

However, it is possible to achieve a sustainable future for the Argane forest system under three main conditions. First, the dependence on the irrigated agriculture has to be reduced. This can be achieved through valuing the products of the forest, thus generating an alternative source of income for the local population. However, this alternative will not be durable unless the regeneration of the forest is insured. Finally, the system studied is only part of a larger system, which has been assumed to be able to absorb the surplus of human population coming from the former through migration. Thus, for the Argane forest system to be entirely sustainable, the population growth needs to be limited in order to avoid the dependence on migration as an external outlet of the system.

Appendix 1 List of Equations

Section IV.1. Human population

Human population revenues = 0.03*(animal population) + 0.015*(forest land +(1/3)*(traditional agricultural land)) + 1.65E-4*(grain production) + 2.47*(traditional irrigated agriculture)

Note: The traditional agricultural land also contains trees, with a density = 1/3 the density of the forest.

Section IV.2. The land

Cultivated area for grain production (ha) = 65368*ln(rainfall of previous year) - 246991

Note: The equation was obtained by curve fit in Ms Excel. Does not include the upper limits, which are shown in the text.

Section IV.3.1. Animal breeding

Animal population (OEI) = $1E6 * e^{(0.0006*(\text{sum of 4 previous years of rainfall}))}$
Carrying capacity of the land (OEI) = (1/(0.5*0.5)) * (0.86*(forest area) + 0.28*(open field area) + 0.28*(agricultural area) + 2.8*(forage area))

Section IV.3.2. Non-irrigated agriculture

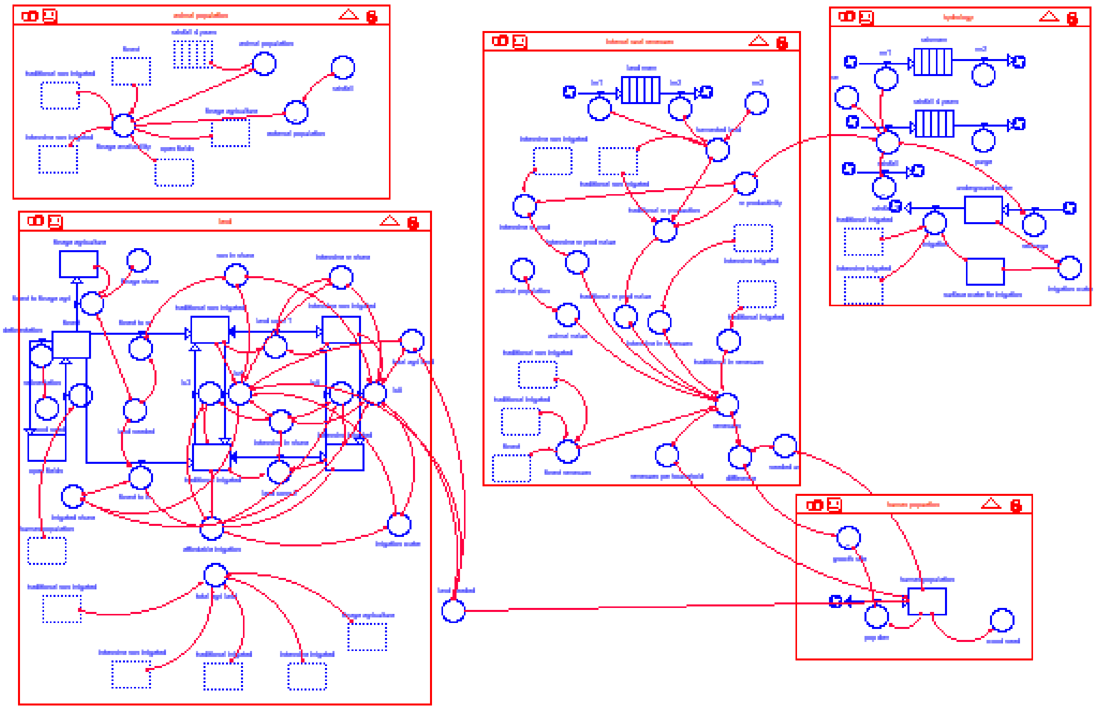
Average grain productivity (kg) = 6.4*rainfall + 3

Appendix 2 The computer model

Animal population

Population revenues

Hydrology



Land

Human population

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