# Rural poverty driven soil degradation under climate change: the sensitivity of the disposition towards the Sahel Syndrome with respect to climate

M.K.B. Lüdeke *, O. Moldenhauer, G. Petschel-Held

QUESTIONS-*project, Potsdam Institute for Climate Impact Research,*
*PO Box 601203, D-14412 Potsdam, Germany*
E-mail: luedeke@pik-potsdam.de

Starting from the basic assumption of the Syndrome Concept that essentially all of the present problematic civilization-nature interactions on the global scale can be subdivided into a limited number of typical patterns, the analysis of the response of these patterns (syndromes) to climate change can make a major contribution to climate impact research, surmounting the difficulties of more common sectoral "ceteris paribus" impact studies with respect to their systemic integration. In this paper we investigate in particular the influence of climate on the regional proneness or "disposition" towards one of the most important syndromes with respect to famines and malnutrition, the "SAHEL SYNDROME". It describes the closely interlinked natural and socioeconomic aspects of rural poverty driven degradation of soil and vegetation on marginal sites. Two strategies of global climate impact assessment on a spatial $0.5° \times 0.5°$ grid were pursued: a) As a measure for the climate sensitivity of the regional proneness, the absolute value of the gradient of the disposition with respect to the global field of $3 \times 12$ monthy normals of temperature, irradiation and precipitation is calculated. b) The disposition was evaluated for two different climate forecasts under doubled atmospheric $CO_2$ concentration. For both strategies two new quantitative global models were incorporated in a fuzzy-logic based algorithm for determining the disposition towards the Sahel Syndrome: a neural net based model for plant productivity and a waterbalance model which calculates surface runoff considering vertical and lateral fluxes, both driven by the set of 36 monthly climatological normals and designed to allow very fast global numerical evaluation.

Calculation (b) shows that the change in disposition towards the Sahel Syndrome crucially depends on the chosen climate forecast, indicating that the disagreement of climate forecasts is propagated to the impact assessment of the investigated socio-economic pattern. On the other hand the regions with a significant increase in disposition in at least one of the climate scenario based model runs form a subset of the regions which are indicated by the local climate sensitivity study (a) as highly sensitive — illustrating that the gradient measure applied here provides a resonable way to calculate an "upper limit" or "worst case" of negative climate impact. This method is particular valuable in the case of uncertain climate predictions as, e.g., for the change in precipitation patterns.

**Keywords:** integrated modeling, climate change impact, rural poverty, soil degradation, syndrome concept, vunerability

## 1. Introduction

In the framework of the Syndrome Concept a set of the most important problematic patterns of present-day interaction between civilization and nature on the global scale is suggested. These patterns describe several interdisciplinary and intersectoral cause-effect complexes and constitute that part of current global development which is not sustainable [1,2,3]. This development is characterized by the degradation of the natural basis for production and reproduction and increasing social disparities, including the snowballing of the number of humans unable to fulfill their basic needs. It is one major tenet of the concept to interrelate the causes and effects of the core problems of Global Change in a systematic manner and to provide robust policy advice for a transition to a sustainable development. Concerning the problem of global climate change as a major core problem, the interlinkage to syndromes is twofold:

- syndrome-specific mechanisms may contribute to climate change by, e.g., contributing to greenhouse gas emissions, or
- regions which are presently not inclined towards a syndrome may become prone to this syndrome in the course of a future change in climate (or vice versa).

* Corresponding author.

In terms of the debate on political and economic measures related to climate change, these two views respectively describe the "mitigation" or "adaption" aspects (e.g. [4]).

If it is accepted that syndromes are a reasonable description of such globally problematic civilization-nature interrelations that have so far emerged, then the response of these patterns to climate change becomes a major task of climate impact research. The main advantage of our approach compared with more common sectoral "ceteris paribus" impact studies, is that the investigation of the response of the observable and therefore non-hypothetical intersectoral structures (syndromes) to climate change surmounts the difficulties involved in later systemic integration. The question of which patterns of closely interacting elements of the social, economic and natural spheres constitute severe problems for humanity is solved in advance by the identification of the syndromes. One may argue that the emergence of totally new and dangerous problem complexes under climate change conditions could not be treated adequately by the syndromatic climate impact analysis — here in fact predictive world models based on first principles (as e.g. the rational choice assumption) would be needed. Without denying that such models would be desireable (the problems are obvious), we investigate here the less hypothetical modes of current problematic civilization-nature interaction.

In this paper we focus on the sensitivity of syndromes with respect to climate, concentrating by means of example on the climate sensitivity of the proneness or "disposition" of a region towards one of the most important Syndromes with respect to famines and malnutrition, the "Sahel Syndrome". In section 2 of this paper, the fuzzy-logic based algorithm for the Sahel Syndrome disposition introduced earlier [3,5] is modified by substituting some of the measured basic indicators and fuzzy inferences by quantitative modelling. Here two newly developed reduced-form models were applied.

In the climate change debate great emphasis is laid on the discussion of the quantitative uncertainty of GCM-forecasts; (with respect to the overall qualitative effect of enhanced greenhouse-gas concentrations in the atmosphere there is a broad consensus). On the other hand, if we have certain knowledge about problematic subsystems in the complex civilization-nature system, which react very sensitively to climate change, the question of the quantitative reliability of climate forecasts becomes less important: the necessity for adaptative measures in order to avoid damage either from a possible anthropogenic climate change, or from natural climate variability such as, e.g., the El Niño phenomenon [6,7,8] is obvious. Another important aspect is that the climate sensitivity analysis shows in which regions of the world the reliability of climate forecasts has to be improved in order to obtain important information on the impact of climate change on the civilization-nature system.

As a first step in identifying such a problematic subsystem in a geographically explicit way, we investigate in section 3 the local (in climate space) sensitivity of the Sahel Syndrome disposition for all regions of the world. Without using a climate forecast this sensitivity study yields regions which could become endangered by the Sahel Syndrome under a possible climate change (and, equally important, those which will not irrespective of the detailed nature of the climate change). Even under the assumption that climate predictions are uncertain, the study indicates where adaptive measures have to be developed and applied in order to avoid the future outbreak of the Sahel Syndrome.

With respect to the consideration of climate change, we additionally follow a conventional approach [9,10] in section 4 and evaluate the Sahel Syndrome disposition under two different climate projections for a $2\times CO_2$ atmosphere. Other than with the local sensitivity study, climate change is now finite and directed, but to some extent quantitatively uncertain. Under this restriction the resulting changes in disposition now allow regions to be identified explicitely where the situation would become worse with respect to the endangerment by the Syndrome under climate change. Comparison with the local sensitivity result allows a judgement to be made on whether the local sensitivity study yields a reasonable "upper limit" for endangered regions.

## 2. Modeling the climate dependence of the Sahel Syndrome Disposition

The main idea of identifying regions which are prone to a syndrome is to investigate whether the most important syndrome-typical interactions could become active under the natural and socio-economic conditions which prevail. Even in the regions most disposed, the syndrome does not have to be active. The actual outbreak of a syndrome in the disposed regions is caused by the so-called exposition factors. The core dynamic pattern of the Sahel Syndrome is formed by a positive feedback loop consisting of the state variables ("symptoms") rural poverty, increased agricultural activity, and soil degradation. The mechanism consists of existential rural poverty which drives farmers to overuse their lands leading to soil degradation, which reduces yields and thereby further exacerbates rural poverty as identified in several case studies in different regions of the world ([11,12,13]). For a detailed description of the whole set of symptoms involved and their interrelations see [14] in this volume. We want to stress that this is *one* (although important) pattern which is frequently accompanied by further syndromes like the Favela Syndrome and the Rural Exodus Syndrome [1]. As shown in former studies [3], the set of necessary conditions for the disposition to the Sahel Syndrome can be divided into a socio-economic and a natural dimension. The first describes the compulsion of the impoverished rural population to further intensify or expand their agricultural activities, whereas the natural dimension assesses whether such an increase in agricultural activity would damage the natural production basis, leading to a (contingently delayed) decrease in yield resulting in further impoverishment. The social dimension is sufficiently covered by the coincedence of two aspects: (1) a high dependency of the livelihood of the rural population on their own agricultural produce (in the extreme case, a *high* proportion of subsistence farming) and (2) the impossibility of escape from the disastrous circle of impoverishment and agricultural over-use due to the lack of alternative sources of income. The natural dimension on the other hand has to indicate agriculturally marginal regions, i.e. fragile regions of low productivity where even agriculture at moderate intensity on a low technological level may easily lead to natural degradation. These are characterized by unfavourable growth conditions, either constituted by poor soils or insufficient climatic conditions. Even under more favourable growth conditions regions with a high risk of erosion have to be considered as agriculturally marginal according to the above argument.

In principle every natural limitation for agriculture can be compensated by technical measures (although this frequently generates negative side effects): e. g. temperature limitation by glass houses, erosion risk by terracing and moisture limitation by irrigation. Besides the fact that some to these measures are not tractable in subsistence farming, they differ in their relation to further natural prerequisites. In the case of irrigation, the vicinity of fresh water sources is such a natural prerequisite (again in the context of subsistence farming) while building and maintenance of terraces in slopy regions is rather unconnected with other natural conditions. (The limiting factor here is, e.g., labor availability.) Therefore factors like surface water availability have to be included into the natural dimension of the Sahel Syndrome disposition, while terracing as a specific method of agricultural management has not.

### *2.1. The qualitative part of the Model*

To formalize the qualitative arguments introduced above on the global scale, a fuzzy-logic algorithm is applied which allows the qualitative reasoning to be mapped using quantitative indicators and avoids the need for explicit quantitative modeling on the basis of uncertain parametrization (Fig. 1).

A detailed description of the natural dimension part of the algorithm is given in [5] including also the fuzzyfication details, i.e., the details of the functions converting quantitative data into a fuzzy logic truth value. Furthermore the results were tested extensively against available regional case studies yielding good agreement [5]. The main elements of this algorithm are linguistic variables (e.g. "climate conditions", "proportion of subsistence farming"), further characterized by linguistic categories (e.g. *insufficient, high*). These logical clauses (e.g. "erosion risk is *high*") are assigned continuous truth values $\mu$ between 0 (false) and 1 (true), which allow for an appropriate mapping of quantitative indicators (e.g. slope) on the qualitative linguistic category. The continuous truth value concept requires the extension of the boolean AND and OR operators which is not unique and has to be adapted to the semantics of the respective connective [15]. The AND connective can, for example, be realized by the minimum of the two truth values where the lowest truth value strictly limits the result (independent of a second truth value possibly near 1). This property is often not the appropriate translation of linguistic expert rules and a slightly compensative character is required. This is, e.g., the case in combining the natural and socio-economic dimension

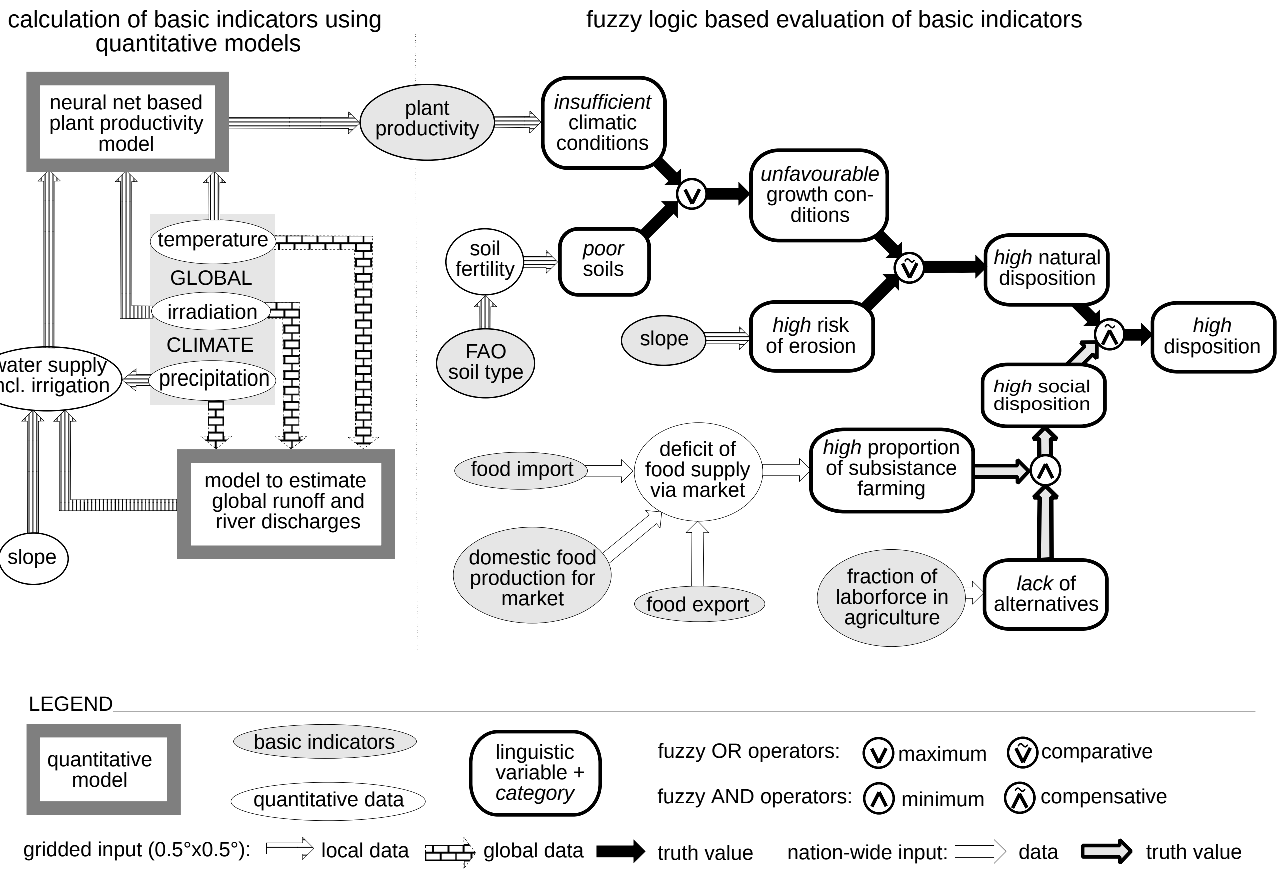


Figure 1. Structure of the algorithm for calculating the disposition towards the Sahel Syndrome, using elements of qualitative and quantitative modelling.

of the disposition where it is clear that under a medium natural proneness the truth value for "*high* disposition" will be enhanced to some extent by a extremely high socio-economic dimension of disposition. Here we use a parametrized operator, the so called $\gamma$-operator, which allows the compensative AND ($\gamma$ near 0, in this case $\gamma = 0.2$ which introduces the intended compensative effect while preserving clearly the characteristics of an AND) to be described.

$$\mu_{A \tilde{\wedge} B} = (\mu_A \cdot \mu_B)^{1-\gamma} \left[1 - (1-\mu_A)(1-\mu_B)\right]^{\gamma} \quad (1)$$
$$0 \leq \gamma \leq 1$$

The same operator (now with $\gamma = 1$) is used to describe the comparative OR connective between unfavourable growth conditions and high risk of erosion: under a medium risk of erosion favourable growth conditions reduce the natural disposition slightly - an effect which could not be described with the simple maximum operator.

A first version of the socio-economic dimension of the Sahel disposition is introduced in [3]. In the present paper we adopt the global determination of the truth value for a *high* proportion of subsistence farming which was derived from the difference between minimum domestic food demand and food supply via the market and combine it according to the above discussion with the *lack* of alternatives for the rural population with an AND operator. We use here the fraction of total labor force employed in the first sector as basic indicator and value the "*lack* of alternatives" as false ($\mu = 0$) up to 10% , as true ($\mu = 1$) from 20% on and interpolate linearly for the remaining values.

### *2.2. The quantitative part of the Model*

In the version of the algorithm for the detection of disposition to the Sahel Syndrome published so far [3], the choice of basic indicators has aimed at the description of the disposition under present-day conditions. Under the perspective of climate change, some alterations are necessary which do not change the underlying ideas of the measurement but operationalize them in a way that allows for the investigation of climate sensitivity and climate scenarios.

The assessment of "*insufficient* climate conditions" which was based

- on a global best-guess field for current net primary productivity of natural vegetation,
- on an independent global field for aridity to identify areas for potential irrigation and
- on the present-day global surface water network in order to assess the potential for irrigation at a low technological level

had therefore to be revisited and the fuzzy combination of these single influencing factors was substituted by a quantitative, model-based description which considers that these factors are all interlinked via basic climate elements and therefore evolve under climate change in a correlated manner. The revised algorithm is based on two reduced-form models developed recently at PIK: NNN, a neural net based model for determining the annual productivity of natural vegetation developed by Moldenhauer and Lüdeke (see appendix A) and the MEGARUS model for determing annually available renewable fresh water considering lateral fluxes of Petschel-Held (see appendix B). Both depend on monthly normals of temperature, precipitation and sunshine hours and allow very rapid numerical evaluation, which is the condition keeping the extensive sensitivity calculations manageable.

Now let $\vec{C}^g = (C_1^g, \ldots, C_c^g, \ldots, C_{36}^g) = \left(\vec{T}^g, \vec{P}^g, \vec{I}^g\right)$ be the vector of monthly climate normals at grid element $g$ ($g = 0, \ldots, G$), consisting of the vectors of temperature, $\vec{T}^g = \left(\vec{T}_1^g, \ldots, T_m^g, \ldots, T_{12}^g\right)$, precipitation, $\vec{P}^g = \left(\vec{P}_1^g, \ldots, P_m^g, \ldots, P_{12}^g\right)$, and sunshine hours, $\vec{I}^g = \left(\vec{I}_1^g, \ldots, I_m^g, \ldots, I_{12}^g\right)$, with $m = 1, \ldots, 12$ denoting the number of the month. Then the natural annual equilibrium primary plant production at grid element $g$, $NPP^g$, is given by the NNN model

$$NPP^g = NPP\left(\vec{C}^g\right) \tag{2}$$

The annually available surface water at grid element $g$, $F^g$, is given by the MEGARUS model (Appendix B)

$$F^g = F^g\left(\vec{C}^1, \vec{C}^2 \ldots \vec{C}^{62483}\right) = \sum_j L_{j,g} \cdot R^j\left(\vec{C}^j\right) \tag{3}$$

where $R^j$ is the annual equilibrium runoff as calculated with a vertical water balance model (neglecting lateral fluxes between grid elements) and $\mathbf{L}$ is the (sparsely occupied) matrix representing lateral fluxes between grid elements.

Different from NPP the local freshwater availability not only depends on the local climate but can also depend on the climate upstream of a specific position. In a next step we define a modified precipitation vector for grid element $g$ which includes easily installable irrigation as a function of available water, $F^g$, and the average slope

$$P_m'^g = P_m^g + f\left(S^g\right)\frac{F^g}{12} \quad . \tag{4}$$

Where $S^g$ is the mean slope of grid element $g$, and $f(S)$ is the fraction of $F$ which can be easily used for irrigation. This fraction will generally decline with increasing slope. On the low technological level we have to consider in the context of the Sahel Syndrome, even in flat regions ($S \approx 0\%$) not more than about a quarter of the total annually available surface water can be used for irrigation ([18]). It can be inferred from comparison of the global distribution of mean slope ($0.5° \times 0.5°$ resolution) with existing irrigation systems that for mean slopes greater than 0.5% irrigation becomes very labor and capital intensive. – Therefore we defined f(S) as a linear function decreasing from $f(0\%) = 0.25$ to $f(0.5\%) = 0.01$ and $f(S > 0.5\%) = 0.01$. Here we allowed even for $S > 0.5\%$ a small fraction of surface water to improve the plant's water supply, thereby accounting for occasionally occuring irrigation possibilities. However, we tested different values for $f(0.5\%)$ between 0.005 and 0.05 and found no significant difference in the disposition and its sensitivity.

The possibly enhanced water supply $P_m'^g$ is now taken as an input for the neural net model, resulting in the basic indicator "plant productivity", to be mapped onto the truth value of the clause "*insufficient* climatic conditions". This indicator is the interface between the quantitative part of the disposition model (left-hand side of figure 1) and qualitative part (right-hand side of figure 1), fuzzyfication is performed in the same way as for net primary production in [5].

The disposition towards the Sahel Syndrome at grid element $g$, $D^g$, or put more mathematically, the truth value of the clause “disposition is *high*” with respect to its climate dependence can now be written as follows

$$D^g = \mu^g \left[ NPP\left( \vec{T}^g, \vec{P}'^g \left( F^g, \vec{P}^g \right), \vec{I}^g \right) \right] \quad (5)$$

where $\mu^g$ is the function to calculate the disposition at a given grid-element. It includes all climate-independent natural and socio-economic aspects of disposition as described in [5,3] and illustrated in figure 1. Through the irrigation aspect the calculation of the disposition $D^g$ becomes non-local, which means that $D^g$ depends also on climate vectors of further grid elements which lie upstream.

The above formula was evaluated on the basis of the CLIMATE 2.1 climatology on a spatial scale of $0.5° \times 0.5°$ and the global result is displayed in figure 2, showing that the performed revision of the algorithm perfectly reproduces the former result [3] for the present-day climate except in those regions where some obvious shortcomings occurred, e.g., the non-vanishing disposition in some northern OECD countries (e.g. Canada and Japan) are now removed by improving the socio-economic indicators to the version shown in figure 1.

To verify the displayed result, it was checked for consistency against the present occurrence of the Sahel Syndrome [14]. In regions which are not disposed according to the above algorithm, the syndrome should not be found to be active. We were able to show that this condition is almost completely fullfilled. Furthermore, we compared regions with a high natural disposition according to the algorithm with various case studies in which soil erosion events under low technology agriculture are indicated and, again, found a good coincidence [5]. The time interval during which the factors not endogeneously modeled are assumed to stay constant is mainly limited by the socio-economic indicators, amounting to some decades while the natural part of the disposition should vary more slowly (centuries). From this follows that the climate-dependence of the disposition as calculated here should be valid also on a time scale of decades.

## 3. Local sensitivity analysis of the Sahel Syndrome disposition with respect to mean monthly climate variables (temperature, precipitation and sunshine hours)

We define the climate sensitivity of the Syndrome disposition as the absolute value of the gradient of the disposition at one location with respect to all influencing climate elements. The gradient indicates the direction and value of the maximum slope of the scalar field $D^g$ and is therefore a measure for the upper limit of sensitivity which would be realized in the case that the direction of climate change is parallel to the gradient (i.e. a worst case estimation). A crucial point in multi-dimensional assessments is the relative weighting of the different dimensions. Important for the magnitudes of the weights assigned for each variable in a study concerned with climate change are not their absolute values, but their potential to change in the future. When we take the current variation in these variables over the world as a first approximation for this potential, we arrive at expressing temperature, precipitation and sunshine hours in units of the standard deviations $\sigma_c$ of their respective global distributions (z-norm).

Let $\mathbf{C}$ be the $36 \times 62483$ global climate matrix consisting of the column vectors $\vec{C}^g$. Then straightforward differentiation of equation (5) to calculate the magnitude of the gradient, $|\nabla_{\mathbf{C}} D^g|$, yields

$$\begin{aligned} |\nabla_{\mathbf{C}} D^g| &= \left| \frac{\partial \mu^g}{\partial NPP} \right| \cdot |\nabla_{\mathbf{C}} NPP^g| \\ &= \left| \frac{\partial \mu^g}{\partial NPP} \right| \left( \sum_{c=1}^{36} \sigma_c^2 \left[ \left( \frac{\partial NPP^g}{\partial C_c^g} + \frac{\partial NPP^g}{\partial F^g} L_{g,g} \frac{\partial R^g}{\partial C_c^g} \right)^2 \right.\right. \\ &\quad \left.\left. + \sum_{k=1;k\neq g}^{G} \left( \frac{\partial NPP^g}{\partial F^g} L_{k,g} \frac{\partial R^k}{\partial C_c^k} \right)^2 \right] \right)^{1/2} \end{aligned} \quad (6)$$

where the first term in square brackets stands for the explicit local dependency of *NPP* on the climate element $C_c$ and the influence of the local water balance on the possibility of irrigation, while the second term describes the influence of irrigation on *NPP* via surface water inflow, which depends on the climate sensitivity of the water balance of all up-stream grid elements. The necessity of using the reduced-form models described in the appendix to keep the calculations manageable becomes clear when it is considered that in the case of the plant productivity model NNN $12 \times 3$ partial

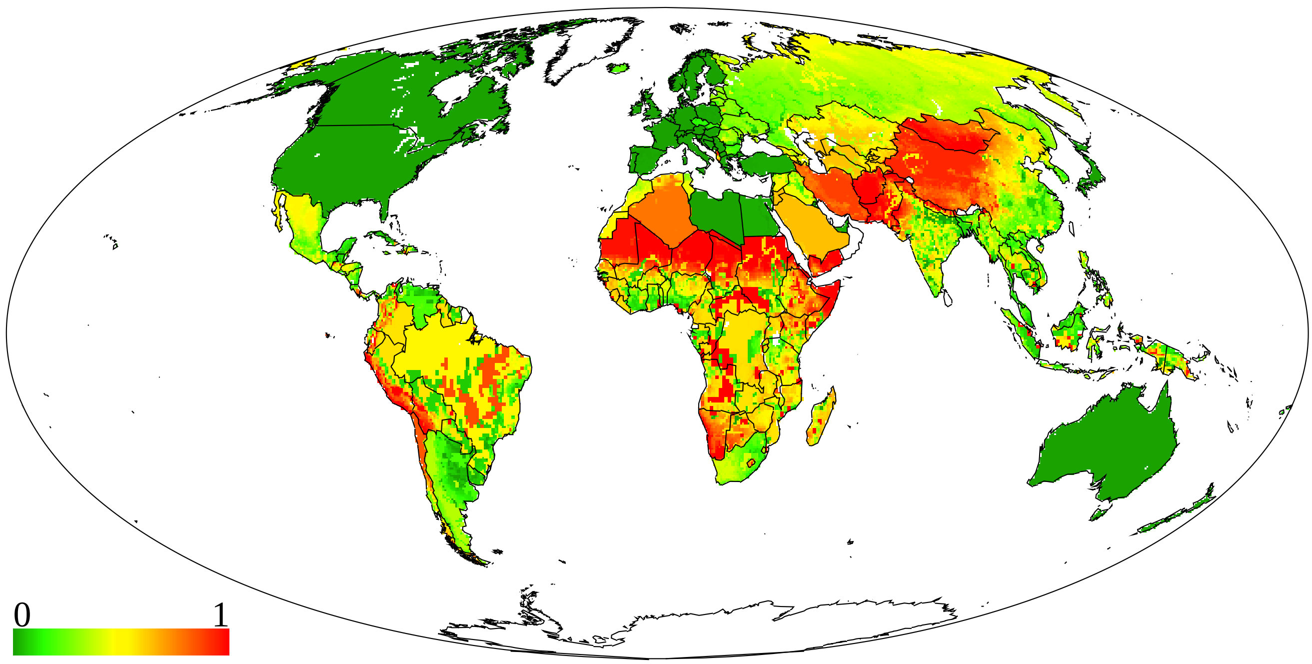


Figure 2. Disposition towards the Sahel Syndrome under the present climate (truth value for "disposition is *high*").

derivatives at 62483 grid elements are required and, in principle, due to the non-locality induced by the lateral fluxes for the water availability model $12 \times 3 \times 62483$ partial derivatives at 62483 grid elements again have to be calculated. (This is fortunately reduced greatly by the global watershed structure).

In figure 3 the above sensitivity measure is displayed, showing a very high sensitivity of the disposition towards the Sahel Syndrome with respect to climate for regions in Mexico, Brazil, Bolivia and Paraguay. In Africa Morocco, Algeria, the Sahel region counties Guinea, Mali, Burkina Faso, Niger, Chad, Sudan, the east African countries Kenya and Tanzania, Mozambique, Madagascar and Zimbabwe show highly sensitive regions. In Asia major parts of India and regions of Iran, Afghanisthan, Pakistan, Myanmar, Thailand, China, Cambodia and the Phillipines are sensitive.

A significant contribution of the non-local effect (which is due to water transport) to the overall sensitivity occurs only in some small regions, e.g. around the lower reaches of the Irtysch (Kazakhstan). This does not mean that in general surface water availability is insensitive to climate change: all downstream areas show a high sensitivity caused by the integrated local upstream sensitivities. But in the case of the SAHEL SYNDROME mechanism, where only simple irrigation technology is considered (e.g. no long-range water transport), this downstream sensitivity hardly affects the disposition to the SAHEL SYNDROME, due to a high availability of fresh water in the downstream areas in general. On the other hand, in regions of low surface water availability where a change in the irrigation possibilities could influence the disposition significantly, the non-local effect is typically small either because of upstream location or even because of small internal basins.

Now it is of particular interest to identify regions which are highly sensitive and at the same time show a low-to-medium disposition at present. Here climate change could induce a qualitative change of the present situation: regions which are not or just slightly endangered by the pattern of rural poverty driven natural degradation could become highly endangered under climate change. To formalize this argument we map the sensitivity measure onto the truth value $\mu^g\begin{pmatrix}\text{high}\\\text{sensitivity}\end{pmatrix}$ for the clause "sensitivity is *high*" with a linear ramp function and combine it with the truth value for NOT "disposition is *high*" with a fuzzy AND connective to obtain the truth value for the clause "possibly *newly* endangered under climate change":

$$\mu^g\left(\begin{pmatrix}\text{high}\\\text{sensitivity}\end{pmatrix}\wedge\neg\begin{pmatrix}\text{high}\\\text{disposition}\end{pmatrix}\right)$$

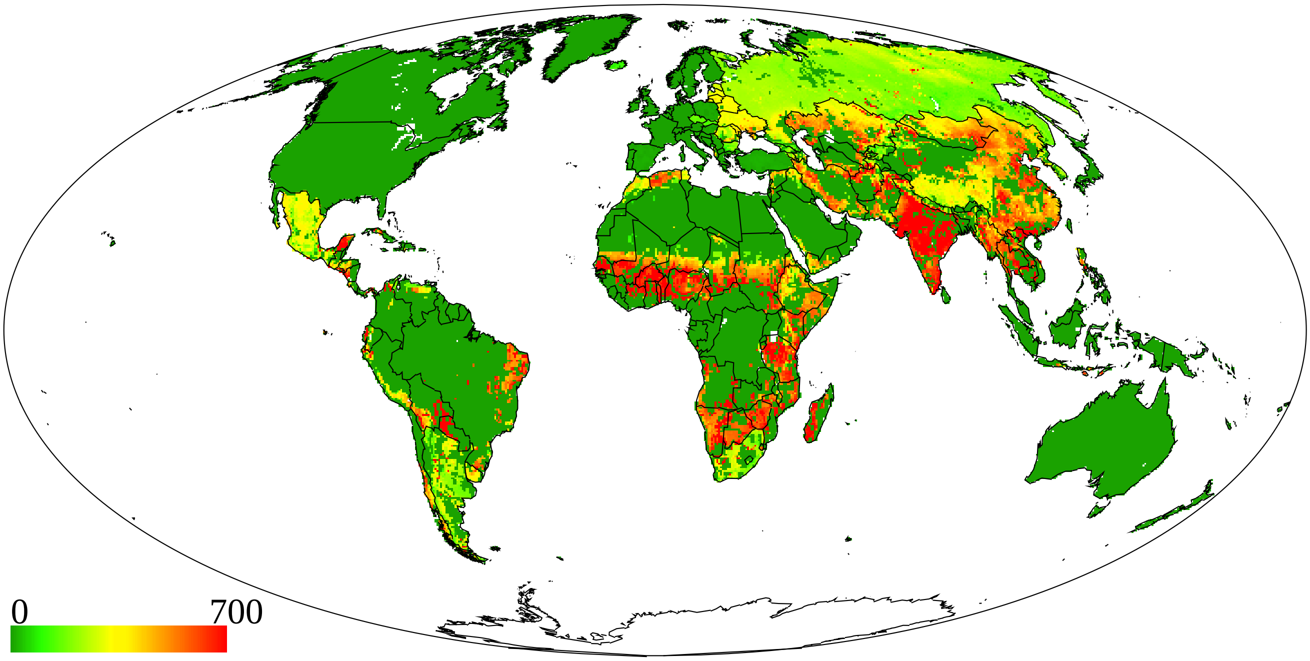


Figure 3. Climate sensitivity of the disposition towards the Sahel Syndrome $[1/\sigma]$

$$= \min\left(\mu^g\left(\begin{matrix}\text{high}\\\text{sensitivity}\end{matrix}\right), 1-\mu\left(\begin{matrix}\text{high}\\\text{disposition}\end{matrix}\right)\right) \quad (7)$$

The result of the above evaluation is displayed in figure 4, which summarizes the worst case interpretation of our sensitivity study: regions with possibly significantly increasing or newly emerging problems with respect to Sahel Syndrome disposition under climate change are Yucatán (Mexico), Bahia (Brazil), the region around the border between Bolivia and Paraguay, the north of Morocco and scattered regions in several west African countries, Tanzania, Madagascar, India, Myanmar, Thailand, Cambodia and Indonesia. In the sense of a risk-averting strategy, prophylactic measures are required in all regions with a high disposition, especially if they are densely populated. However, here we want to put here special emphasis on the regions indicated in figure 4 since they are not traditionally prone to these problems and could therefore be overlooked. These prophylactic measures may either aim at the strict avoidance of exposition factors which are defined as those able to start the syndrome in a disposed region (e.g. civil wars, forcing nomads to a sedentary lifestyle, drastic changes of terms of trade), or, as a certainly more robust measure, changes of relevant disposition factors (e.g. improvement of soil properties, development of the second and third sector to establish alternative sources of income).

## 4. Evaluation of the Sahel Syndrome Disposition under a double $CO_2$ climate

Now we evaluate the Sahel Syndrome disposition according to equation (5) under two different climate projections for a $2\times CO_2$ atmosphere, firstly the ECHAM3 result from the MPI for Meteorology in Hamburg [19] and secondly a recent prediction from the Hadley Centre [20]. The interpolated version of these results was provided by W. Cramer ([17]).

Other than with the local sensitivity study in section 3, climate change is now finite and directed. In figures 5 and 6 the difference between the disposition under the respective climate change predictions and the present disposition are displayed. These results now allow regions to be identified explicitly where the situation would become worse with respect to endangerment by the Syndrome under climate change. Comparing the two results yields a similar pattern at first glance, in particular with respect to regions where the disposition remains constant (white areas). Also both evaluations show an improvement of the situation in the northern parts of Eurasia. However, a closer inspection shows significant differences, even in sign! So the ECHAM-based disposition prognosis predicts major regions of

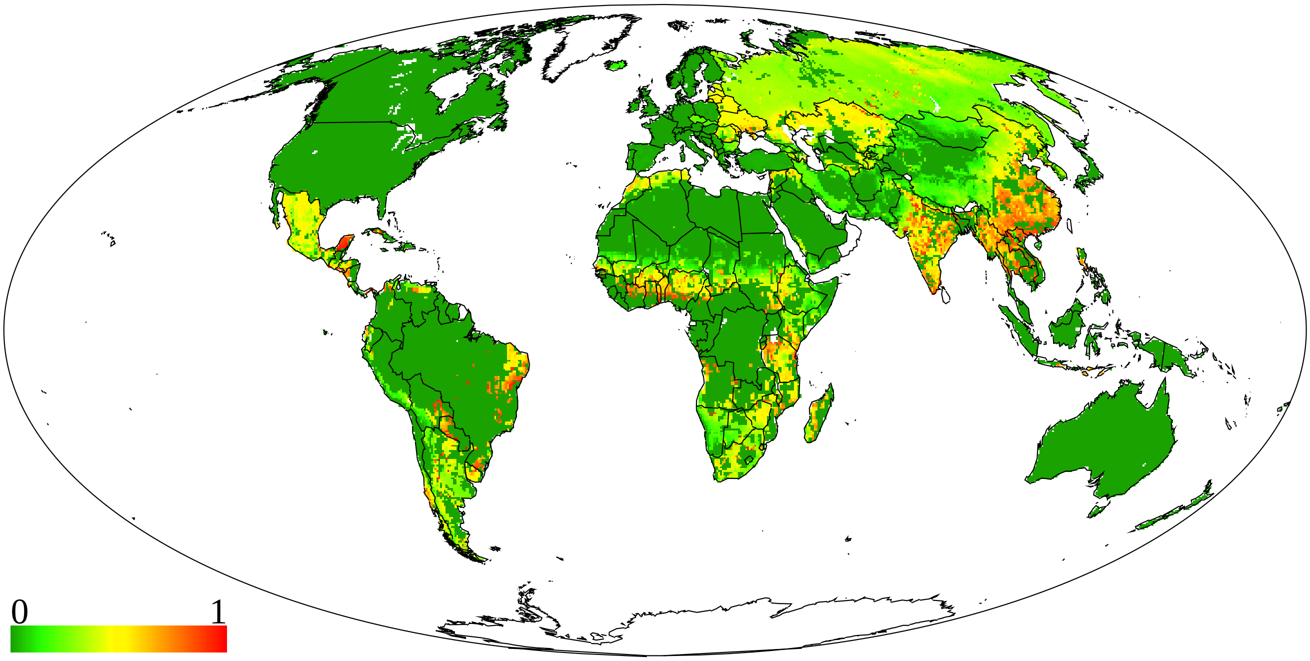


Figure 4. Regions endangered by a qualitative change under climate change: truth value for "presently *low* disposition and *high* climate sensitivity"

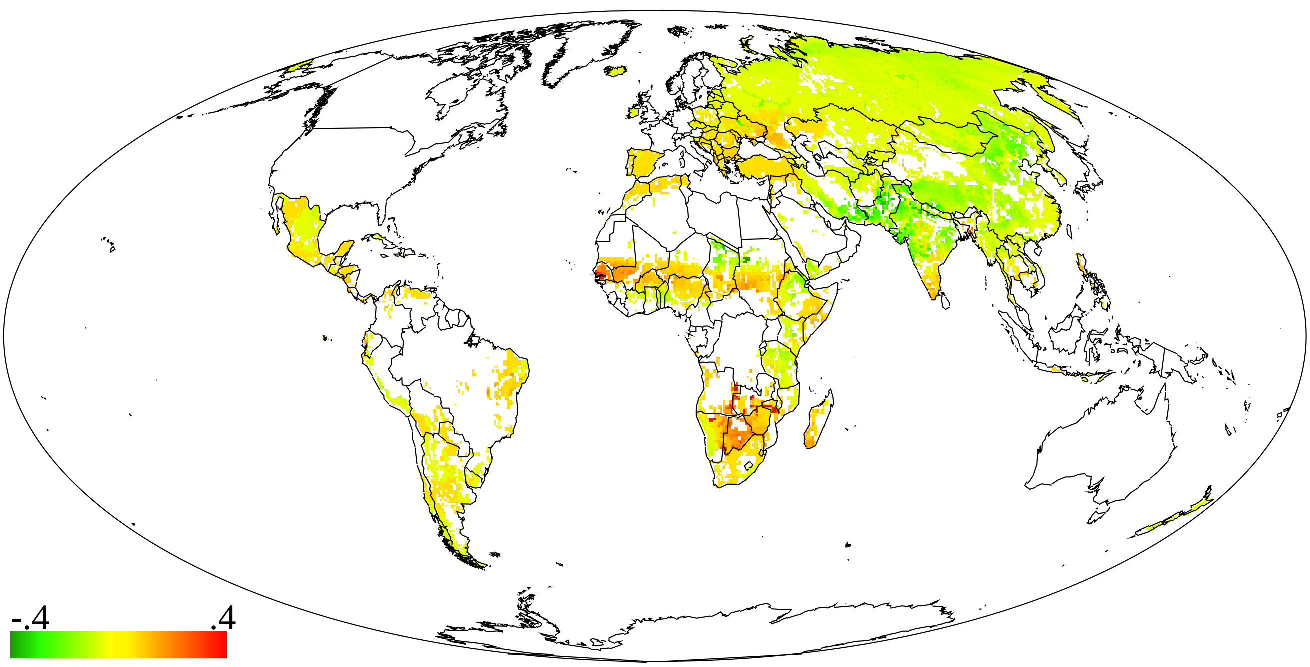


Figure 5. Change in disposition under the ECHAM 3 climate prediction: D(changed climate) - D(present climate)

improvement in Pakistan, India, Myanmar, Thailand, Ivory Coast, Ghana, and Argentina, regions which are predicted to become worse on the basis of the Hadley Centre prognosis. The opposite holds true for the regions around the Black Sea. From this follows that the differences in the climate forecasts produce qualitative differences in the prediction of the Sahel Syndrom disposition and therefore cause severe problems in deciding where mitigation measures have to be performed.

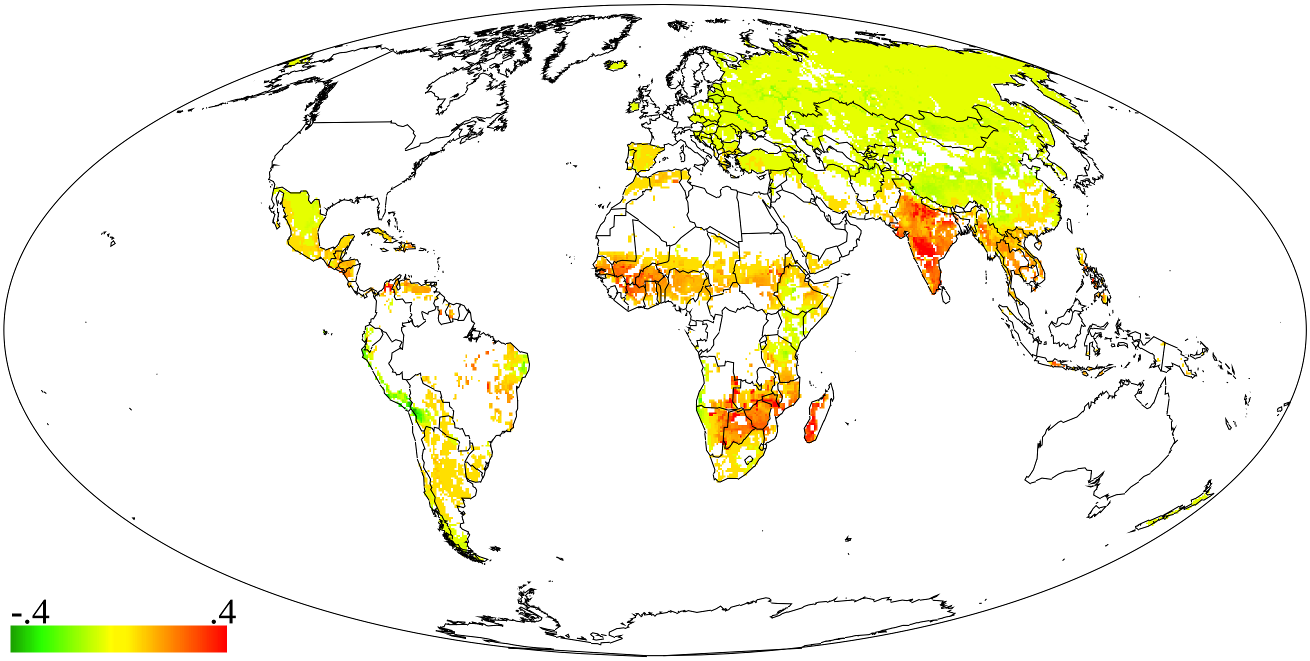


Figure 6. Change in disposition under the Hadley-Centre climate prediction: D(changed climate) - D(present climate)

## 5. Discussion

The starting point of our analysis was one typical existing pattern of problematic civilization-environment interaction, the Sahel Syndrome, which caused and causes severe environmental degradation and human suffering. In the first place this pattern has to be mitigated where it currently occurs: for a discussion of the identification of infected regions and the development of mitigation measures under incomplete and qualitative knowledge see [14, this volume]. An equally important question asks for regions which are presently prone to the Syndrome: here prophylactic measures, either reducing the present disposition by influencing the main disposition factors (e.g. via promotion of alternative sources of income, see [21] ) or the strict avoidance of exposition factors which could start the disastrous mechanism (see e.g. [14, this volume]), have to be applied.

The influence of climate change on the complex described above is threefold:

- The dynamics of the already active syndrome could be modified (e.g. accelerated by climate-induced modification of the strength of important interactions).
- Disposed but still uninfected regions could become infected by the syndrome via a climate change related exposition (e.g. extreme drought events in regions not previously prone to these).
- The disposition of a region may be modified by climate change.

The third aspect which we investigated in this study is of particular interest as additional regions of newly emerging disposition to those presently endangered by the Sahel Syndrome are identified, describing a qualitative change with respect to the necessity of developing specific adaption measures. The scenario based computations (section 4) have shown good mutual agreement for an increase in the disposition towards the Sahel Syndrome in several regions of the world. In particular, regions adjacent to those already disposed to or even affected by the syndrome are becoming endangered: regions in the north-east of Brazil, countries in southern Africa, and a broad strip directly south of the Sahel. Due to the high danger of migration out of regions affected by syndromes and to possible spatial couplings by natural processes like sand storms, or local and regional climate change in the Sahel Syndrome, there is not only an increased disposition in the regions indicated, but also an enhanced chance of exposition. Taken the two together this leads to an actual outbreak of the syndrome.

In many regions of the world the different climate change scenarios used in this paper lead to significantly different dispositions. To cope with this frequently discussed uncertainty of climate forecasts, we performed in addition to the scenario calculations a sensitivity study independent of a particular climate scenario.

Comparing the result of the sensitivity study (fig. 3) with the results of the calculations based on two different climate predictions (figs. 5 and 6) shows that

- only <0.1% of the grid elements with a sensitivity greater than 0 remain constant in both scenario calculations.
- 90.5% of the grid elements with vanishing sensitivity remain constant in both scenario calculations.

From this one can conclude that the local (in climate space) sensitivity analysis is an almost perfect predictor of change and a reasonable predictor of constancy under climate change when compared to the scenario based calculations. Furthermore one may compare the meaningfulness of the sensitivity study and the scenario calculations concerning the identification of endangered regions. Even assuming that agreement of the different predictions is an indication of validity (which is not necessarily true), the scenario-based predictions yield no additional information for large areas compared to the sensitivity study due to their ambiguity even in the direction of change. Interestingly for many of the regions identified as endangered by emerging SAHEL SYNDROME disposition (see section 3, fig. 4), the scenario calculations are ambiguous, as they are for parts of India, China and the west African countries. Possible strategies coping with this incomplete knowledge for these regions could be (ordered with respect to risk averting): to start immediately specific adaption measures or to improve the quality of the climate predictions in particular for these regions, for example by nesting a high-resolution regional climate model in GCM calculations as firstly performed by Giorgi [22]. To hope that the respective "positive" prediction holds true seems irresponsible.

## 6. Acknowledgments

We would like to thank Hans-Joachim Schellnhuber for bringing the idea of local sensitivity analysis into Syndrome analysis.

We gratefully acknowledge Gerd Esser, Jörg Kaduk, Gundolf Kohlmaier, Bill Parton, Matthias Plöchl, Colin Prentice, Pièrre Warnant and Ian Woodward together with their collaborators, who provided their NPP results for this study. Furthermore we thank Jürgen Kropp for advice in the 'alchemy' of neural network use, and, again, Jörg Kaduk for very helpful discussions on the mathematics of the neural network used here. Also we acknowledge Andreas Zell and his group for supplying the Stuttgart Neural Network Simulator, SNNS, [23] which was used for design and training of the neural net described here.

This work was supported in part by the German Federal Ministry for Education, Science and Technology under grant number 01LG9401.

## Appendix

### A. The Neural Net based Npp model – NNN

For the calculation of the terrestrial net primary productivity (NPP) from the local climate a reduced form model was needed for this study, since the available models are too slow and unwieldy for this kind of sensitivity analysis. To build a statistic reduced form model a best guess for the global distribution of NPP and Climate was needed. The best guess equilibrium NPP field was derived by averaging the results of eight state-of-the-art NPP models in equilibrium with the current climate. This had to be done since there are not enough NPP measurements available to calibrate the reduced form model due to the large number of parameters necessary to take all 36 inputs into consideration. The eight models were HRBM [24], BIOME3 [25], PLAI [26,27], SILVAN [28], CARAIB [29], DOLY [30], FBM [31,32], CENTURY [33]. If one does not have any information about how reliable the results from each individual model are, as it is the case for state-of-the-art NPP modeling, it is sensible to assume for each model the same probability of being correct. If one is doing this it is advantageous to average the model results, since the expectation value of the mean absolute error of the averaged NPP is smaller or equal than the expectation value of the mean absolute error of a randomly chosen model, as can be easily calculated, assuming a complete (although unknown) field of observed NPP values.

Each of the eight models was run using the same climate data on a 0.5° by 0.5° grid as input, CLIMATE

2.1 [17], and returned annual equilibrium NPP values at the same resolution. Climate data and the average of these NPP values give us a "training set" to fit the NPP-function on.

$$NPP^g = NPP\left(\vec{C}^g\right) \quad (8)$$

where $\vec{C}^g$ denotes the climate data vector at grid cell $g$ ($g = 1, \ldots, 62483$). The training set was then used to train a feedforward neural net with 21 neurons in one hidden layer using the standard backpropagation algorithm. However, only a part of the available training set was used for actual training, so that there is an independent data set for validation. The neural net function in detail is given by

$$NPP(C_1, \ldots, C_{36}) = f\left(\theta_0 + \sum_{k=1}^{36} \omega_{0,k} C_k + \sum_{j=1}^{21} \omega_{0,j+36} \cdot f\left(\theta_j + \sum_{k=1}^{36} \omega_{j,k} C_k\right)\right) \quad (9)$$

where the $C_k$ are the 36 climate variables at a given grid cell. $f(x) = (1 + e^{-x})^{-1}$ is the so-called activation function, and the 835 different $\omega$ and $\theta$ are the parameters that allow the function to be fitted to the data by the backpropagation learning algorithm. To counter the problem of the backpropagation algorithm being stuck in a local minimum, we run the backpropagation algorithm 30 times with different initial values and took the best of these fits. (The differences between the good fits are not large. The mean standard deviation of the outputs produced by the 15 best fits at a given grid point average 0.011 $kgC/m^2/a$.)

This statistical model yields a good reproduction of the training set with a mean absolute error of 0.024 $kgC/m^2/a$, which is significantly less than the mean uncertainty of the best guess $NPP$ field originating from the disagreement of the underlying vegetation models (mean standard deviation: 0.124 $kgC/m^2/a$). After training, the net parameters were fixed and the model can then be described as a simple analytical function mapping $\Re^{36} \to \Re$. Model testing showed that it calculates moisture limited regions correctly, indicating that functional properties of the original mechanistic models are reproduced. Also it is able to reproduce the NPP distribution for a whole continent which has not been included in the training set (North America) with almost equal accuracy. The model can be found in FORTRAN and C versions on http://www.pik-potsdam.de/~oliver/NPP.html.

## B. The MEGARUS model for fresh water availability

In this appendix we describe the MEGARUS-Tool which in this paper provides the amount of available surface water within a given grid cell. The model and its validation is described in much more detail in an future publication [34]. Here, we describe the most important properties of MEGARUS necessary for our analysis. It uses the same input variables as the neural net computing the net primary productivity, NNN, which is described in the first appendix, i.e. mean monthly temperatures, monthly precipitation sum, and mean monthly solar radiation.

The model is divided into two independent submodules where the second uses the output of the first as an input:

1. A *vertical component* to compute the local water balance between precipitation, actual evapotranspiration (AET), soil water uptake and surface runoff.

2. A *horizontal component* aggregating the surface runoff of all grid cells identified as belonging to the corresponding catchment. The identification of the catchments has been carried out using the World Data Bank II [35] and graph theoretical methods.

The local water balance is computed as follows. First a small slope dependent amount of precipitation $Prec$ is directly assigned to surface water runoff. Here the same measure for "slope" is used as in equation (4). In the model this direct runoff amounts to 15% of precipitation in completely flat regions and to 65% in case of 5% slope which indicates a rather energetic surface relief. The residual water is assumed to fill a first soil layer (bucket) whose size is assumed to be equal to 50% of the total spatially dependend retention capacity of the soil. The AET is computed as in [36], i.e. as the smaller value of the potential evapotranspiration according to Prietley-Taylor and a water supply function depending on the actual soil moisture $SM$. The latter is given for time step $i$ by the balance equation

$$SM_i = SM_{i-1} + Prec_i - AET_i. \quad (10)$$

In contrast to the version in the latter paper, however, a second soil layer (bucket) can be filled by the excess water from the first layer. Also snow is now included similar as in [37], i.e. it accumulates at days with temperatures less than $0.5^oC$ and melts on the other days. This melt water together with the excess water of the second soil layer yields the surface runoff. In summary, the vertical component computes the mean monthly surface runoff within a single grid cell. The water balance computation neglects, however, inflow from a neighboring box. This is reasonable to the extent that the spatial extention of these flows can be considered to be much smaller than the box size itself.

In the second step a global directed rivers network (GDRN) is used to summarize the available water within a box by adding up the surface runoff of all grid cells previously identified to be upstream of the current cell by the GDRN. In its outcome GDRN produces structures similar to [38]. Our network here, however, is in its basic skeleton structure constructed by using a digital network of rivers. Using different kinds of discretization schemes it has been checked whether the networks are well connected or not: If the different discretization schemes yield contradictory results, the site has been checked by comparison with the Times World Atlas. In this manner a set of well connected river networks has been constructed. Next, we have made use of a global ocean mask to determine the river deltas of these different networks. Whenever this procedure has not been able to identify a delta, again the Times World Atlas has been used to do so. Using simple graph theoretical tools together with the rule that water should not flow in cycles, we have been able to put a direction on each part of the river networks.

This analysis which does not use information of any kind of digital elevation model in contrast to several other similar efforts. Yet it does not allow us to put a river direction onto every grid cell of the basic lattice as about 50% of the cells are not occupied by any river segment in the original data bank. We therefore have used the $5' \times 5'$ digital elevation model to determine the direction of flow of the remaining empty cells. In this way we have been able to track the flow to the "next" river segment for every one of these unoccupied cells. Following the river network we obtain a complete routing scheme which, however, does not yet allow a temporal resolution. It only serves for estimating the annual mean surface water flow - which is exactly the information needed for our analysis.

The model has been tested against the data of 260 river stations world wide, provided by the GEMS/Water data base [39]. It does very well in predicting the area of the upstream basins ($R^2 = 0.995$) which indicates a sufficient quality of the horizontal component. Still satisfying, though somewhat minor, is the reconstruction of the river discharge itself ($R^2 = 0.93$). This hints to the limited reliabilty of the "bucket approach" used for the vertical component. For a detailed discussion of the results we again refer to an upcoming paper [34].

## References


[1] German Advisory Council on Global Change. *World in Transition: Ways towards Global Environmental Solutions.* Springer, Berlin, 1996.

[2] M. K. B. Lüdeke and G. Petschel-Held, in: *SCOPE 58 Sustainability indicators: A report on the project on indicators of sustainable development*, eds. B. Moldan et al., John Wiley & Sons, 1997.

[3] H.J. Schellnhuber, A. Block, M. Cassel-Gintz, J. Kropp, G. Lammel, W. Lass, R. Lienenkamp, C. Loose, M.K.B. Lüdeke, O. Moldenhauer, G. Petschel-Held, M. Plöchl, and F. Reusswig. Syndromes of global change. *GAIA*, 6(1997)19–34.

[4] IPCC. *Climate Change 1995: Impacts, Adaptions and Mitigation of Climate Change. Contribution of Working Group II to the second Assessment Report of the Intergovernmental Panel of Climate Change.* University Press, Cambridge New York., 1996.

[5] M. Cassel-Gintz, M. K. B. Lüdeke, G. Petschel-Held, F. Reusswig, M. Plöchl, G. Lammel, and H.-J. Schellnhuber. Fuzzy logic based global assessment of the marginality of agricultural land use. *Climate Research*, 8(1997)135–150.

[6] R. S. Bradley, H. F. Diaz, G. N. Kiladis, and J. K. Eischeid. ENSO signal in continental temperature and precipitation records. *Nature*, 327(1987)497–501.

[7] H. N. Bhalme, A. B. Sikder, and S.K S. K. Jadhav. Coupling between the El Niño and planetary-scale waves and their linkage with the indian monsoon rainfall. *Meteorology and Atmospheric Physics*, 44(1990)293–305.

[8] X. B. Yang and Harald Scherm. El Niño and infectious disease. *Science*, 275(1997)739.

[9] Cynthia Rosenzweig and Martin L. Parry. Potential impact of climate change on world food supply. *Nature*, 367(1994)133–138.

[10] J. M. Melillo, A. D. McGuire, D. W. Kicklighter, B. Moore III, C. J. Vörösmarty, and A. L. Schloss. Global climate change and terrestrial net primary production. *Nature*, 363(1993)234–240.

[11] Anette Reenberg and Bjarke Paarup-Laursen. Determinants for land use strategies in a sahelian agroecosystem – anthro-

pogological and ecological geographical aspects of natural resource management. *Agricultural Systems*, 53(1997)209–229.

[12] H. Jeffrey Leonhard, editor. *Environment and the Poor: Development Strategies for a common Agenda*. Transaction Books, New Brunswick and Oxford, 1989.

[13] R. W. Kates and V. Haarmann. Where the poor live: Are the assumptions correct? *Environment*, 34(1992)4–11, 25–28.

[14] G. Petschel-Held, A. Block, M. Cassel-Gintz, J. Kropp, M.K.B. Lüdeke, O. Moldenhauer, F. Reusswig, and H.J. Schellnhuber. Syndromes of global change. A qualitative modelling approach to assist global environmental management. Submitted to Environmental Modeling and Assessment, 1998.

[15] H. J. Zimmermann. *Fuzzy Set Theory - and its Applications*. Kluwer Academic Publishers, Dordrecht, 1991.

[16] I. C. Prentice, W. Cramer, S. P. Harrison, R. Leemans, R. A. Monserud, and A. M. Solomon. A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography*, 19(1992)117–134.

[17] Wolfgang Cramer. private communication, 1997. Potsdam, www.pik-potsdam.de.

[18] Welt-Ressourcen. Fakten – Daten – Trends. Ökonomisch-ökologische Zusammenhänge. Deutsche Fassung: Handbuch des Umweltschutzes. Technical Report 76. Erg. Lfg. 12/1994, World Resource Institute / International Institute for Environment and Development, 1992/93.

[19] U. Cubasch. Das Klima der nächsten 100 Jahre. *Physikalische Blätter*, 48(1992)85–89.

[20] J. F. B. Mitchell, T. C. Johns, J. M. Gregory, and S. F. B. Tett. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature*, 376(1995)501–4.

[21] M. Leach and R. Mearns. Poverty and the environment in developing countries: an overview study. Technical report, Final report to ESRC, Global Environmental Change Programme and the Overseas Development Administration, 1991.

[22] F. Giorgi. Simulation of regional climate using a limited area model nested in a general circulation model. *J. Clim.*, 3(1990)941–963.

[23] A. Zell. *Simulation Neuronaler Netze*. Addison-Wesley, 1994.

[24] G. Esser, J. Hoffstadt, F. Mack, and U. Wittenberg. *High Resolution Biosphere Model: Documentation Model version 3.00.00*. Institut für Planzenökologie, Justus-Liebig-Universität Gießen, 1994.

[25] A. Haxeltine and I. C. Prentice. BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competion among plant functional types. *Global Biogeochemical Cycles*, 10(4) (1996) 693–709.

[26] M. Plöchl and W. C. Cramer. Coupling global models of vegetation structure and ecosystem processes. an example from arctic and boreal ecosystems. *Tellus*, 47B (1995) 240–250.

[27] M. Plöchl and W. C. Cramer. Possible impacts of global warming on tundra and boreal forest ecosystems: comparison of some biogeochemical models. *J. Biogeogr.*, 22 (1995) 775–783.

[28] J. Kaduk and M. Heimann. A prognostic phenology scheme for global terretrial carbon cycle models. *Clim. Res.*, 6 (1996) 1–19.

[29] P. Warnant, L. Francois, D. Strivary, and J. C. Gérard. CARAIB: A global model of terrestrial biological productivity. *Global Biogeochemical Cycles*, 8(3) (1994) 255–270.

[30] F. I. Woodward, T. M. Smith, and W. R. Emanuel. A global land primary productivity and phytography model. *Global Biogeochem. Cycles*, 9(4) (1995) 471–490.

[31] M. K. B. Lüdeke, F. W. Badeck, R. D. Otto, C. Häger, S. Dönges, J. Kindermann, G. Würth, T. Lang, U. Jäkel, A. Klaudius, P. Ramge und S. Habermehl, and G. H. Kohlmaier. The frankfurt biosphere model. a global process oriented model for the seasonal and longterm $CO_2$ exchange between terrestrial ecosystems and the atmosphere. Part 1: Model description and illustrating results for the vegetation types cold deciduous and boreal forests. *Clim. Res.*, 4(2) (1994) 143–166.

[32] G. H. Kohlmaier, F. W. Badeck, R. D. Otto, C. Häger, S. Dönges, J. Kindermann, G. Würth, T. Lang, U. Jäkel, A. Nadler, A. Klaudius, P. Ramge, S. Habermehl, and M. K. B. Lüdeke. The frankfurt biosphere model: A global process-oriented model for the seasonal and long-term $CO_2$ exchange between terrestrial ecosystems and the atmosphere. Part 2: Global results for potential vegetation in an assumed equilibrium state. *Clim. Res.*, 8 (1997) 61–87.

[33] D. S. Schimel, B. H. Braswell, R. McKeown, D. S. Ojima, W. J. Parton, and W. Pulliam. Climate and nitrogen controls on the geography and time scales of terrestrial biogeochemical cycling. *Global Biogeochem. Cycles*, 10(4) (1996) 677–692.

[34] G. Petschel-Held, W. Cramer, V. Krysanova and M. Plöchl. A model to estimate global runoff and river discharges. In preparation, 1998.

[35] D. M. Danko. The digital chart of the world. *GeoInfo System*, 2 (1992) 29–36.

[36] I. Colin Prentice, Martin T. Snykes, and Wolfgang Cramer. A simulation model for the transient effects of climate change. *Ecological Modelling*, 65 (1993) 51–70, 1993.

[37] Beate Klöcking. Ein Modell zur Beschreibung des Wasser, Wärme und Stickstoff Haushalts im Boden unter besonderer Berücksichtigung des Winterzeitraums. PhD thesis, Univ. Dresden, 1991.

[38] S. Hagemann and L. Dümenil. A parametrization of the lateral waterflow for the global scale. *Climate Dynamics*, 14 (1998) 17–31.

[39] Global Environmental Monitoring System Freshwater Quality Programme (GEMS/WATER). Internet Page: http://www.cciw.ca/gems/intro.html.