LU-CDM, A Conceptual Model of Desertification

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Assessing and Monitoring Desertification
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LU-CDM, A Conceptual Model of Desertification

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DeSurvey Deliverable 1.3.3.8: Completion of Stella scenario model, Version 1

LU-CDM, A Conceptual Model of Desertification

Ulf Helldén, Partner 7 (Lund University)

0. ABSTRACT

This paper presents a generic system dynamic model to simulate and analyze a desertification system and its stability for different desertification syndromes.

The study is one of many desertification related modelling approaches carried out by different project partners within the frames of DeSurvey (A Surveillance System for Assessing, Monitoring and Modelling Desertification; 2005-2010). DeSurvey is an EU FP6 Integrated Project (IP) on desertification considering the inter-action and importance of socio-economy, climate and landscape vulnerability to land degradation.

The human-environment coupled model integrates socio-economic drivers with bio-physical drivers of land degradation and desertification. It is based on the UN and GEF definitions of desertification. It illustrates the concept of desertification through differential equations, simulation output graphics and through causal loop diagrams demonstrating the existing feed-back mechanisms. It may be useful for land use system stability/equilibrium condition analysis and for sustainable strategic land policy and management decision support.

The model relates population pressure and dynamics over time to the removal and availability of biomass resources. The population stock is described as a function of growth rate, death rate and resources dependent in and out migration of people. The relative growth rate of the stock of resources is modeled as a function of climate and exploitation pressure affecting soil erosion and water availability. Biomass recovery from serious degradation/desertification events follows the logistic growth function modified by population pressure, erosion and water availability conditions.

The conceptual desertification model is applied for the Sahelian syndrome using input data to illustrate and simulate a 150 years period (1900-2050) in Kordofan, Sudan. The model indicates that it is difficult to generate irreversible desertification in a system where there is an open market and free population mobility unless serious climate change and/or extremely serious soil erosion creates long term wasteland conditions leading to ultimate land abandonment

1. DESERTIFICATION

Desertification is land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Land degradation implies the reduction of the resource potential of the landscape through different processes (UNCED 1992).

A reduction of the resource potential of the landscape is often understood as a reduction of the potential to produce biomass (food/crops, fodder, and woody biomass). However, the losses of soil or water are also reductions of the resource potential of the landscape and accordingly desertification.

Embedded in the term desertification is much controversy on the actual magnitude of the problem with published figures suggesting that anything between 17 to more than 70 per cent of the worlds drylands may be seriously affected and 'desertified' (Reynolds et al. 2003). Another crucial issue relates to the actual causes of desertification with much of the debate focusing on the extent to which it is mainly driven by climate or by human influences. A third crucial issue refers to how desertification can or will manifest itself in environmental, social and/or economic terms. Can it be measured?

The issues mentioned imply that the interpretation of the UNCED desertification definition can differ a lot. The varying interpretations have given rise to varying land degradation and desertification conceptual schools. The different schools may provide different syndrome descriptions depending on scientific experience and geographic "desertification" background of the members of the schools.

In March 2006 we carried out a survey among the scientists of DeSurvey (about 90 persons) to find out about their desertification/land degradation concepts. We offered everyone an opportunity to provide an anonymous opinion about what key indicator/ variable they would prefer as a proxy and most significant "stock" for desertification if they were to assess or simulate desertification through system dynamic modeling. Sixty five of them responded. Each person had two votes. A vast majority of the votes fell on the following two alternatives (Fig. 2.1):

D) Green & woody biomass (natural & crops productivity)
E) Vegetation fractional cover (canopy and field cover)

It is obvious that a majority of the DeSurvey scientists agree that serious desertification ultimately results in long lasting and observable loss of vegetation cover and biomass productivity over time and in space (Fig. 2.1). It may of course also result in a degradation and loss of water and soil resources as well as a loss in vegetation quality (palatability and bio-diversity), and a row of additional indicators of different types.

Sticking to vegetation as the major desertification proxy, it is assumed that one of the two main limiting and driving factors of vegetation growth and coverage in the drylands of the world is water availability. The second factor is the production/ management and removal/consumption of biomass through human induced activities (food, fodder and fuel wood/energy production and consumption) as exemplified by the LU-Conceptual Model of Desertification indicated by Thornes and Helldén (2006).

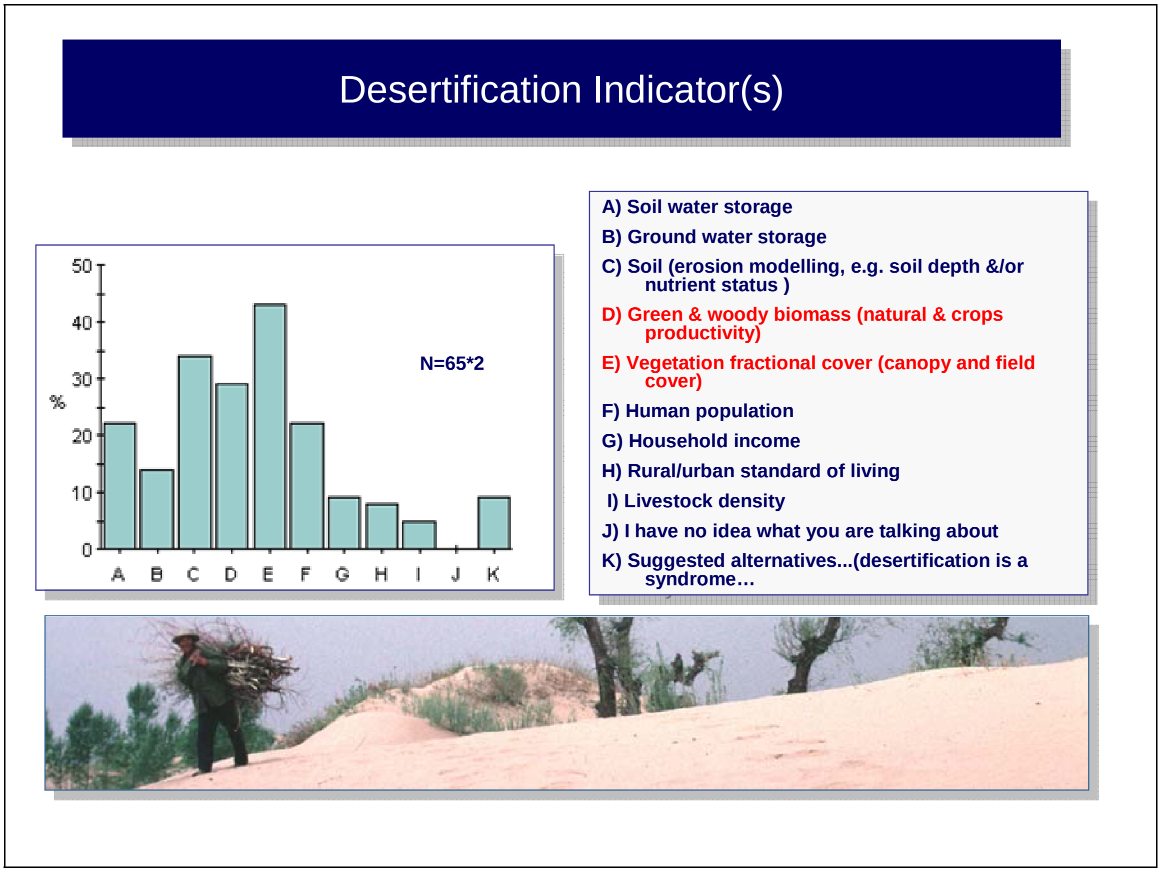


Fig. 2.1. The result of a survey of DeSurvey desertification concepts in March 2006. The histogram illustrates the distribution of votes. Each scientist supplied two votes. 65 out of 90 scientists answered. A vast majority of the DeSurvey scientists preferred vegetation related indicators as proxies for desertification in a theoretical system dynamic modeling attempt. (Photo: Woody biomass removal in Khorquin Sandy Lands, Naiman County, Inner Mongolia, China, U.Helldén 1994)

Please refer to DeSurvey deliverable 1.3.3.1 by Thornes and Helldén (2006) for a comprehensive summary of desertification history, prevailing concepts of desertification and a discussion of its syndromes.

2. OBJECTIVES

The objective of this report is to present a human-environment coupled conceptual desertification model (LU-CDM), based on numerical simulations, to complement the UNCED definition.

The varying concepts of desertification, inside and outside DeSurvey, calls for a unifying and harmonizing concept that can explain land degradation and desertification more precisely than the UN-based rather vague and interpretable definition. The development of a human-environment coupled system dynamic model that defines, simulates and describes desertification in terms of equations, feedback loops and graphics might be a plausible complementary solution that can be accepted and used by DeSurvey and the international community.

- Such a mathematical model should be able to simulate and illustrate the behavior of major desertification relevant stocks of resources over time together with their most important human (socio-economic) and bio-physical drivers.
- The model should be easy to understand and use, simple and robust i.e. there should be as few user provided inputs as possible.
- It should provide information on vulnerability and stability conditions of a given land production system.
- It should give guidance for sustainable land management (SLM)

A first sketch of such a model was indicated by Thornes and Helldén (2006).

3. MODELLING REVIEW

Desertification and land degradation have most commonly been modelled and mathematically described in terms of soil erosion, corresponding soil loss and surface water run-off. The soil erosion process is often described as a function of vegetation ground cover, rainfall characteristics, topography, soil characteristics and land management (Morgan 1995, Rose 1998, Thornes 2003, Nearing 2003, Nearing et al. 1994, Kirkby et al. 2004, Mulligan and Wainwright 204).

Many of the EC Framework Programs research projects on European desertification focused on soil erosion e.g. Medalus I-III running 1992-1998. However, the erosion feedback on vegetation growth (food, fodder, woody biomass) and crop yields is seldom obvious unless the erosion/denudation rate overtakes the soil formation rate. A decreasing soil depth may lead to decreasing water holding capacity and the eventual total disappearance of the soil cover in the long run.

A first approach to model desertification through a human-environment coupled model approach was probably carried out by Puigdefábregas (1995). He considered desertification to be stress beyond resilience, i.e. irreversible. He modelled it through a predator-prey system approach based on a known model designed for describing the behavior of closed grazing systems and non-territorial ungulates, slightly modified for population migration. As most predator-prey models, it was based on two linked differential equations describing the evolution of both a human population (predator) and natural resources (prey) in terms of gains, losses and interaction. The model description below illustrates the basic model. It is extracted from Puigdefábregas (1995).

The pair of linked differential equations that define the system are given below.

$$\frac{dR}{dt} = R\,r_1\left(1-\frac{R}{R_0}\right) - Hc_1\left(1-e^{-d_1 R}\right)$$

$$\frac{dH}{dt} = Hr_2\left(1-e^{-d_2 R}\right) - Hc_2 + \frac{\left(R/H^{-d_3}\right)}{k}$$

if R/H > d_3 then $k = k_1$
if R/H < d_3 then $k = k_2$

R and H stand for natural resources and human population;
R_0 and r_1 are the carrying capacity and the intrinsic rate of increase for natural resources respectively;
c_1 is the maximum rate of resource intake per unit of population;
d_1 is a search efficiency factor when the resource is scarce;
r_2 is the maximum multiplication rate of the human population;
d_2 is a demographic efficiency when resources are scarce;
c_2 is the rate of loss of human population;

The migration term describes the in- or out-flow of population in terms of the gradient of resources concentration R/H and a resistance to flow *k* which my be different for immigration and emigration (k_1 and k_2);

d_3 is the outside resource concentration which is considered constant, i.e. the external environment acts a source or sink of population.

Puigdefábregas suggested that environmental variability may be introduced in R_0 as a random, cyclical or pulsating factor. Fertility or recovery rates may be fitted in r_1. Technological changes that modify the accessibility to resources as well as economical complexity, such as handling and adding value to primary resources, are aspects that may be included in the consumption parameters c_1 and d_1. The population parameters of the second equation are not only demographic, but they may be referred to man power units or to some other combination of demography and capital. Therefore, as stated by Puigdefábregas, r_2, d_2 and c_2 not only deal with nativity and mortality, but also with growth and destruction of capital, work and investment. Migration resistances include aspects such as social or political freedom of movement and barriers set by the receptor population (k_1) or deterrent effects for potential emigrants of investments in the source areas (k_2).

A conceptual man-resources coupled model of the desertification process was further outlined by Puigdefábregas (1998). He discussed world wide reported desertification cases and concluded that most cases share a common feature of system boundary disturbances that had not been experienced before in their history. Given possible examples included changes in climate, market conditions, agricultural policies, demographic booms and technological revolutions. Large scale climatic and anthropogenic factors were assumed to have synergetic effects on dryland ecosystems. Changes in one makes the ecosystem more sensitive to changes in the other. It was concluded that system transition triggers often start from an alternation of humid and dry periods. The humid periods supports a growing human population and creates consequent pressure on the resources. The dry periods eventually leads to irreversible degradation if steps are not taken to release the pressure before existing resilience thresholds are passed and the system is forced to extinction or desertification.

Regev et al. (1998) developed the classical predator-prey model approach to include a model of human harvesting of renewable resources. The model includes development technology, economic profit maximization theory and the effects of market forces on the sustainability of common property resources.

Stephénne and Lambin (2001) presented a simulation model to project land cover changes at a national level for Sudano-Sahelian countries. The land demand in the model is calculated under the assumption that there should be equilibrium between the land production and consumption of basic resources derived from different land use types. If this was not the case, but a deficit was generated e.g. through land degradation or desertification, people had to find alternatives. The farmer was assumed to compensate himself by expanding his land claims, i.e. new land was cleared for the purpose (if available), or by intensifying the use of his existing lands to increase production.

Puerta et al. (2008) described a model approach to assess desertification risk using system stability condition analysis. It is a further development of the modelling strategies proposed by Puigdefábregas (1995, 1998) and Regev et al. (1998). It is based on the assumption that soil erosion and the soil sub-system play an overriding final role in the desertification processes. It is also stressing the role and importance of economic units, production costs, investments and profitability in natural resources exploitation.

The impact of boundary disturbances, like change in climate, market conditions, demographic booms, on the sustainability of threatened human-resource systems is discussed by Puerta et al. (2008). It is assumed that the overall effect of such system disturbances or of internal “over-exploitation” may take the threatened systems beyond their resilience thresholds referring to at least the economic and ecological thresholds. It is stated that the former mostly occur earlier than the latter, leading people to ease their pressure on the renewable resources. However, in desertification cases, it is assumed that people (economic units) cannot get out but are forced to continue exploiting resources beyond their ecological resilience threshold until land degradation is irreversible (Puerta et al. 2008) . The assumed reason for this behavior is not stated explicitly by Puerta et al. (1998) but could possibly be the need of the people (economic units) to safeguard their capital investments. This may perhaps be a valid position in a capital market economy like Spain, but not necessarily in a development country like the Sudan, or elsewhere in the African Sahel, where the subsistence economy, or possibly mixed economy, is a reality for most people in the arid lands. There are seldom any long lasting capital investments, or related bank interests, to protect. The driver of land use and management strategies is rather hunger and local energy needs than economic profit.

Liu et al.(2007) presented a review of integrated studies of coupled human and natural systems and stressed the complexity of such systems. Desertification is a complex system. The LU-CDM model described below gives a simplistic and generic picture of the desertification concept.

4. METHODS AND ASSUMPTIONS

LU-CDM is a human-environment two-level (resource-man) coupled predator-prey based model. The human population is the predator and the biomass resource is the prey. The model simulates desertification over a 150 years period, 1900-2050, applying a numerical step size (delta time, DT) of 0.5 years. It generates graphic output to illustrate the status and dynamics of all converters, system flows and stocks over time.

The model is developed in the system dynamic modelling software environment of Stella (Isee Systems 2007). Stella is based on the combination of "converters", "stocks" and "flows", where all equations are solved through computer based numerical simulations replacing tedious and complicated analytical solutions of differential equations.

In its present stage LU-CDM is based on the original concept of the Lotka-Volterra Predator-Prey model, further developed to simulate consumer-resource interactions. For a general description of system dynamic modelling please refer to e.g. Ford (1999), Jörgensen and Bendoricchio (2001), and Wainwright and Mulligan (2004).

The model is built to illustrate and test the assumption that a land use/land production system (crop land, rangeland or forest/woodland) can degrade to such an extent that it reaches a point of no return, the system stability and its resilience threshold are broken, and the production system breaks down. At that stage, the system is supposed to find a new level of equilibrium where almost no biomass is produced. The level of biomass (food, fodder, woody biomass) production becomes insufficient for human survival for a "very long period of time", possibly even irreversible. A "very long period of time" is assumed to be a man age or two in a developing country. Meanwhile the affected self-subsistent population is left without a local livelihood option. They may ultimately face famine unless they leave the area or they are assisted with imported food and other needed resources in time.

The degradation of the land (the production system) is assumed to take place through human (man and his animals) "over-use" or "over exploitation" of the local natural resources, through climate variability or change or through the combined effect of human impact and climate as suggested by the UNCED definition of desertification (UNCED 1992). It is generally assumed that the land degradation/desertification system process is accelerated through positive feedback loops.

The assumed positive feedback loops that are running, or even accelerating the degradation process, are started by the initial net-removal of vegetation by humans or climate and involve as a result increased water run-off, increased soil water erosion, decreasing water infiltration to the root zone, and also increased wind erosion and soil/sand mobility for sandy soil types. The sandy soils particle mobility makes the establishment and growth of new vegetation difficult or even impossible until the soil is stabilized through soil conservation means. The total effect of the loops is supposed to yield a positive feedback on the vegetation removal process by gradually enhancing the systems inability to support vegetation growth and cover. This will again result in further water run-off, soil erosion…. The biomass/vegetation cover degradation rate is supposed to increase or even accelerate for every loop. This is usually considered to be desertification, ultimately leading to irreversible conditions, according to prevailing concepts. LU-CDM was developed under the assumption that this complex process can be simulated and verified.

Soil loss by soil erosion is often pointed out to play a major overriding role in the desertification process (Puerta et al. 2008). However, this may be true for thin soils on steep slopes and when considering very long time spans only. It should be kept in mind that a severe annual net sheet erosion of e.g. 700 m^3/km^2 (~20 ton/ha/year) corresponds to a soil surface lowering rate (denudation rate) of 700 mm/1000 years. It implies it would take almost 3000 years to half a 4 m deep soil and almost 6000 years to deplete the resource completely. This is obviously far beyond any political consideration related to existing national and international land degradation/desertification programs and conventions.

The exemplified soil erosion rate is a European upper end extreme rate, modelled and mapped by the Pan European Soil Erosion Risk Assessment (PESERA) (IES-JRC 2005).

The issue of ground water exploitation and irrigation/salinization problems are excluded from the modelling approach presented here. However, in principle the biomass stock in the model can be replaced by a “water resource” stock.

5. LU-CDM; THE CONCEPTUAL DESERTIFICATION MODEL

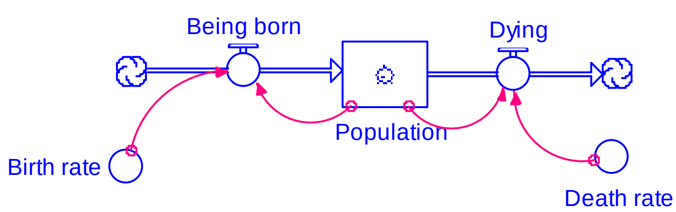
5.1. The population component.

The human population component is a traditional population model (Fig. 5.1.1). The population itself is rural people in a subsistence economy in North Kordofan, the Sudan. They live on a mix of settled rain-fed farming (cropping, livestock, and woody biomass), nomadism and semi-nomadism.

The population stock starts with 20 people/km^2 which is a common population density for rural North Kordofan, Sudan (Elmqvist 2006). The population net growth depends on the difference of *birth rate* (3.7 per cent/year) dependent growth, migration rates and the loss of people depending on *death rate* (initial death rate is 1 per cent/year). Both death rate and birth rate are dependent on a number of external factors not considered in the model e.g.

family policy, governmental subsidies and taxes, labor, access to markets and health service. For the time being we consider the system to be closed from external impacts. The population growth is mainly dependent on the local availability of biomass resources i.e. food, fodder and woody biomass for energy production and building material. The dependency is demonstrated in the coupled model below where migration is added as another important factor affecting the population stock.

LU-CDM Population Component



Population(t) = Population(t - dt) + (Being_born - Dying) * dt
INIT Population = 20
INFLOWS:
Being_born = Population*Birth_rate
OUTFLOWS:
Dying = Population*Death_rate
Birth_rate = 0.037
Death_rate = 0.01

Fig. 5.1.1. The LU-CDM population component.

Less resources/capita will ultimately generate famine and make people leave the area for more attractive areas e.g. urban areas to look for jobs, or remote rangelands to look for better grazing and a better life. Good times with good access to resources will attract people and make them settle in the area.

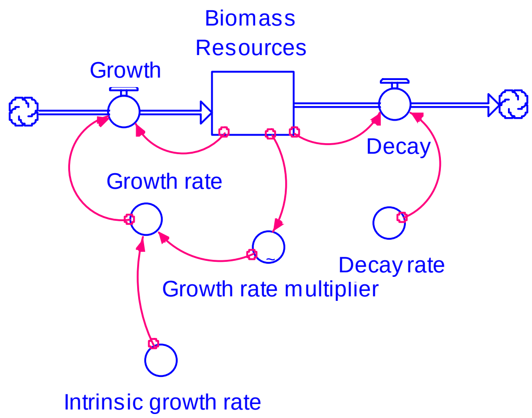
5.2. The resources component.

5.2.1. The S-shaped growth curve

In a subsistence economy, like the prevailing one in North Kordofan, Sudan, people are dependent on the local natural resources. The resource model component is based on a simplified biomass growth model. It starts with a stock of biomass of 800 tons/km^2 corresponding to a net primary production (NPP) of 800 g/m^2/year (dry organic matter). This is the NPP for temperate grasslands, characterized by an annual precipitation of 600-900 mm (Christoffersen 2003).

The *actual growth rate* determines the growth of the biomass stock at the current point in time (Fig 5.2.1). The *decay* of the vegetation/biomass is based on a *decay rate* of 20 percent/year. The *intrinsic growth rate*, i.e. the growth rate in an almost empty stock, is set to 100 percent per year. This rate applies when the stock is almost empty of vegetation, i.e. there are no space (density) limitations for growth. As the vegetation fills our stock, the

LU-CDM Biomass Resource Component

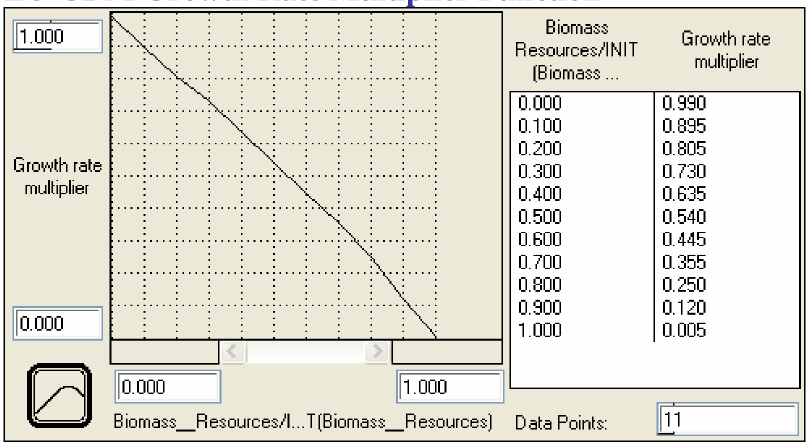


Biomass__Resources(t) = Biomass__Resources(t - dt) + (Growth - Decay) * dt
INIT Biomass__Resources = 800
INFLOWS:
Growth = Biomass__Resources*Growth_rate+10
OUTFLOWS:
Decay = Biomass__Resources*Decay_rate
Decay_rate = 0.15
Growth_rate = Intrinsic_growth_rate*Growth_rate_multiplier
Intrinsic_growth_rate = 1
Growth_rate_multiplier = GRAPH(Biomass__Resources/INIT(Biomass__Resources))
(0.00, 0.99), (0.1, 0.895), (0.2, 0.805), (0.3, 0.73), (0.4, 0.635), (0.5, 0.54), (0.6, 0.445), (0.7, 0.355), (0.8, 0.25), (0.9, 0.12), (1, 0.005)

Fig. 5.2.1. LU-CDM biomass resource component.

fraction occupied land, or amount of biomass, increases and the *actual growth rate* will decrease because of competition for the limited resources of e.g. light, water, nutrients and space. This is also true the other way around, i.e. when vegetation is removed from the area (e.g. through grazing and fuel wood collection), the *actual growth rate* will increase with the removal. The changes in the growth rate are achieved with a *growth rate multiplier* converter (Fig 5.2.1 and 5.2.2). In this case the multiplier is equal to 1.0 (100 percent) when the biomass stock is close to zero and the rate decreases to close to zero when the stock is growing full. It implies the actual growth rate will be identical to the intrinsic growth rate when the stock is almost empty and that the actual growth rate decreases with growing stock until the carrying capacity of the system has been reached.

LU-CDM Growth Rate Multiplier Function



Biomass Resources/INIT (Biomass ...	Growth rate multiplier
0.000	0.990
0.100	0.895
0.200	0.805
0.300	0.730
0.400	0.635
0.500	0.540
0.600	0.445
0.700	0.355
0.800	0.250
0.900	0.120
1.000	0.005

Fig. 5.2.2. The graphical representation of the LU-CDM growth Rate Multiplier Function defined in Fig. 5.2.1.

The stock will not be allowed to become zero to simulate the existence of a seed bank in the soil that has the potential to grow even when all surface biomass has been removed. A suggested linear function of the growth rate multiplier is illustrated as "Series 1" in Fig. 5.2.3. together with examples of alternative functions. If we plot the actual growth of the stock over time, applying the suggested growth rate multiplier, we will see that the stock growth follows the "logistic equation" given in Fig. 5.2.4. It illustrates the S-shaped growth starting with an exponential growth before reaching a state of dynamic equilibrium. The growth of the stock approaches zero when the carrying capacity of the system is reached.

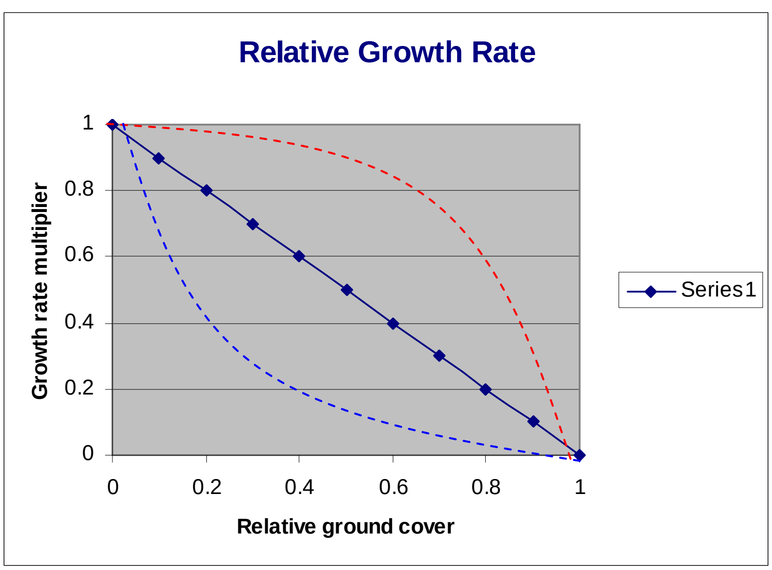


Fig. 5.2.3. Examples of density related growth rate multiplier functions. The LU-CDM assumes there is a linear relationship between ground cover and biomass stock.

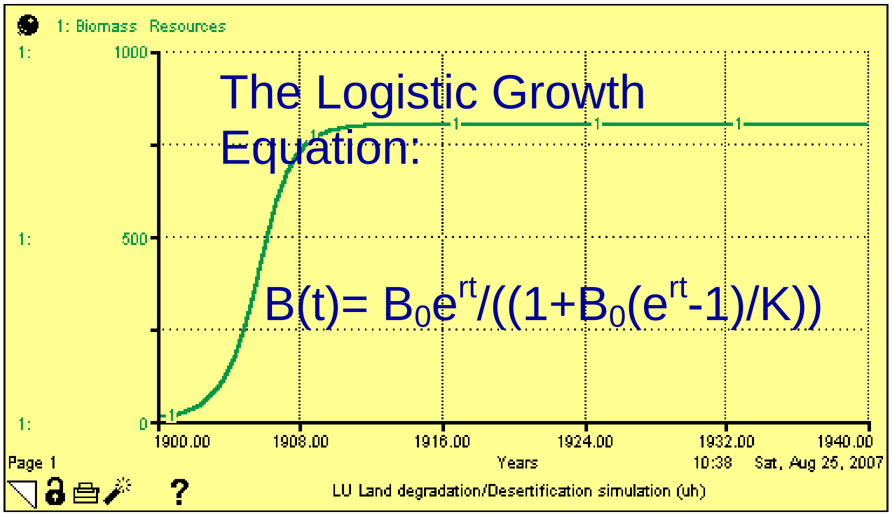


Fig. 5.2.4. The logistic growth function generated through numeric simulation with Stella applying the Series 1 density related growth rate multiplier function in Fig 5.2.3 (1900-1940). In this demonstration case we start with 1% (10 ton) out of a potential of 1000 tons and get equilibrium at about 800 tons after 8-10 years. The growth follows the Logistic growth equation (Ricklefs 1990, Ford 1999) based on the solution of the differential equation dB(t)/dt=r*B(t)*M(t);

where M=(K-B)/K corresponds to the growth rate multiplier i.e. it is a function of the biomass density.
B=Biomass stock; M=growth rate multiplier; r=growth rate; K=”carrying capacity” (1000 ton)

The growth development over time corresponds to the differential equations given in Puigdefábregas (1995) model and is explained below following a discussion of the subject presented by Ford (1999).

Assume we let A(t) stand for an area or stock of vegetation as a function of time. In the differential equations below:

K; (the carrying capacity) stands for the maximum possible area that can be covered by vegetation, or the maximum NPP of biomass that can be produced in that area (the maximum stock).

r; is the growth rate and net increase rate of vegetation when A is at zero.

dA(t)/dt = r * A(t) * M(t)
M is the growth “multiplier, M = (K-A)/K

The differential equation can be rewritten:

dA/dt = r * A * (K-A)/K

the solution (the logistic equation) is:

$$A(t) = \frac{A_0 e^{r\,t}}{1 + A_0 \left(e^{r\,t} - 1\right) / K}$$

For further information about the logistic equation and S-shaped exponential population growth, please refer to e.g. Mulligan and Wainwright (2004), Ford (1999) and Jörgensen and Bendoricchio (2001).

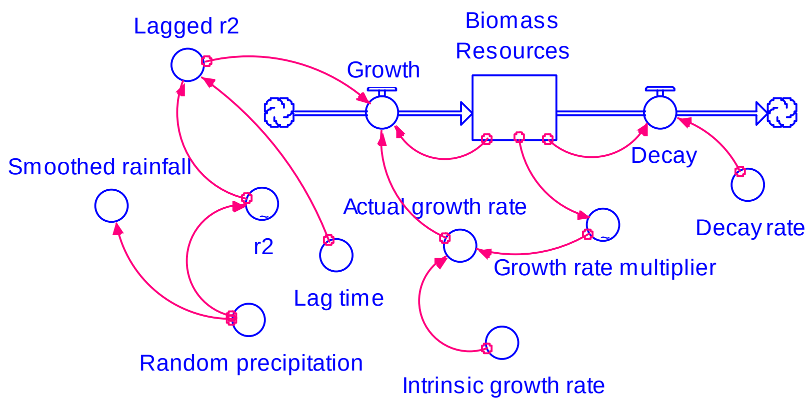
5.2.2. Rainfall impact on growth

The actual growth rate is not only dependent on the density limitation as discussed above. The *intrinsic growth*, generating the *actual growth* through a multiplication with the *growth rate multiplier*, is also very much dependent on the variability of rainfall. The rainfall in the dryland area of Kordofan, Sudan varies between 100 mm and 1000 mm/year with an estimated mean of 550 mm/year. It is generated by a random generator providing annual data between 100-1000. We assume the intrinsic growth rate, as well as the actual growth rate is close to 10 percent only of its potential when the annual rainfall approaches 100 mm and that it grows to 100 percent when the rainfall increases to1000 mm/year as illustrated in Fig. 5.2.5-5.2.6.

This is simulated by creating a *precipitation effect multiplier, r2*, which is 0.1 when the rainfall is 100 mm and 1.0 when the rainfall approaches 1000 mm. The rainfall multiplier *r2* is time lagged with a smooth function resulting in a somewhat time lagged impact of the factor. Approximately 2/3 of the impact has materialized spread over a period of 1.5 years. This is a way to simulate the impact of drought years and high rainfall extremes that are assumed to have an impact on growth rate not only the actual growing season but also to a declining extent the next one or two seasons. The time lagged *rainfall factor r2* was connected to the *growth flow* directly (multiplied with the actual growth and actual biomass stock).

An example of varying rainfall impact on the growth rate is given in Fig. 5.2.7a and 5.2.7b. It is based on the assumption of recurring long droughts and rainy periods, simulated by a sinusoidal driven function combined with random precipitation (100-1000 mm). The amplitude of the function is set to 200 mm varying around the mean annual precipitation of 550 mm. The period is set to 35 years. The accompanying multiplier graph function is illustrated in 5.2.7.a where r2 is set to 0.01 for 100 mm annual precipitation and 1.0 for 1000 mm.

LU CDM Biomass Resource Component with rainfall impact



Biomass__Resources(t) = Biomass__Resources(t - dt) + (Growth - Decay) * dt
INIT Biomass__Resources = 800
INFLOWS:
Growth = Biomass__Resources*Lagged_r2*Actual_growth_rate+10
OUTFLOWS:
Decay = Biomass__Resources*Decay_rate
Actual_growth_rate = Intrinsic_growth_rate*Growth_rate_multiplier
Decay_rate = 0.15
Intrinsic_growth_rate = 1
Lagged_r2 = SMTH1(r2,Lag_time)
Lag_time = 1.5
Random_precipitation = RANDOM(100,1000)
Smoothed_rainfall = SMTH1(Random_precipitation,5)
Growth_rate_multiplier = GRAPH(Biomass__Resources/INIT(Biomass__Resources))
(0.00, 0.315), (0.1, 0.725), (0.2, 0.895), (0.3, 0.95), (0.4, 0.925), (0.5, 0.87), (0.6, 0.805), (0.7, 0.67), (0.8, 0.445), (0.9, 0.2), (1, 0.005)
r2 = GRAPH(Random_precipitation)
(100, 0.1), (190, 0.145), (280, 0.208), (370, 0.258), (460, 0.316), (550, 0.37), (640, 0.433), (730, 0.487), (820, 0.55), (910, 0.649), (1000, 0.991)

Fig. 5.2.5. LU CDM Biomass Resource Component with rainfall impact on the growth rate.

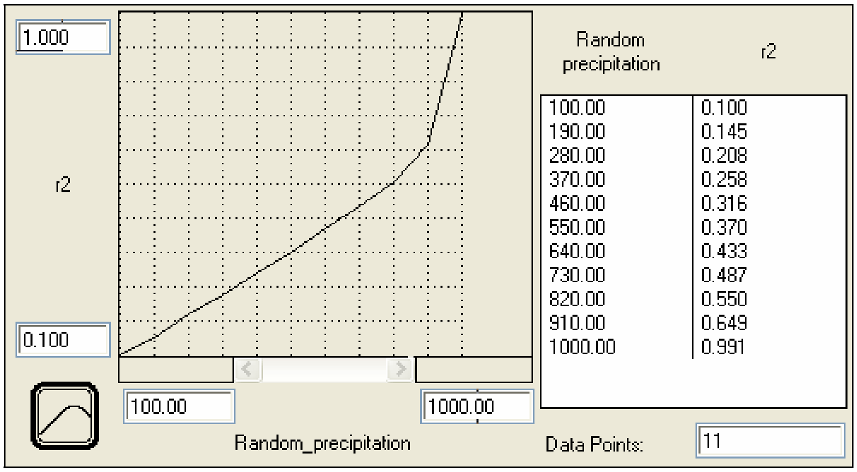


Fig. 5.2.6. LU-CDM precipitation effect multiplier, r2, plotted against annual precipitation. The multiplier graph function is defined in Fig. 5.2.5
.

A human-environment coupled model simulation is given later in the report to illustrate how a long rainy period attracts and maintains a growing population which becomes too large for the system to sustain when the rainy period turns into a long drought (Cf Fig 5.4.3).

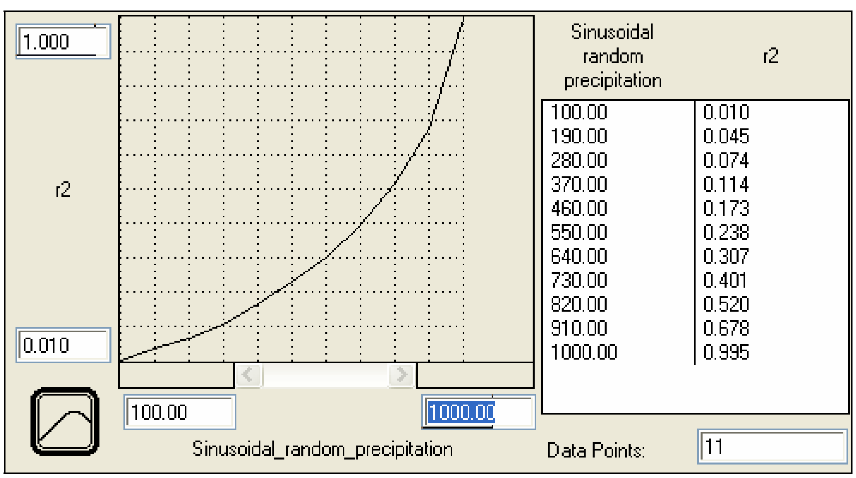


Fig. 5.2.7. a. LU-CDM precipitation effect multiplier, r2, plotted against annual precipitation. The rainfall reduction factor r2 is set to 0.01 for 100 mm annual precipitation and 1.0 for 1000 mm. The effect is illustrated in Fig. 5.2.7.b below.

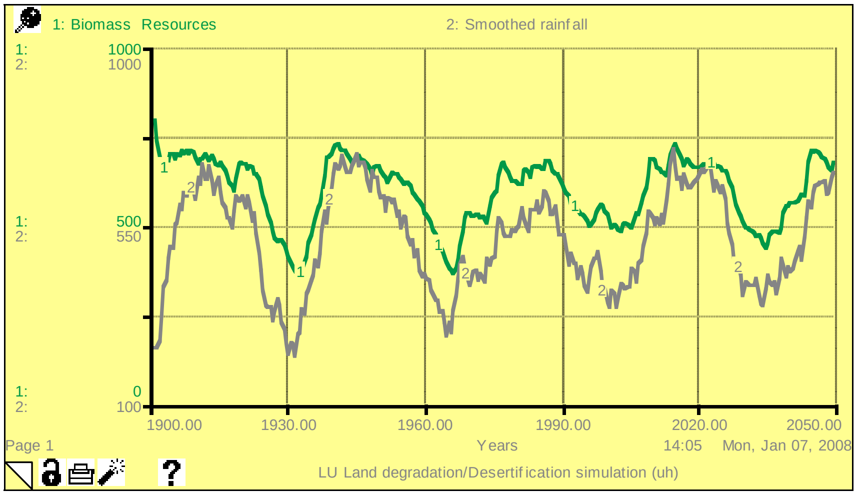


Fig. 5.2.7b. Recurring long droughts and rainy periods, simulated by a sinusoidal driven function combined with random precipitation (100-1000 mm) (1900-2050).

5.2.3. **Erosion related feedback loops caused by vegetation removal**

The over consumption related desertification syndromes have a least common denominator. They all refer to a situation where the consumption or exploitation, i.e. the removal, of local landscape generated biomass related resources (food, fodder, wood), soils or water is larger than the production over a long period of time. When referring to biomass, it leads to a decreasing vegetation ground cover in turn resulting in increased surface water runoff, accelerated soil erosion & sand mobility, loss of soil nutrients and reduced water infiltration possibly having an adverse impact on the actual vegetation growth rate.

Wind erosion operates not only by the deflation/denudation - accumulation (sand sheets and dunes covering vegetation) interactive process but also by the mere fact that no vegetation can settle and establish as long as the sand particles are moving around. In many desertification case stories, sand movement does not lead to a net annul erosion or accumulation of sand but prevents vegetation from establishment by its mere movement forward and backward.

A reduction of the biomass resources beyond a certain threshold is often assumed to generate a positive feed-back mechanism enhancing the degradation and decreasing the biomass re-growth/ regeneration capacity of the system as illustrated by the causal feedback loops in Fig. 5.2.8. The general relationship between vegetation cover and soil erosion driving the feed-back loops is illustrated by Fig 5.2.9.

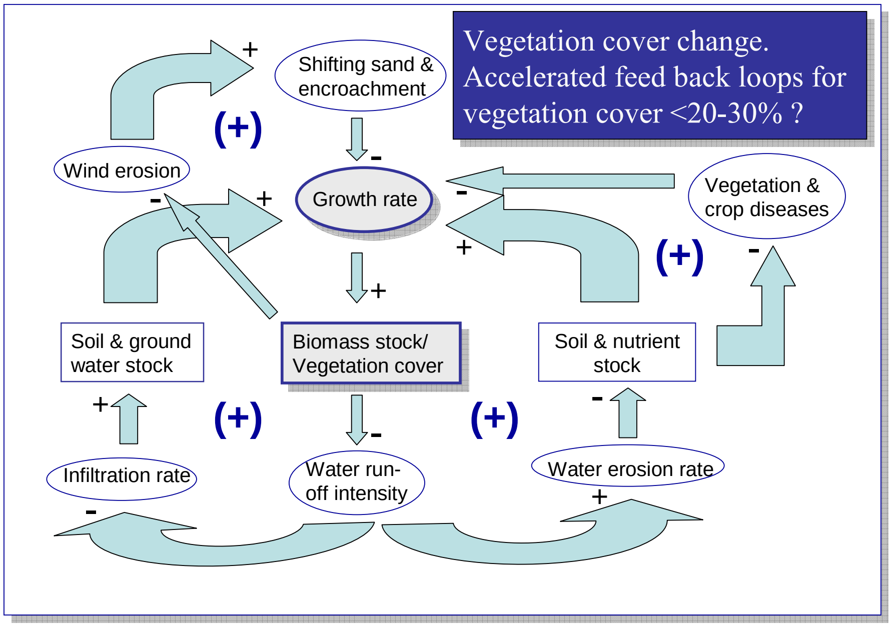


Fig. 5.2.8. Casual loop diagram indicating the feed back mechanisms involved when vegetation is removed from the stock. The four positive feedback loops (+) are assumed to accelerate when the vegetation cover/stock goes below 20-30% as indicated by the erosion-vegetation plot below.

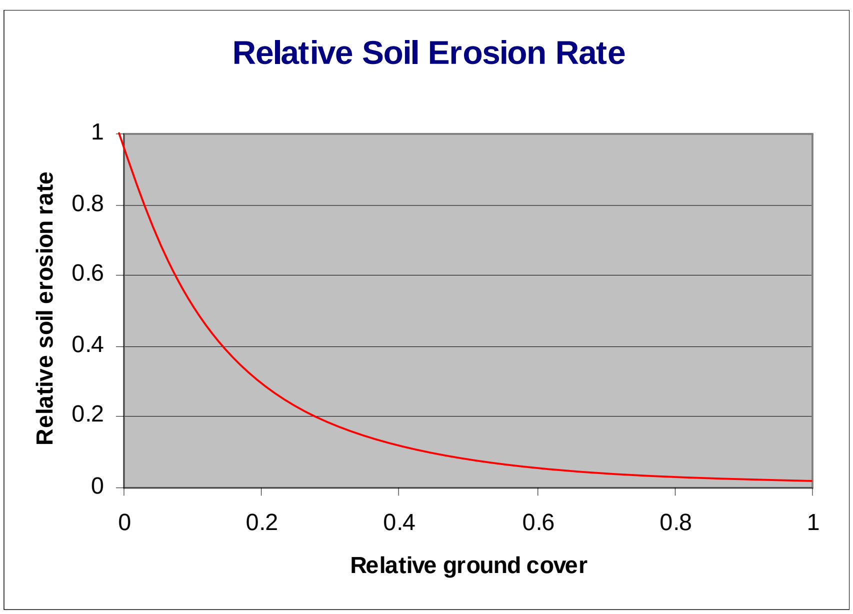


Fig. 5.2.9. Soil erosion rate plotted as a function of relative ground cover.

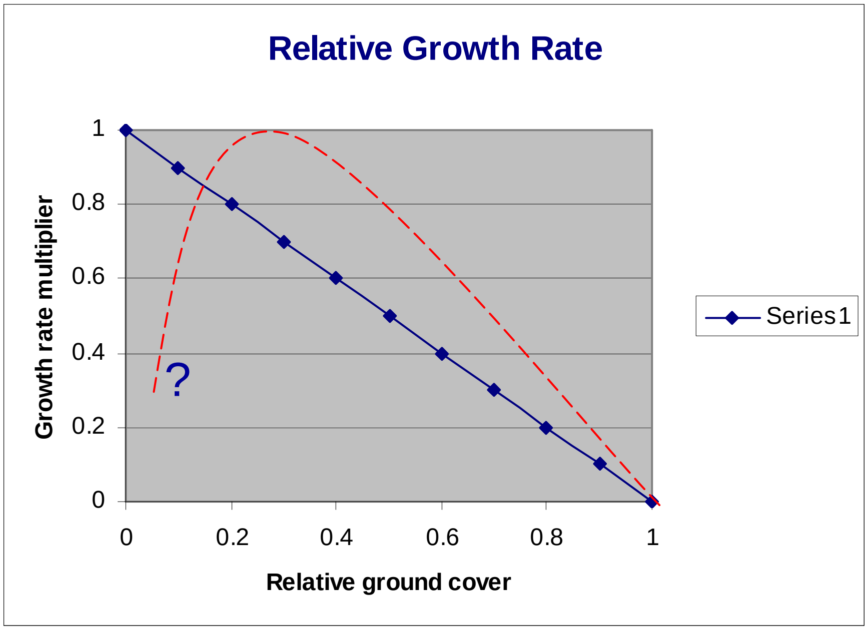


Fig. 5.2.10. The red line indicates the possible impact of the “soil erosion” feed back loops on the density dependent growth rate multiplier function. The blue line indicates the density dependent (no erosion) function of the growth rate multiplier generating a growth following the “logistic function”.

Assume the feedback loops do have an impact on *the intrinsic growth rate* and *actual growth rate* of the system. If so, the actual growth rate should be affected as illustrated in Fig. 5.2.10. When the vegetation stock and corresponding cover decreases below some 20-30% fractional cover the effect of the feedback loops will enhance the process of the vegetation decrease. This is illustrated and simulated by a considerable decrease at the beginning of the actual growth rate function. It will approach zero if the soil disappears.

5.3. The coupled system

The people in the population stock are dependent on natural resources for their survival. The rural people in a subsistence economy, i.e. a more or less closed system with insignificant import or export of capital and goods, must rely on the local production and consumption of biomass resources (food, fodder, woody biomass) for their livelihood. The annual food and fiber consumption was converted into total vegetation biomass removal, *resources consumed per person*, and set to 4000 kg/capita when there are no restrictions on the access of biomass resources (Fig. 5.3.1a).

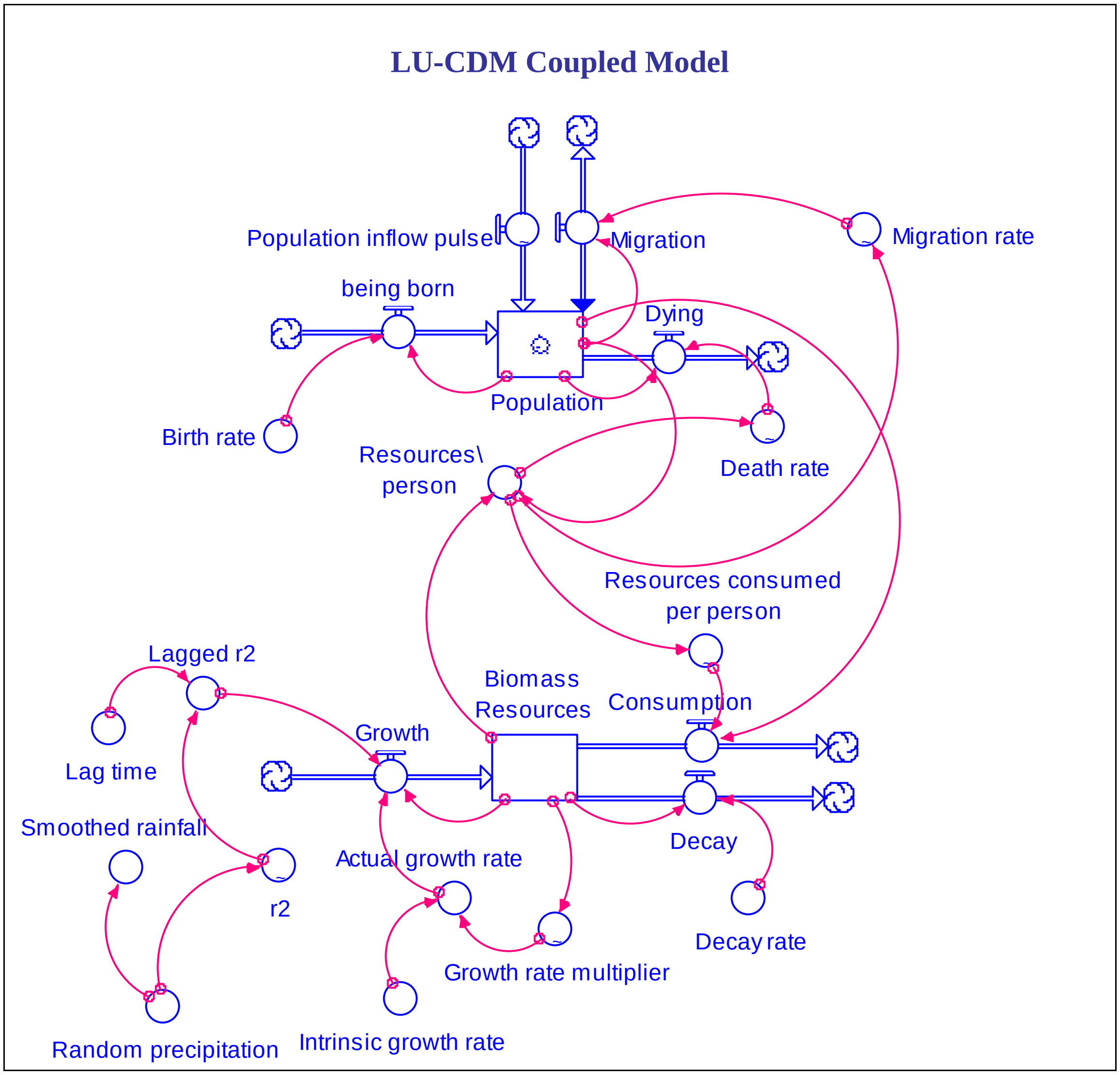


Fig. 5.3.1.a LU-CDM Coupled Model.

```
Biomass__Resources(t) = Biomass__Resources(t - dt) + (Growth - Consumption - Decay) * dt
INIT Biomass__Resources = 800
INFLOWS:
    Growth = Biomass__Resources*Lagged_r2*Growth_rate+10
OUTFLOWS:
    Consumption = Population*Resources_consumed_per_person
    Decay = Biomass__Resources*Decay_rate
Population(t) = Population(t - dt) + (being_born + Population_inflow_pulse - Dying - Migration) * dt
INIT Population = 20
INFLOWS:
    being_born = Population*Birth_rate
    Population_inflow_pulse = GRAPH(TIME)
    (1900, 0.00), (1901, 0.00), (1902, 0.00), (1903, 0.00), (1904, 0.00), (1905, 0.00), (1906, 0.00), (1907, 0.00), (1908, 0.00), (1909,
    0.00), (1910, 0.00), (1911, 0.00), (1912, 0.00), (1913, 0.00), (1914, 0.00), (1915, 0.00), (1916, 0.00), (1917, 0.00), (1918, 0.00),
    (1919, 0.00), (1920, 0.00), (1921, 0.00), (1922, 0.00), (1923, 0.00), (1924, 0.00), (1925, 0.00), (1926, 0.00), (1927, 0.00), (1928,
    0.00), (1929, 0.00), (1930, 0.00), (1931, 0.00), (1932, 0.00), (1933, 0.00), (1934, 0.00), (1935, 0.00), (1936, 0.00), (1937, 0.00),
    (1938, 0.00), (1939, 0.00), (1940, 0.00), (1941, 0.00), (1942, 0.00), (1943, 0.00), (1944, 0.00), (1945, 0.00), (1946, 0.00), (1947,
    5.00), (1948, 10.0), (1949, 20.0), (1950, 25.0), (1951, 20.0), (1952, 0.00)...
OUTFLOWS:
    Dying = Population*Death_rate
    Migration = Population*Migration_rate
Birth_rate = 0.037
Decay_rate = 0.15
Growth_rate = Intrinsic_growth_rate*Growth_rate_multiplier
Intrinsic_growth_rate = 1
Lagged_r2 = SMTH1(r2,Lag_time)
Lag_time = 1.5
Random_precipitation = RANDOM(100,1000)
Resources\_person = Biomass__Resources/Population
Smoothed_rainfall = SMTH1(Random_precipitation,5)
Death_rate = GRAPH(Resources\_person/INIT(Resources\_person))
(0.00, 0.0198), (10.0, 0.0193), (20.0, 0.0186), (30.0, 0.0178), (40.0, 0.0166), (50.0, 0.0154), (60.0, 0.0141), (70.0, 0.0129), (80.0,
0.0122), (90.0, 0.0112), (100, 0.01)
Growth_rate_multiplier = GRAPH(Biomass__Resources/INIT(Biomass__Resources))
(0.00, 0.315), (0.1, 0.725), (0.2, 0.895), (0.3, 0.95), (0.4, 0.925), (0.5, 0.87), (0.6, 0.805), (0.7, 0.67), (0.8, 0.445), (0.9, 0.2), (1, 0.005)
Migration_rate = GRAPH(Resources\_person)
(0.00, 0.44), (5.00, 0.12), (10.0, 0.055), (15.0, 0.0325), (20.0, 0.0175), (25.0, 0.00), (30.0, -0.0175), (35.0, -0.04), (40.0, -0.0525), (45.0,
-0.0625), (50.0, -0.0875)
r2 = GRAPH(Random_precipitation)
(100, 0.1), (190, 0.145), (280, 0.208), (370, 0.258), (460, 0.316), (550, 0.37), (640, 0.433), (730, 0.487), (820, 0.55), (910, 0.649), (1000,
0.991)
Resources_consumed_per_person = GRAPH(Resources\_person)
(1.00, 1.00), (10.9, 2.73), (20.8, 3.36), (30.7, 4.00), (40.6, 4.00), (50.5, 4.00), (60.4, 4.00), (70.3, 4.00), (80.2, 4.00), (90.1, 4.00), (100,
4.00)
```

Fig. 5.3.1.b. TheLU-CDM model definitions including an assumed soil erosion and land degradation positive feedback loop mechanism affecting the growth rate through the modelled growth rate multiplier.

The total per capita vegetation removal, including food (crops, animal products, vegetables, roots), fiber, woody biomass (building & energy) , i.e. human average per capita appropriation of terrestrial net primary production, was estimated by Imhof et al. (2004), Rojstaczer et al. (2001) and Vitousek et al. (1998). They provide figures varying between 4-7 tons/capita and year of dry organic matter. I selected the lower figure as representative of a low productive and poor dryland region like the North Kordofan, Sudan.

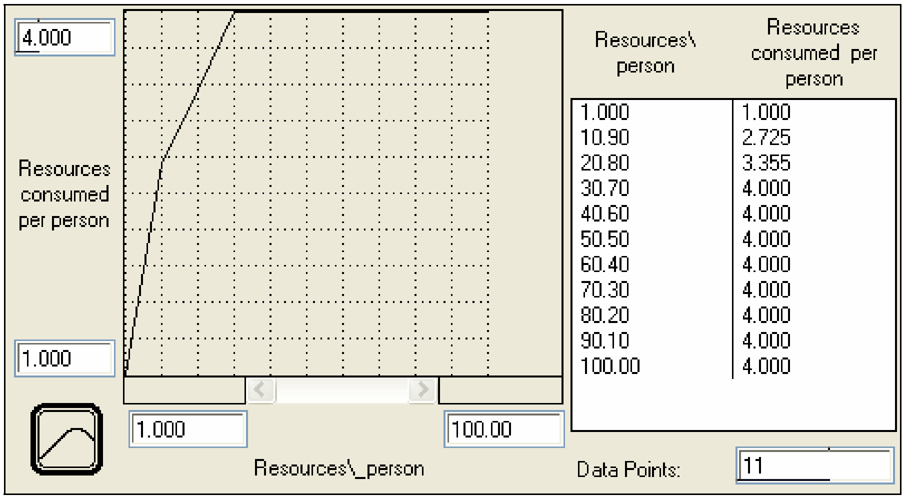


Fig. 5.3.2. The total per capita vegetation removal, including food (crops, animal products, vegetables, roots), fiber, woody biomass (building & energy), i.e. human average per capita appropriation of terrestrial net primary production, as a function of resources available per person (tons dry biomass matter/capita).

The *resources consumed per person* vary with access to resources, i.e. the size of the biomass stock, as illustrated in Fig. 5.3.2. The total removal of vegetation is set to 4 tons/capita and year when the biomass stock is full and until there is still 100 tons/person available. After that point, the consumption/vegetation removal decreases following a non-linear function. People are assumed to adapt their behavior to a consumption of 1 ton/capita and year, when the available *resources/person* decreases to 10 ton/capita and less. It implies the society is already starving and close to a serious famine.

As indicated, the coupled model keeps track on the actual resources available in the biomass stock and the size of the population through the *resources/person* converter. Besides providing information to calculate the *resources consumed/person* it also provides information and a feedback to the *death rate*. The *death rate* grows from 1 per cent to 2 per cent, following a non-linear function, as illustrated in Fig. 5.3.3. The *death rate* is set to 1% when the *resources/person* corresponds to a full satisfaction of the per capita needs, i.e. when the resources/person is 100% of the potential, and it is set to 2% when it corresponds to no satisfaction, i.e. when the supply (*resources/person*) approaches zero per cent of the potential.

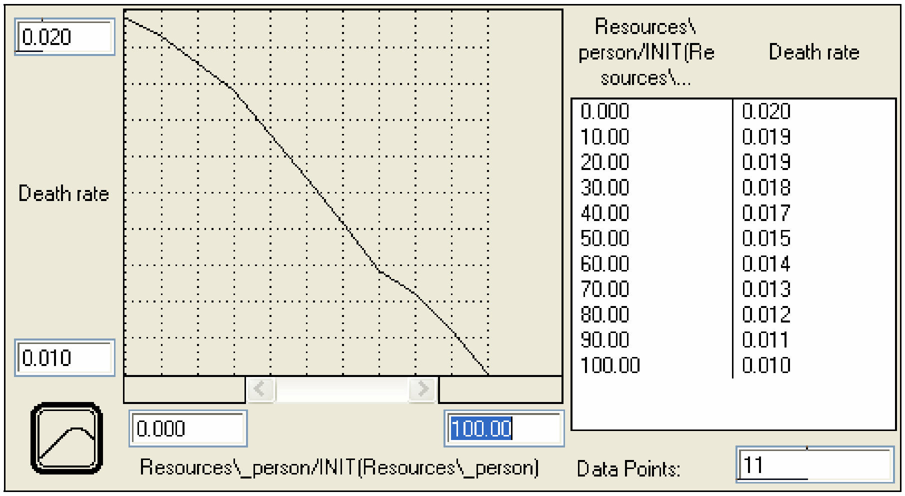


Fig. 5.3.3. Death rate (%) as a function of available resources/person. The letter is expressed in per cent of the potential.

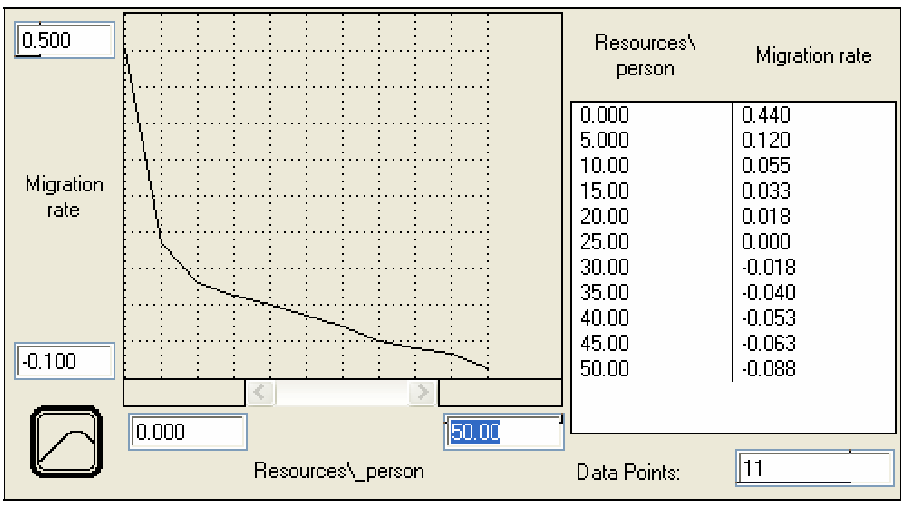


Fig. 5.3.4. LU-CDM migration rate (%) plotted against available resources/ person (ton biomass dry matter/capita). + indicates outflow and – inflow of people.

The *resources/person* converter also provides feedback to the *migration rate* converter. The *migration rate* is described as a non-linear function of the per cent of the *resources/person* (Fig. 5.3.4). In the model, there is an out-*migration flow* of people from the area when the resources are scarce and a slight in-*migration flow* of people when there is a significant surplus of available resources. The out-migration rate is set to 50% per year when the resources/ person approaches zero per cent of its full potential. The in-migration rate into the area is set to 10% per year when the resources available/person are approaching the maximum i.e. 100 per cent of its potential.

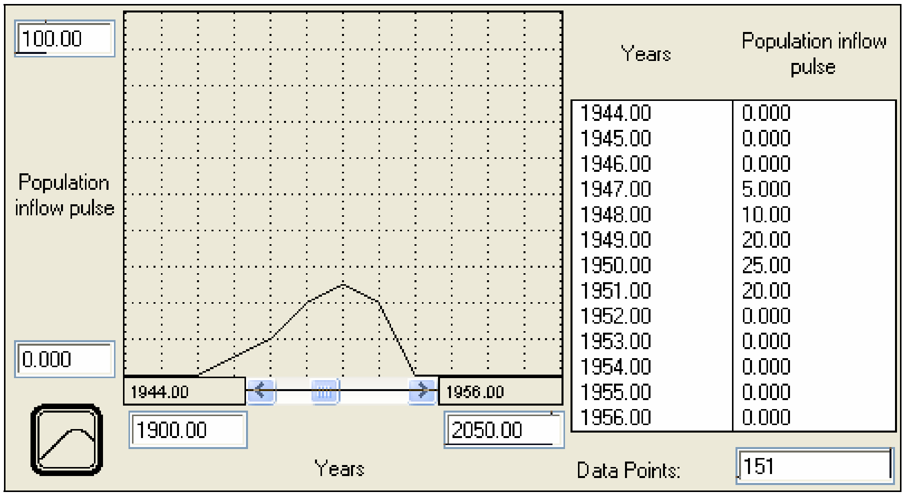


Fig. 5.3.5. A population *inflow pulse* function was added to the population module of the coupled system as illustrated by the function above.

A population *inflow pulse* function was added to the population module of the coupled system. It was added to make it possible for the model user to manipulate with additional in-migration and the optional establishment of new settlements in the area over time. For the purpose of demonstration and study of the system response, an additional 80 people were simulated to settle in the area during the period 1947-1951 as illustrated in Fig. 5.3.5. The population density increased from 20 inhabitants/km^2 in 1946 to 100 people/km^2 five years later. The impact of this population spike is obvious in all the simulations described below. The spike may symbolize a likely settlement of new people in this part of the Sahel at the beginning of the 1950´ies as a combined consequence of pilgrims' migration from West Africa towards Mecca and a favorable climate caused by a period of increasing precipitation as discussed below.

5.4. Simulations

A number of simulations are presented below in Fig 5.4.1-5.4.3. Some of them illustrate the principle difference between degradation/vegetation removal with and without the "erosion" positive feedback loops on the degradation process. Assuming there is a seed bank in the soil, a vegetation recovery will always take place. It will be delayed by the "erosion loops" but it will never go into an irreversible stage, unless the soil becomes extremely thin or ultimately disappears. A recovery of biomass followed by an establishment of a new system equilibrium is taking place as soon as the population and/or climate generated pressure on land ceases and allows it to happen. In the actual simulation cases, the population pressure decreases because people are modelled to start leaving the area when the resources are degrading and the death rate is modelled to increase. Most people are likely to eventually leave their homes for refugee camps when the resources are almost depleted and famine is a growing reality. However, most of them are likely to return to their homes when the environment conditions allow them to.

”NO EROSION”

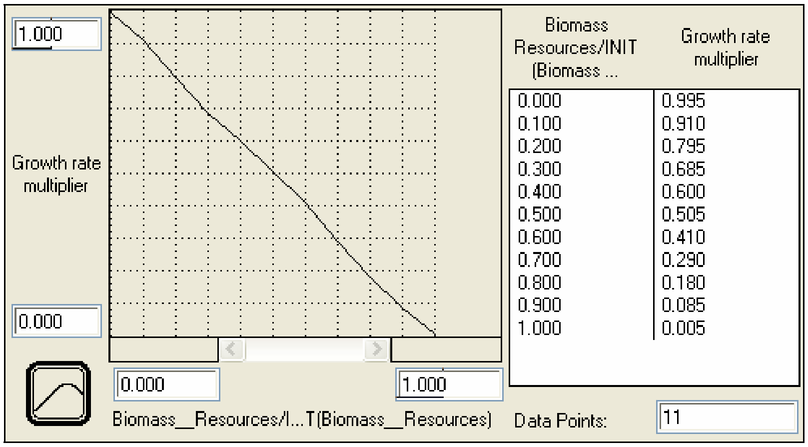


Fig. 5.4.1a. LU-CDM growth rate multiplier plotted against biomass resource illustrating a ”no erosion” case simulating the ”logistic growth”

”NO EROSION”

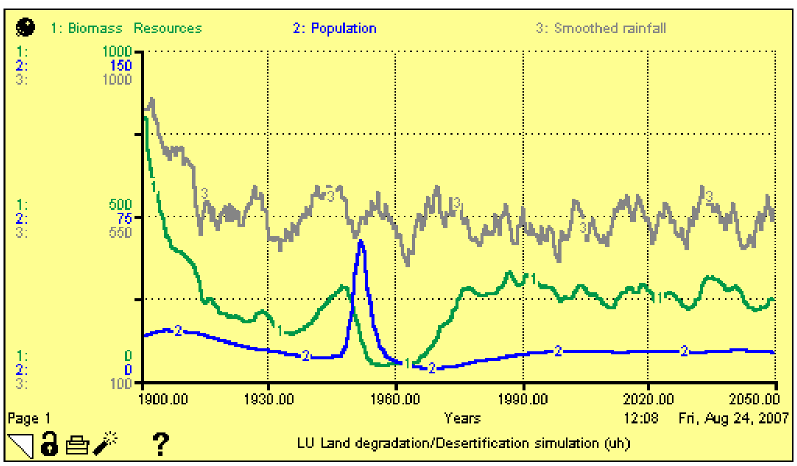


Fig. 5.4.1b. A LU-CDM example of biomass simulated development (1900-2050) for a ”no erosion” case.

”NO EROSION”

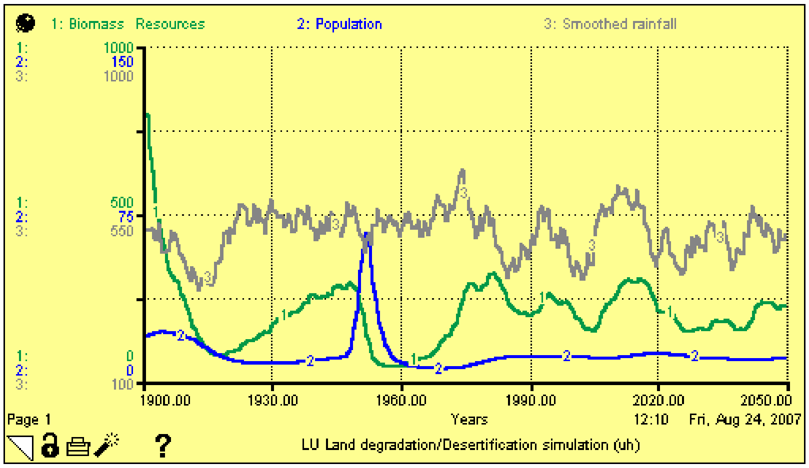


Fig. 5.4.1c. A LU-CDM example of biomass simulated development (1900-2050) for a ”no erosion” case.

”NO EROSION”

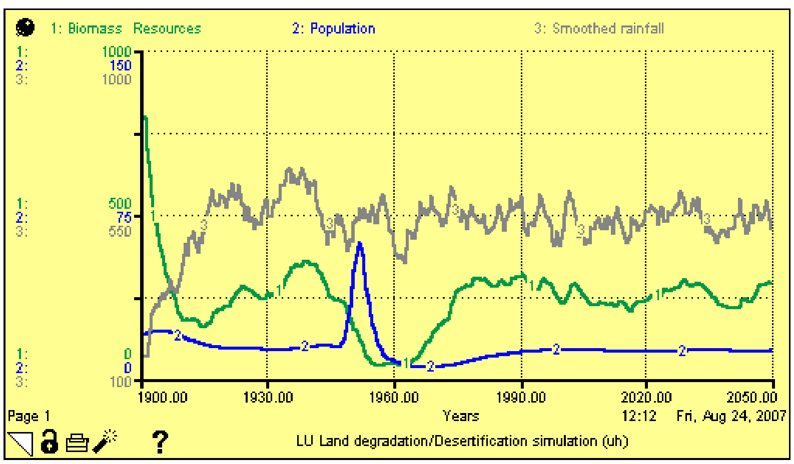


Fig. 5.4.1d. A LU-CDM example of biomass simulated development (1900-2050) for a ”no erosion” case.

”EROSION CASE”

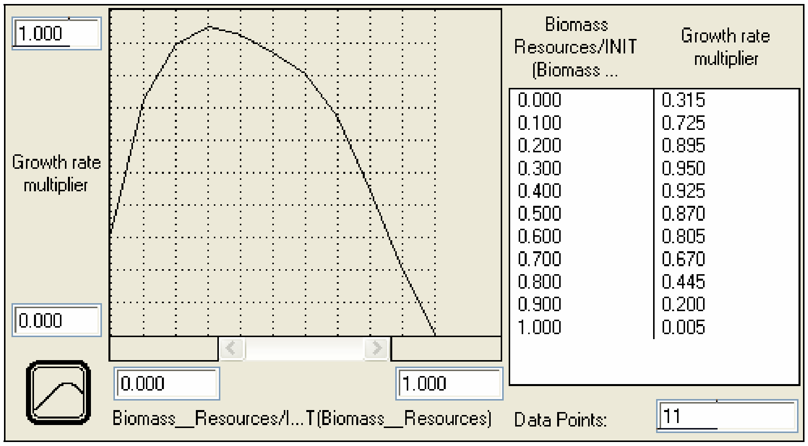


Fig. 5.4.2a. LU-CDM growth rate multiplier plotted against biomass resource illustrating an erosion case.

”EROSION CASE”

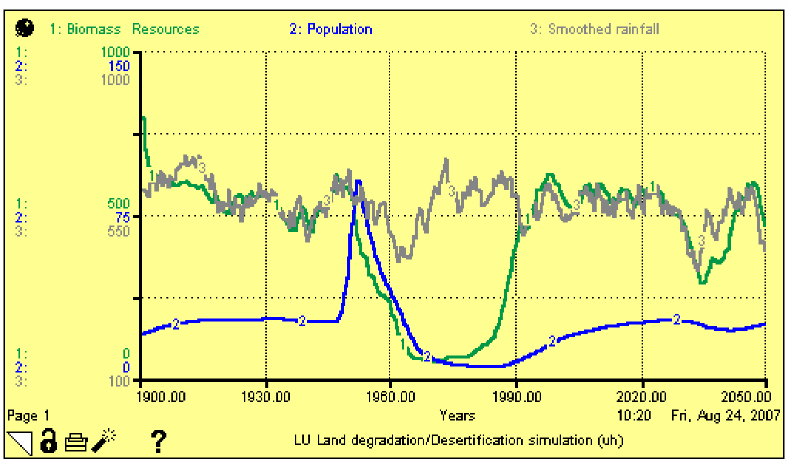


Fig 5.4.2b. A LU-CDM example of biomass simulated development (1900-2050) for an erosion case.

”EROSION CASE”

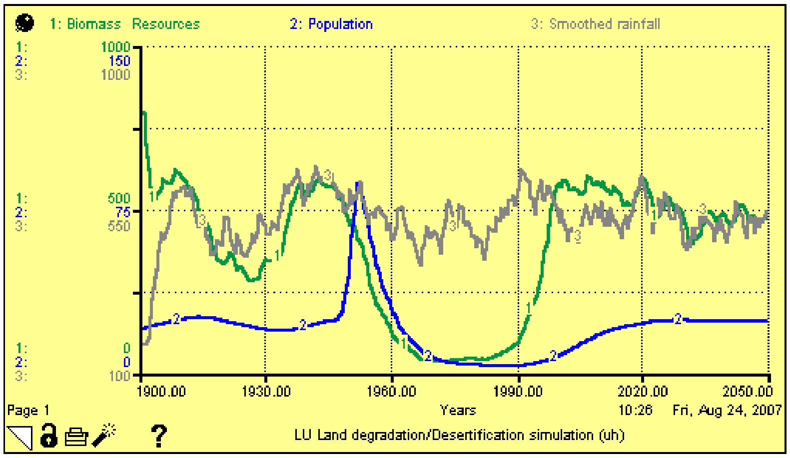


Fig. 5.4.2c. A LU-CDM example of biomass simulated development (1900-2050) for an erosion case.

”EROSION CASE”

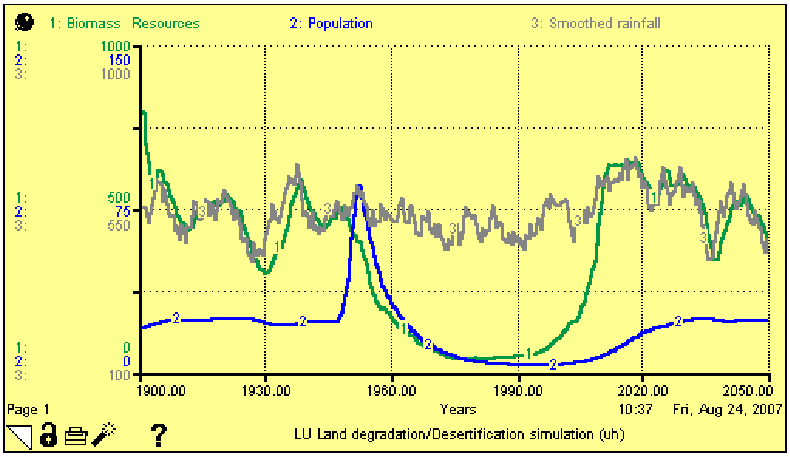


Fig 5.4.2d. A LU-CDM example of biomass simulated development (1900-2050) for an erosion case.

”EROSION CASE” and sinusoidal random rainfall simulation

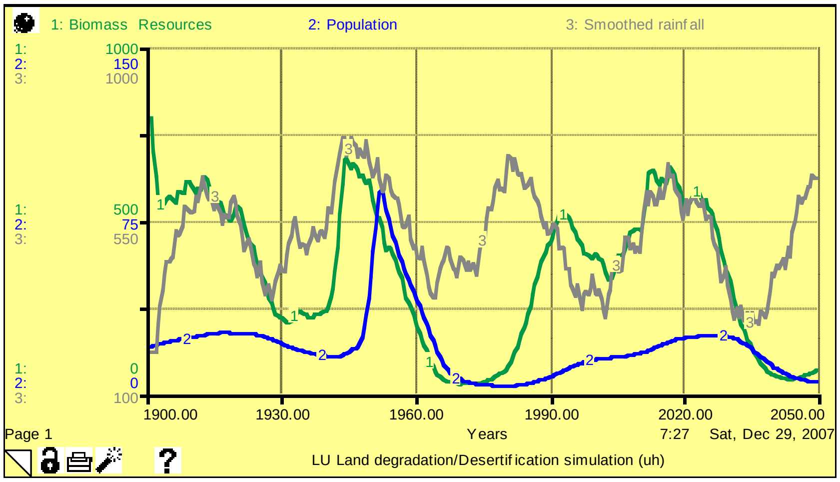


Fig. 5.4.3. The LU-CDM simulation (1900-2050) illustrates how a long rainy period attracts and maintains a growing population which becomes too large for the system to sustain when the rainy period turns into a long drought. The system resilience threshold is possibly broken by the combined effects of population pressure and insufficient rainfall, resulting in desertification and an eventual famine lasting for a long period of time (~30 years). However, the system recovers in the present coupled model. It takes place because of the built in population pressure release caused by out-migration.

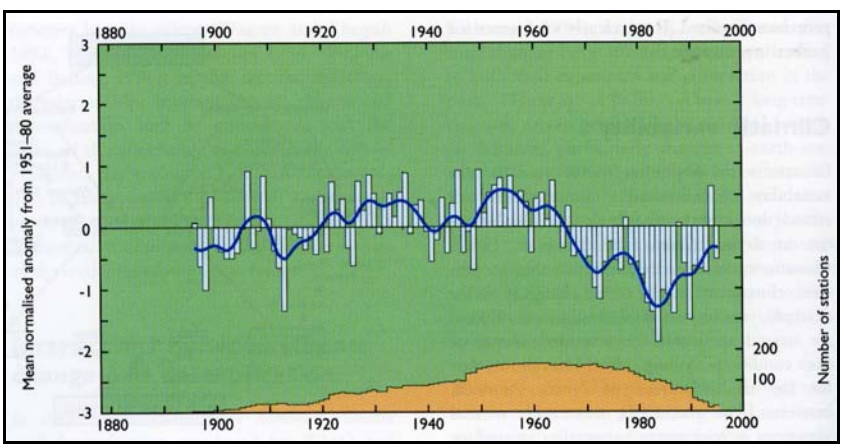


Fig. 5.4.4. Sahel annual rainfall anomalies 1896-1995 (1951-1980 mean = 524 mm). From UNEP (1997).

This is probably what happened in the Sahel during the period 1940-2003. Positive rainfall anomalies in the 1940-1950´ies attracted people and made them settle and cultivate new drylands e.g. in North Kordofan, Sudan. The long and very humid period, 1944-1963, was replaced by the long and severe Sahelian Drought. The drought lasted for more than 35 years from around 1964 to the beginning of this century. It had a major impact on the Sahel and its people and created disastrous famines around 1968-1973 and again around the driest years 1982-1983 (Cf. Fig 5.4.3 and 5.4.4). The rains have increased since then and returned to normal, i.e. average, conditions. The NPP and vegetation has recovered correspondingly as has been indicated by several recent satellite and model based studies of the Sahel (Töttrup and Helldén 2007, Eklundh and Olsson 2003, Hickler et al. 2005, Herrmann et al. 2005).

5.5. Suggested future validation and development of the model

The model will be validated against empirical data on climate variability, biomass production, resource consumption, degradation, famines and demography in several of the DeSurvey European and non-European study sites. It is likely to perform well only in recent or historic subsistence like economies. It will also be tested and adjusted further through sensitivity tests and equilibrium analysis for varying desertification syndromes.

There is a potential to develop the model and open it for simulating import and export of goods and capital, of foreign or national aid, soil conservation projects and sustainable land management activities to compensate or improve the actual land productivity. There is also a potential to develop a socio-economic and cost-benefit “push-pull and resistance” simulating component complementing the present resource density dependent migration forcing. The present model assumes that hunger rather than money is the main driving force steering the human behavior in a subsistence economy.

The model is open for possibilities to add and integrate additional levels (stocks) like ground water and soil resources. Some development is needed to have them combined with production-consumption related functions including soil erosion and soil generation e.g. to keep track on the soil stock and find ways to simulate its possible feedback to biomass production and long term vegetation carrying capacity.

6. CONCLUSIONS

The results of the model experiments indicate that it is difficult to generate irreversible desertification in a subsistence economy where there is an open market and no political restrictions on population mobility. This is true unless serious climate change and/or extremely serious soil erosion creates long term waste-land conditions leading to ultimate land abandonment. It is possible to simulate desertification, including long lasting periods of very low total biomass productivity. However, if adverse climate effects and or human induced pressure on the production system are released, the productivity of the environment will recover and new production equilibrium and stability conditions will be established. The recovery will follow the logistic growth function. The time span for recovery is some

10-40 years under the prevailing simulation conditions. Somewhat longer recovery periods are needed under "soil erosion " feedback assumptions (20-40 years) than under "no-soil erosion" re-vegetation and succession rate conditions (10-20 years) (Cf. Fig. 6.1.).

However, it should be noted that the issue of vegetation quality and palatability is not handled by the model. A possible recovery of NPP does not exclude a possible impoverishment of the environment leading to the distribution of less "useful" vegetation of "lower than before quality", e.g. resulting in decreased palatability.

The objectives of the model development and study have been achieved. LU-CDM simulates desertification and can be used as an instrument to analyze coupled human-environment system equilibrium and stability conditions under simulated and empirical conditions. It can probably be used for simulation studies of any optional desertification syndrome. LU-CDM has a high potential to be used as a decision support tool for land degradation related Sustainable Land Management (SLM) studies and applied objectives.

Fig. 6.1. Fenced grassland in Horquin Sandy Lands, Naiman County, Inner Mongolia, China. The fenced experimental plot (1 ha) was protected from grazing and cultivation during 5 years. (Photo Ulf Helldén, Oct. 1996)

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